Perfect Conductivity Lecture 2

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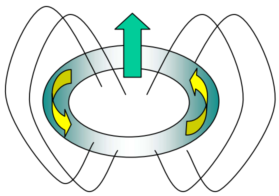
Outline

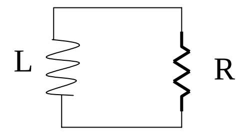
1. **Persistent Currents**
2. **Parts of a Physical Theory**
3. **Circuits and Time Constants**
4. **Distributive Systems and Time constants**

   A.Quasistatics

   B.MagnetoQuasiStatics (MQS)

Persistent Currents





If the field is turned off, then $I(t) = I|_{t=0}\, e^{-t/\tau_{LR}}$

The time constant $\tau_{LR} = L/R$

If the loop is made out of a superconductor,

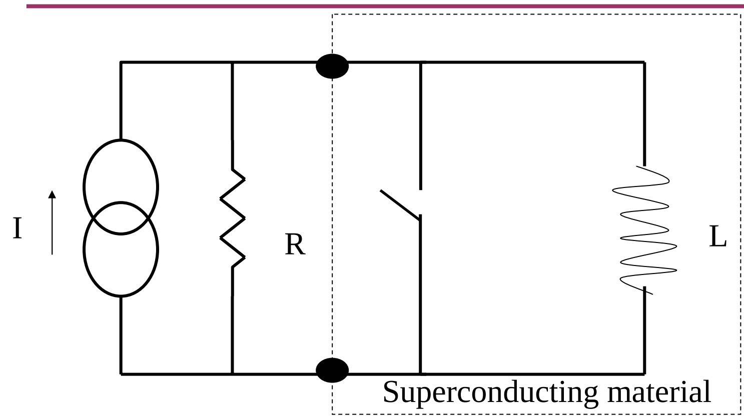
$$\lim_{R \to 0} \tau_{LR} \to \infty \qquad I(t) = I|_{t=0} \qquad \text{for } t \geq 0.$$

Experimentally the dc resistivity of a superconductor is at least as small as $10^{-25}\ \Omega\text{-m}$. The superconducting state is “truly” zero dc resistance.

Perfect Conductivity: t << τ_{RL}= L/R, sytem looks like R is zero

Superconductivity: for all time, R is zero

Charging up a superconducting loop



This Persistent Mode is the basis of MRI magnets, SMES, flux memory….

Parts of a Physical Theory

1. Governing Laws:

   Maxwell's Equations, Newton's equations,

2. Constitutive Laws:

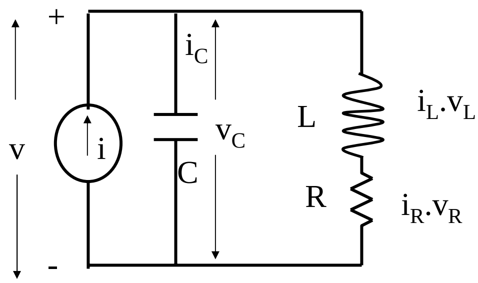
   Models of the system

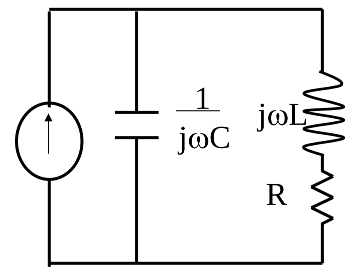
   like ohm's law,

3. Summary Relations:

   Transfer functions, Dispersion relations

LRC Circuit





1. Governing Equations

Current conservation: $i=i_C + i_L$ $i_L = i_R$

Energy Conservation $v = v_C = v_R + v_L$

2. Constitutive Relations

For the resistor

$$v_R = i_R R\,,$$

for the inductor as

$$v_L = L\frac{d}{dt}i_L\,,$$

and for the capacitor as

$$i_C = C\frac{d}{dt}v_C\,,$$

$$\hat{\imath} \equiv |i|\,e^{j\phi}$$

and

$$v = \mathrm{Re}\left\{\hat{v}\,e^{j\omega t}\right\}$$

so that

$$v = \mathrm{Re}\left\{\hat{v}\,e^{j\omega t}\right\}$$

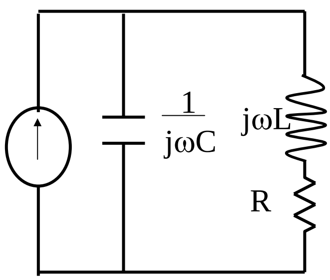
$$\hat{v}_R = \hat{\imath}_R\,,$$

$$\hat{v}_L = j\omega L\,\hat{\imath}_L$$

$$\hat{\imath}_C = j\omega C\,\hat{v}_C$$

3. Summary Relation

$$Z(\omega) = R\left(\frac{1 + j\omega\tau_{RL}}{\left(1 - (\omega\tau_{LC})^2\right) + j\omega\tau_{RC}}\right) .$$



