PHYS12 CH: 23.1-23.7

Electromagnetic Induction and Its Applications

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Outline

Learning Objectives

By the end of this presentation, you will be able to:

- Define magnetic flux and explain electromagnetic induction
- State and apply Faraday's Law and Lenz's Law
- Calculate motional emf in a conductor moving through a magnetic field
- Explain the concepts of eddy currents and magnetic damping
- Describe the operation of electric generators
- Understand the concept of back emf in motors
- Analyze transformer operation and calculate voltage/current relationships

Magnetic Flux

Definition

Magnetic flux (Φ) is a measure of the total magnetic field passing through a given area.

$$\Phi = BA\cos\theta \tag{1}$$

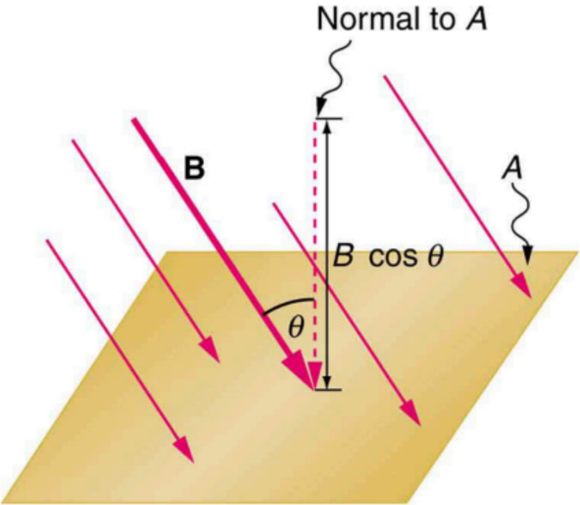
where: (2)

$$B = \text{magnetic field strength} \tag{3}$$

$$A = \text{area} \tag{4}$$

$$\theta = \text{angle with perpendicular} \tag{5}$$

- Units: Tesla·meter² (T·m²)
- Maximum when $\theta = 0$ (field perpendicular to area)
- Zero when $\theta = 90$ (field parallel to area)



$$\Phi = BA\cos\theta = B_{\perp}A$$

Electromagnetic Induction

Fundamental Principle

Any change in magnetic flux induces an electromotive force (emf).

- Discovered independently by Michael Faraday and Joseph Henry
- The induced emf can drive current through a circuit
- The induced current creates its own magnetic field
- Basis for generators, transformers, and many electrical devices

Key Insight

It's the **change** in magnetic flux that induces emf, not the flux itself.

[PHET showing a magnet moving through a coil and the resulting induced current]

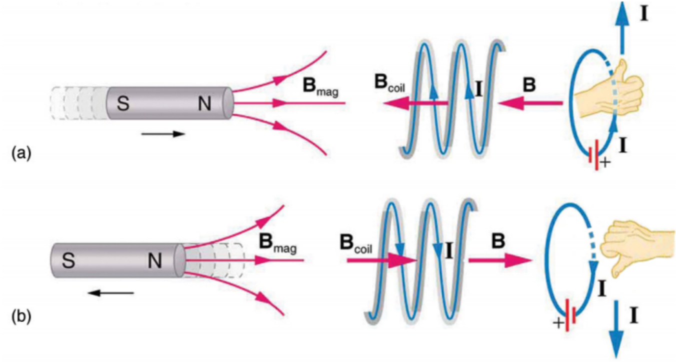
Faraday's Law of Induction

Mathematical Form

$$\text{emf} = -N\frac{\Delta\Phi}{\Delta t} \tag{6}$$

- N = number of turns in a coil
- $\Delta\Phi$ = change in magnetic flux
- Δt = time interval for the change
- The negative sign is due to Lenz's Law

- Ways to change flux:
  - Change B (field strength)
  - Change A (area)
  - Change θ (orientation)



(a)
S
N
B_{mag}
B_{coil}
I
B
I
I
+
(b)
S
N
B_{mag}
B_{coil}
I
B
I
I
+

Lenz's Law

The Minus Sign in Faraday's Law

The induced emf creates a current that produces a magnetic field opposing the change in flux that induced it.

- Conservation of energy principle
- If flux is increasing, induced field opposes the increase
- If flux is decreasing, induced field opposes the decrease
- Works against the cause of the flux change

Important Note

Lenz's Law explains why work must be done against the induced magnetic force to maintain flux changes.

Motional EMF

Definition

EMF induced by motion of a conductor through a magnetic field.

For a straight conductor:

$$\text{emf} = B\ell v \tag{7}$$

- B = magnetic field strength
- ℓ = length of conductor
- v = velocity of conductor

- Applies when B, ℓ, and v are mutually perpendicular
- Causes charge separation in the conductor
- Creates potential difference across the conductor

phys12-magnetism-electromagnetic-field-magnitude.png

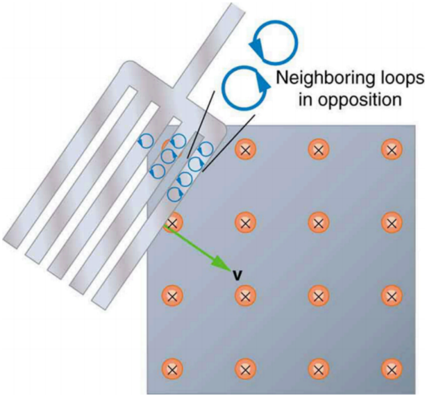
Eddy Currents

Definition

Current loops induced in moving conductors or changing magnetic fields.

