Class 21: Outline

Hour 1:
   Expt. 9: Faraday’s Law

Hour 2:
   Faraday’s Law
   Transformers
   Magnetic Materials
Last Time:
Faraday’s Law
Faraday’s Law of Induction

\[ \mathcal{E} = -N \frac{d \Phi_B}{dt} \]

Changing magnetic flux *induces* an EMF

Lenz: Induction *opposes* change
What can change?

\[ \mathcal{E} = -N \frac{d}{dt} (BA \cos \theta) \]

Quantities which can vary with time:

- Magnitude of B
- Area A enclosed by the loop
- Angle \( \theta \) between B and loop normal
Falling magnet slows as it approaches a copper ring which has been immersed in liquid nitrogen.
Example: Magnitude of B
Magnet Falling Through a Ring

Falling magnet approaches a copper ring
or Copper Ring approaches Magnet
Moving Towards Dipole

As ring approaches, what happens to flux?
It increases
Moving Over Dipole

Flux increases then decreases
Note we have arbitrarily assigned $dA$ up
Moving Over Dipole

Current first goes in one direction, then other.
It ALWAYS opposes the changing flux.
Five PRS Questions: Predictions for Experiment 9
Faraday’s Law
Experiment 9:
Faraday’s Law of Induction
Imperfect current 0
Four PRS Questions:
Force on A Loop Below Magnet Moving Upward;
Moving Rail;
Moving Rectangle near Wire;
Generator.
Brakes
Magnet Falling Through a Ring

What happened to kinetic energy of magnet?
Eddy Current Braking


What happened to kinetic energy of pendulum?
Eddy Current Braking

http://demoroom.physics.ncsu.edu/multimedia/video/5K20.22.1.MOV

What happened to kinetic energy of disk?
Demonstration: Eddy Current Braking
Eddy Current Braking

The magnet induces currents in the metal that dissipate the energy through Joule heating:

1. Current is induced counter-clockwise (out from center)
2. Force is opposing motion (creates slowing torque)
Eddy Current Braking

The magnet induces currents in the metal that dissipate the energy through Joule heating:

1. Current is induced clockwise (out from center)
2. Force is opposing motion (creates slowing torque)
3. EMF proportional to \( \omega \)
4. \( F \propto \frac{E^2}{R} \)
Demonstration: Levitating Magnet
Superconductor & Magnet

PRS Questions: Loop in Uniform Field
Mutual Inductance
Mutual Inductance

A current $I_2$ in coil 2, induces some magnetic flux $\Phi_{12}$ in coil 1. We define the flux in terms of a “mutual inductance” $M_{12}$:

$$N_1 \Phi_{12} \equiv M_{12} I_2$$

$$\rightarrow M_{12} = \frac{N_1 \Phi_{12}}{I_2}$$

$$\mathcal{E}_{12} \equiv -M_{12} \frac{dI_2}{dt}$$
Demonstration: Remote Speaker
Transformer

Step-up transformer

\[ V_p \quad N_p \quad N_s \quad N \quad \Phi \quad \frac{d\Phi_B}{dt} \]

\[ E_p = N_p \frac{d\Phi_B}{dt} \]

\[ E_s = N_s \frac{d\Phi_B}{dt} \]

\[ \frac{E_s}{E_p} = \frac{N_s}{N_p} \]

\[ N_s > N_p: \text{ step-up transformer} \]
\[ N_s < N_p: \text{ step-down transformer} \]
Demonstrations:

One Turn Secondary:
Nail

Many Turn Secondary:
Jacob’s Ladder
Transmission of Electric Power

Power loss can be greatly reduced if transmitted at high voltage
Example: Transmission lines

An average of 120 kW of electric power is sent from a power plant. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is sent at (a) 240 V, and (b) 24,000 V.

(a) \[ I = \frac{P}{V} = \frac{1.2 \times 10^5 W}{2.4 \times 10^2 V} = 500 A \]

\[ P_L = I^2 R = (500 A)^2 (0.40 \Omega) = 100 kW \]

83% loss!!

(b) \[ I = \frac{P}{V} = \frac{1.2 \times 10^5 W}{2.4 \times 10^4 V} = 5.0 A \]

\[ P_L = I^2 R = (5.0 A)^2 (0.40 \Omega) = 10 W \]

0.0083% loss
Magnetic Materials
Recall Polar Dielectrics

Dielectric polarization decreases Electric Field!
Para/Ferromagnetism

Applied external field $B_0$ tends to align the atomic magnetic moments.
Para/Ferromagnetism

The aligned moments tend to *increase* the B field

\[ \vec{B} = \kappa m \vec{B}_0 \]

Compare to:

\[ \vec{E} = \frac{\vec{E}_0}{\kappa E_{P21-33}} \]
Para/Ferromagnetism

Paramagnet: Turn off $B_0$, everything disorders
Ferromagnet: Turn off $B_0$, remains (partially) ordered

This is why some items you can pick up with a magnet even though they don’t pick up other items.
Magnetization Vector

Useful to define “Magnetization” of material:

\[
\mathbf{\vec{M}} = \frac{1}{V} \sum_{i=1}^{N} \mathbf{\vec{\mu}}_i = \frac{\mathbf{\vec{\mu}}}{V}
\]

\[
\mathbf{\vec{B}} = \mathbf{\vec{B}}_0 + \mu_0 \mathbf{\vec{M}}
\]
Hysteresis in Ferromagnets

The magnetization $M$ of a ferromagnetic material depends on the history of the substance.

Magnetization remains even with $B_0$ off !!!