the *inductive time constant:*

$$\tau_{RL} \equiv \frac{L}{R} , \qquad (1)$$

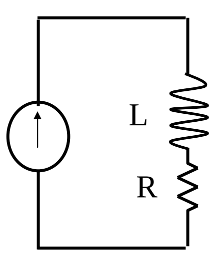
the *capacitive time constant:*

$$\tau_{RC} \equiv RC , \qquad (2)$$

and the *coupling time constant:*

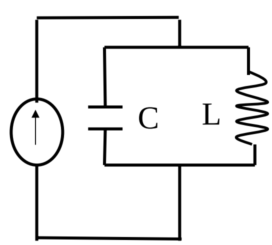
$$\tau_{LC} \equiv \sqrt{LC} = \sqrt{\tau_{RL}\,\tau_{RC}} . \qquad (3)$$

Simpler Circuits and Time Constants



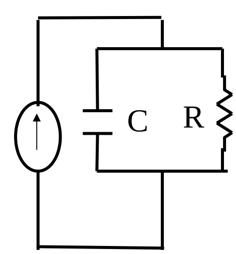
$$\tau_{RL} \equiv \frac{L}{R}$$

Energy stored in inductor



$$\tau_{LC} \equiv \sqrt{LC}$$

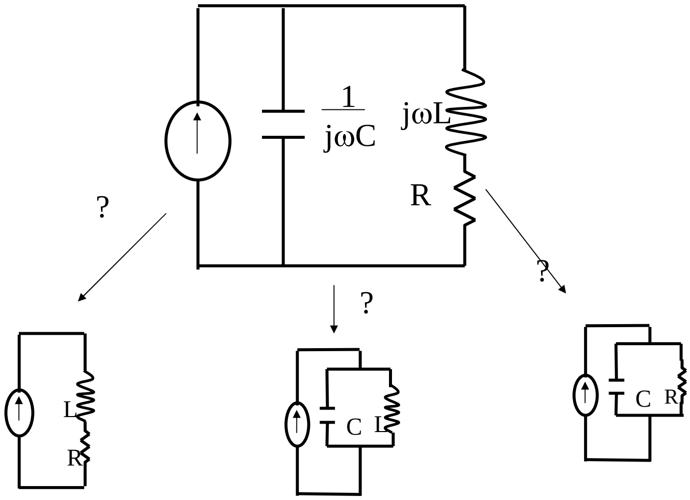
Resonant transfer of energy between L and C



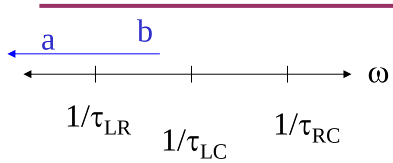
$$\tau_{RC} \equiv RC$$

Energy stored in capacitor

Reducing the Circuit to a simpler form ?



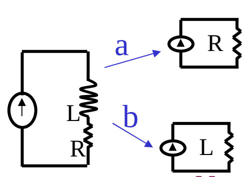
Order of time constants

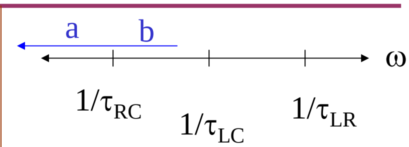


$\tau_{LR} > \tau_{RC}$ Low R $R < \sqrt{\frac{L}{C}}$

$$\lim_{\substack{\omega\tau_{LC} \ll 1 \\ \tau_{RC} < \tau_{RL}}} Z(\omega) \approx R(1 + j\omega\tau_{RL})$$

Low frequency circuit

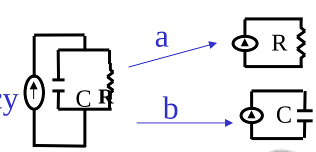




$\tau_{LR} < \tau_{RC}$ High R $R > \sqrt{\frac{L}{C}}$

$$\lim_{\substack{\omega\tau_{LC} \ll 1 \\ \tau_{RL} < \tau_{RC}}} Z(\omega) \approx R\left(\frac{1}{1 + j\omega\tau_{RC}}\right)$$

Low frequency circuit



Moral of time constants

If you know what frequency range you want to study or what physics dominates the problem,

then you can solve a simpler problem.