- Occur in solid conductors moving through magnetic fields
- Flow in closed loops within the conductor
- Can cause significant heating (I^2R losses)
- Used in induction heating and cooking

- **Magnetic Damping**:
  - Drag force from eddy currents
  - Opposes the motion that created it
  - Used in braking systems
  - Can be reduced by slotting conductors


Neighboring loops
in opposition
v

Electric Generators

Working Principle

A coil rotating in a magnetic field induces a time-varying emf.

$$\text{emf} = NAB\omega\sin(\omega t) \tag{8}$$
$$\text{where:} \tag{9}$$
$$N = \text{number of turns} \tag{10}$$
$$A = \text{area of coil} \tag{11}$$
$$B = \text{magnetic field strength} \tag{12}$$
$$\omega = \text{angular velocity} \tag{13}$$

- Peak emf: $\text{emf}_0 = NAB\omega$
- Produces sinusoidal AC voltage
- Converts mechanical energy to electrical energy
- Basis for power generation worldwide

phys12-magnetism-electric-generator-diagram.png

Back EMF in Motors

Definition

Induced emf in a motor that opposes the applied voltage.

- Motors are generators in reverse: convert electrical to mechanical energy
- When a motor rotates, it also acts as a generator
- This self-generated emf opposes the applied voltage
- Magnitude increases with motor speed
- Limits current in a running motor
- Back emf $= 0$ when motor is first starting (why starting current is high)

Safety Note

The high starting current is why motors need special starters or current limiters.

Transformers

Basic Purpose

Transform AC voltage from one value to another using electromagnetic induction.

Voltage Relationship:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \tag{14}$$

Current Relationship:

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \tag{15}$$

- Primary coil: Connected to AC source
- Secondary coil: Delivers transformed voltage
- N_p, N_s: Number of turns in primary and secondary
- V_p, V_s: Primary and secondary voltages
- I_p, I_s: Primary and secondary currents

- **Step-up transformer:** $N_s > N_p$ (increases voltage, decreases current)

Example Problem: "I do"

Motional EMF Problem

A metal rod of length 1.0 m moves at 2.0 m/s perpendicular to a magnetic field of 0.50 T. Calculate the induced emf.

- **Given:**
  - Length of rod: $\ell = 1.0$ m
  - Speed of rod: $v = 2.0$ m/s
  - Magnetic field: $B = 0.50$ T
- **Find:** The induced emf

Example Problem: "I do"

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  - Magnetic field: $B = 0.50$ T
- **Find:** The induced emf

$$\text{emf} = B\ell v \tag{16}$$

$$= (0.50\ \text{T})(1.0\ \text{m})(2.0\ \text{m/s}) \tag{17}$$

$$= 1.0\ \text{V} \tag{18}$$

Example Problem: "We do"

Generator Problem

A generator has 100 turns of wire in a coil with area 0.05 m² and rotates in a magnetic field of 0.75 T at 60 Hz. Calculate the peak emf.

- **Given:**
  - Number of turns: $N = 100$
  - Area of coil: $A = 0.05\ \mathrm{m}^2$
  - Magnetic field: $B = 0.75\ \mathrm{T}$
  - Frequency: $f = 60\ \mathrm{Hz}$
- **Find:** The peak emf (emf_0)

Let's work through this together:

$$\omega = 2\pi f = 2\pi(60\ \mathrm{Hz}) = 377\ \mathrm{rad/s} \tag{19}$$

$$\mathrm{emf}_0 = NAB\omega \tag{20}$$

$$= 100 \times 0.05\ \mathrm{m}^2 \times 0.75\ \mathrm{T} \times 377\ \mathrm{rad/s} \tag{21}$$

$$= ? \tag{22}$$

Example Problem: "You do"

Transformer Problem

A transformer has 400 primary turns and 100 secondary turns. If the primary voltage is 120 V, what is the secondary voltage?

- **Given:**
  - Primary turns: $N_p = 400$
  - Secondary turns: $N_s = 100$
  - Primary voltage: $V_p = 120$ V
- **Find:** Secondary voltage (V_s)

Hint

Use the voltage relationship for transformers: $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

Try to solve this problem on your own!

Key Equations

Concept	Equation
Magnetic Flux	$\Phi = BA\cos\theta$
Faraday's Law	$\text{emf} = -N\frac{\Delta\Phi}{\Delta t}$
Motional EMF	$\text{emf} = B\ell v$
Generator EMF	$\text{emf} = NAB\omega\sin(\omega t)$
Peak Generator EMF	$\text{emf}_0 = NAB\omega$
Transformer Voltage	$\frac{V_s}{V_p} = \frac{N_s}{N_p}$
Transformer Current	$\frac{I_s}{I_p} = \frac{N_p}{N_s}$

Summary of Key Concepts

- **Electromagnetic Induction:** Process by which changing magnetic flux induces an emf
- **Faraday's Law:** Quantifies the relationship between changing flux and induced emf
- **Lenz's Law:** Determines the direction of induced current to oppose the change
- **Motional EMF:** Produced when a conductor moves through a magnetic field
- **Eddy Currents:** Closed loops of current induced in solid conductors
- **Generators:** Convert mechanical energy to electrical energy using induction
- **Back EMF:** Self-induced voltage in motors that opposes applied voltage
- **Transformers:** Convert AC voltage levels using mutual induction

Real-World Applications

Power Generation & Distribution

- Electric generators in power plants
- Step-up transformers at power plants
- Step-down transformers near consumers

Consumer Electronics

- Induction cooktops
- Wireless charging systems
- Microphones and speakers

Transportation

- Electric motors in vehicles
- Magnetic braking systems
- Induction sensors

Medical Technology

- MRI machines
- Electromagnetic flow meters
- Transcranial magnetic stimulation

Questions?

Thank you for your attention!

Any questions?