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Electromagnetic Induction

Magnetic Flux and Faraday's Laws

Electromagnetic induction is the process of generating an electromotive force (emf) or voltage in a conductor due to a change in magnetic flux through it. Magnetic flux (Φ) is the measure of the total magnetic field passing through a given area and is given by:

$$\Phi = BA \cos \theta$$

where B is the magnetic field strength, A is the area, and θ is the angle between the magnetic field and the normal to the surface.

Faraday's First Law states that an emf is induced in a conductor when the magnetic flux linked with it changes. Faraday's Second Law quantifies this emf as proportional to the rate of change of magnetic flux:

$$\varepsilon = -N \frac{d\Phi}{dt}$$

where N is the number of turns in the coil. The negative sign indicates the direction of induced emf as given by Lenz's Law.

Self and Mutual Induction

Self-induction occurs when a changing current in a coil induces an emf in the same coil. The magnetic flux linked with the coil is proportional to the current:

$$\Phi = LI$$

where L is the self-inductance of the coil. The induced emf is:

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

Mutual induction occurs when a changing current in one coil induces an emf in a nearby coil. The mutual inductance M relates the magnetic flux in the secondary coil to the current in the primary coil:

$$\Phi = MI$$

The induced emf in the secondary coil is:

$$\varepsilon = -M \frac{dI}{dt}$$

Solved Examples

Example 1: A square loop of side 0.1 m is placed in a magnetic field of 0.5 T at an angle of 45°. The magnetic field decreases to zero in 0.1 s. Calculate the induced emf and current if the resistance of the loop is 2 Ω .

Solution:

Area of loop, $A = 0.1 \times 0.1 = 0.01 \text{ m}^2$

Initial magnetic flux,

$$\Phi_i = BA \cos \theta = 0.5 \times 0.01 \times \cos 45^\circ = 0.5 \times 0.01 \times 0.707 = 0.003535 \text{ Wb}$$

Final magnetic flux, $\Phi_f = 0$ (since field decreases to zero)

Change in flux, $\Delta\Phi = \Phi_f - \Phi_i = -0.003535 \text{ Wb}$

Time interval, $\Delta t = 0.1 \text{ s}$

Induced emf, $\varepsilon = \left| \frac{\Delta\Phi}{\Delta t} \right| = \frac{0.003535}{0.1} = 0.03535 \text{ V}$

Induced current, $I = \frac{\varepsilon}{R} = \frac{0.03535}{2} = 0.0177 \text{ A}$

Example 2: A circular coil of radius 10 cm with 500 turns and resistance 2Ω is rotated 180° in Earth's magnetic field of $0.5 \times 10^{-4} \text{ T}$ in 0.1 s. Find the induced emf and current.

Solution:

Radius, $r = 0.1 \text{ m}$

Area, $A = \pi r^2 = 3.1416 \times (0.1)^2 = 0.0314 \text{ m}^2$

Number of turns, $N = 500$

Initial flux, $\Phi_i = NBA \cos 0^\circ = 500 \times 0.5 \times 10^{-4} \times 0.0314 = 0.000785 \text{ Wb}$

Final flux after 180° rotation, $\Phi_f = NBA \cos 180^\circ = -0.000785 \text{ Wb}$

Change in flux, $\Delta\Phi = \Phi_f - \Phi_i = -0.000785 - 0.000785 = -0.00157 \text{ Wb}$

Time interval, $\Delta t = 0.1 \text{ s}$

Induced emf, $\varepsilon = \left| \frac{\Delta\Phi}{\Delta t} \right| = \frac{0.00157}{0.1} = 0.0157 \text{ V} = 15.7 \text{ mV}$

Induced current, $I = \frac{\varepsilon}{R} = \frac{0.0157}{2} = 0.00785 \text{ A} = 7.85 \text{ mA}$

Practice Set

- **Level 1 (Easy):** Define magnetic flux and state Faraday's First Law of electromagnetic induction.
- **Level 2 (Moderate):** A coil of 100 turns and area 0.02 m^2 is placed in a magnetic field of 0.3 T . The coil is rotated such that the magnetic flux changes from maximum to zero in 0.05 s . Calculate the induced emf.
- **Level 3 (Challenging):** Two coils with inductances 2 H and 3 H are coupled with a coupling constant of 0.8 . Calculate the mutual inductance. If the current in the first coil changes at a rate of 5 A/s , find the induced emf in the second coil.

Answer Key

- **Level 1:** Magnetic flux is the total magnetic field passing through a given area. Faraday's First Law states that an emf is induced in a conductor when the magnetic flux linked with it changes.
- **Level 2:** Area $A = 0.02 \text{ m}^2$, Number of turns $N = 100$, Magnetic field $B = 0.3 \text{ T}$, Time $\Delta t = 0.05 \text{ s}$. Initial flux $\Phi_i = NBA = 100 \times 0.3 \times 0.02 = 0.6 \text{ Wb}$. Final flux $\Phi_f = 0$. Induced emf $\varepsilon = \frac{\Delta\Phi}{\Delta t} = \frac{0.6}{0.05} = 12 \text{ V}$.
- **Level 3:** Mutual inductance $M = k\sqrt{L_1L_2} = 0.8 \times \sqrt{2 \times 3} = 0.8 \times 2.45 = 1.96 \text{ H}$. Rate of change of current $\frac{dI}{dt} = 5 \text{ A/s}$. Induced emf $\varepsilon = M\frac{dI}{dt} = 1.96 \times 5 = 9.8 \text{ V}$.

Quick Reference Table

Magnetic Flux: $\Phi = BA \cos \theta$

Faraday's Law: $\varepsilon = -N \frac{d\Phi}{dt}$

Self-Inductance: $\varepsilon = -L \frac{dI}{dt}$

Mutual Inductance: $\varepsilon = -M \frac{dI}{dt}$, $M = k\sqrt{L_1 L_2}$

Unit of Inductance: Henry (H)

Common Mistakes and Misconceptions

- Confusing magnetic field strength with magnetic flux; only changing magnetic flux induces emf.
- Ignoring the negative sign in Faraday's law, which indicates the direction of induced emf.
- Mixing up self-induction and mutual induction effects.
- Using inconsistent units, leading to calculation errors.
- Assuming a constant magnetic field induces emf; only changing fields do.

Glossary

- **Electromagnetic Induction:** Generation of emf due to change in magnetic flux.
- **Magnetic Flux:** Total magnetic field passing through an area.
- **Faraday's Laws:** Laws describing induced emf due to changing magnetic flux.
- **Lenz's Law:** Direction of induced emf opposes the change causing it.
- **Self-Inductance:** Induction of emf in the same coil due to changing current.
- **Mutual Inductance:** Induction of emf in one coil due to changing current in another coil.
- **Inductance:** Property of a coil to oppose change in current.