Useful, especially in more complex situations.

Distributed Systems

1. Governing Equations: Maxwell's Equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$ Faraday's Law

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$ Ampere's Law

$$\nabla \cdot \mathbf{D} = \rho$$ Gauss Law

$$\nabla \cdot \mathbf{B} = 0$$ Gauss' Magnetic Law

Conservations laws

$$\nabla \cdot \mathbf{J} + \frac{\partial \rho}{\partial t} = 0$$ Charge conservation Also Poynting's

Distributied systems con't

2. Constitutive Relations

$$\mathbf{B}(\mathbf{r},\omega) = \mu(\omega)\,\mathbf{H}(\mathbf{r},\omega)$$

$$\mathbf{D}(\mathbf{r},\omega) = \epsilon(\omega)\,\mathbf{E}(\mathbf{r},\omega)$$

Local in space,
linear time invariant

$$\mathbf{J}(\mathbf{r},\omega) = \sigma(\omega)\,\mathbf{E}(\mathbf{r},\omega) \longrightarrow$$ Ohm's Law

3. Summary relations

Complex: Search first for first order in time approximation

Quasistatic Limit

$$\ell \ll \lambda_{em} = \frac{2\pi c}{\omega}$$

ℓ → Length scale of system

λ_{em} → Wavelength of E&M wave

c → Speed of light

ω → Frequency (angular)

If the dimensions of a structure are much less than the wavelength of an electromagnetic field interacting with it, the coupling between the associated electric and magnetic fields is weak and a quasistatic approximation is appropriate.

Time Constants

$$\tau_{em} \equiv \frac{\ell}{c} = \ell\sqrt{\mu\epsilon}$$ Electromagnetic coupling time

$$\tau_e \equiv \frac{\epsilon}{\sigma_o}$$ Charge relaxation time

$$\tau_m \equiv \mu\sigma_o\ell^2$$ Magnetic diffusion time

$$\tau_{em} = \sqrt{\tau_e\tau_m}$$

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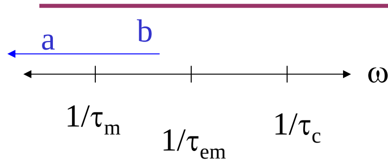
Please see: Figure 2.9, page 34, from Orlando, T., and K. Delin. *Foundations of Applied Superconductivity*. Reading, MA: Addison-Wesley, 1991. ISBN: 0201183234.

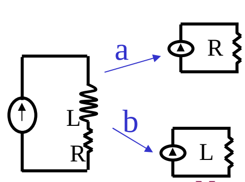
Order of time constants

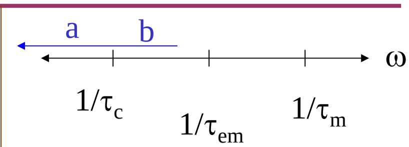


$\tau_m > \tau_c$ High conductivity $\sigma_o > \frac{1}{\ell}\sqrt{\frac{\epsilon}{\mu}}$

MQS

Low frequency circuit

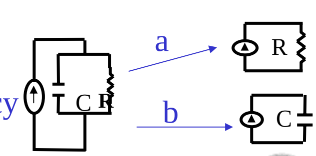




$\tau_m < \tau_e$ Low conductivity $\sigma_o < \frac{1}{\ell}\sqrt{\frac{\epsilon}{\mu}}$

EQS

Low frequency circuit



MagnetoQuasiStatics

$$\left.\begin{aligned}\nabla \times \mathbf{H} &= \mathbf{J} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \cdot \mathbf{J} &= 0\end{aligned}\right\}$$ Solve first

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$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Solve for **E** once **B** is found

Boundary conditions:

$$n \times (H_2 - H_1) = K \qquad n \cdot (B_2 - B_1) = 0 \qquad n \cdot (J_2 - J_1) = 0$$

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MQS: Magnetic Diffusion Equation

For a metal **B** = μ_0 **H**, **D** = ε_0 **E** and **J** = σ_0**E**, so that

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$$\left(\mu\sigma_o \frac{\partial}{\partial t} - \nabla^2\right) \mathbf{H} = 0$$

Magnetic Diffusion Equation

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