Permittivity of free space: $\epsilon_0 = 8.854 \times 10^{-12}$
Elementary charge: $e = 1.602 \cdot 10^{-19}$
Proton mass: $1.673 \cdot 10^{-27}$ Electron mass: $9.11 \cdot 10^{-31}$
Speed of light: $c = 3 \cdot 10^8$ Permeability constant: $\mu_0 = 1.26 \times 10^{-6}$

Moving Conductor

$$I = \frac{\Delta V}{R} = \frac{\varepsilon}{R} = \frac{vlB}{R}$$

$$F_{\text{mag}} = F_{\text{pull}} = IlB = \frac{vl^2B^2}{R}$$

$$P_{\text{input}} = P_{\text{dissipated}} = I^2R = \frac{v^2l^2B^2}{R}$$

$$\Phi_m = \vec{A} \cdot \vec{B} = |A||B|\cos\theta \quad \text{(uniform magnetic field)}$$

- Increasing flux: The induced magnetic field points opposite the applied magnetic field.
- Decreasing flux: The induced magnetic field points in the same direction as the applied magnetic field.
- Steady flux: There is no induced magnetic field.

$$\varepsilon_{\text{induced}} = -N\frac{d\Phi_m}{dt} \quad I_{\text{induced}} = \frac{\varepsilon_{\text{induced}}}{R}$$

$$E_{\text{inside}} = \frac{r}{2}\left|\frac{dB}{dt}\right| \quad \text{Solenoid}$$

Transformers

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \quad P_1 = P_2 \quad V_1I_1 = V_2I_2 \quad \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Inductors

$$L = \frac{\Phi_m}{I} \text{ henry (H)}$$

$$\Delta V_L = -L\frac{dI}{dt} \quad U_L = L\int_0^I IdI = \frac{1}{2}LI^2$$

LC Circuits

$$I = -\frac{dQ}{dt} \quad Q(t) = Q_0\cos\omega t \quad \omega = \frac{1}{\sqrt{LC}}$$

LR Circuits

$$I = I_0e^{-t/(L/R)}$$

$$\tau = \frac{L}{R} \quad \text{where current has decreased to } e^{-1}$$

Right-hand rule (wire)

1. Point thumb in the direction of current
2. Point fingers in the direction of magnetic field
3. Point palm in the face of force on wire

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A \quad \vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

$$a \times b = \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ a_x & a_y & a_z \\ b_x & b_y & b_z \end{vmatrix}$$

Maxwell changed Ampere's Law because it only applied to steady current.

$$I_{\text{disp}} = \epsilon_0\frac{d\Phi_e}{dt} = \epsilon_0\frac{dE \cdot A}{dt}$$

Displacement current is from changing electric field rather than flow of charges.

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{in}}}{\epsilon_0} \quad \text{Gauss's Law}$$

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad \text{Gauss's Law for Magnetism}$$

$$\oint \vec{E} \cdot d\vec{s} = -N\frac{d\Phi_m}{dt} \quad \text{Faraday's Law}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0I_{\text{through}} + \epsilon_0\mu_0\frac{d\Phi_e}{dt} \quad \text{Ampere-Maxwell Law}$$

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{Lorentz Force Law}$$

$$E(x,t) = E_0\cos(kx - \omega t + \phi)$$

$$c = \frac{\omega}{k} = \frac{\omega\lambda}{2\pi} = f\lambda = \frac{E}{B}$$

$$I = \frac{P}{4\pi r^2} = \frac{c\epsilon_0E_0^2}{2}$$

$$\langle S \rangle = \frac{1}{\mu_0}EB\sin\theta \quad \text{(Poynting Vector) energy flux of an electromagnetic wave}$$

Right-hand rule (electromagnetic waves)

Index: electric field, Middle: magnetic field, Thumb: motion

$$I_{\text{transmitted}} = \frac{1}{2}I_0 \quad \text{(unpolarized)} \quad I_{\text{transmitted}} = I_0\cos^2\theta \quad \text{(polarized)}$$

$$\varepsilon = \varepsilon_0\cos\omega t \quad \omega = 2\pi f$$

$$v_R = i_RR = V_R\sin\omega t \quad \text{(AC circuit) and } V_R \text{ is the maximum voltage}$$

Capacitor circuit

$$v_C = V_C\cos\omega t \quad q = Cv_C$$

$$i_C = -\omega CV_C\sin\omega t = \omega CV_C\cos(\omega t + \frac{\pi}{2})$$

$$X_C = \frac{1}{\omega C} \quad I_C = \frac{V_C}{X_C} \quad (X_C \text{ is Capacitive reactance})$$

$$\omega_C = \frac{1}{RC} \quad \text{(RC Circuit)}$$

Inductor circuit

An inductor is a coil of wire that generates a magnetic field when current flows through it and resist changes in current by inducing an emf opposite to the charge.

$$i_L = I_L\cos(\omega t - \frac{\pi}{2})$$

$$X_L = \omega L \quad I_L = \frac{V_L}{X_L} \quad (X_L \text{ is Inductive reactance})$$

Series RLC Circuit

$$V = \sqrt{V_R^2 + (V_L - V_C)^2}$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad \text{(impedance)} \quad I_{\text{peak}} = \frac{\varepsilon_0}{Z}$$

$$\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \quad \text{(angle between emf and current)}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \text{(resonance frequency) when } X_L = X_C \text{ and } Z = R$$

- If $V_C > V_L$, the circuit operates below resonance frequency
- If $V_L > V_C$, the circuit operates above resonance frequency

$p = i\varepsilon$ (AC circuit) i and ε are current and potential difference

$$P_R = \frac{1}{2}I_R^2R = I_{\text{rms}}V_{\text{rms}}$$

$$x_{\text{rms}} = \frac{x}{\sqrt{2}}$$

$$P_{\text{source}} = \frac{1}{2}I\varepsilon_0\cos\phi = I_{\text{rms}}\varepsilon_{\text{rms}}\cos\phi = P_{\text{max}}\cos^2\phi$$

$\cos\phi$ is the power factor, ϕ is the phase between current and emf, and $P_{\text{max}} = \frac{1}{2}I_{\text{max}}\varepsilon_0$.

- AC circuit with capacitor: current leads voltage by $\frac{\pi}{2}$ (current reaches maximum $\frac{T}{4}$ before voltage)
- AC circuit with inductor: current lags voltage by $\frac{\pi}{2}$ (current reaches maximum $\frac{T}{4}$ after voltage)
- AC circuit with resistor: current is in phase with voltage