СӘТБАЕВ УНИВЕРСИТЕТІ
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Lecture 13

Magnetic Circuits and Electromagnetic Induction

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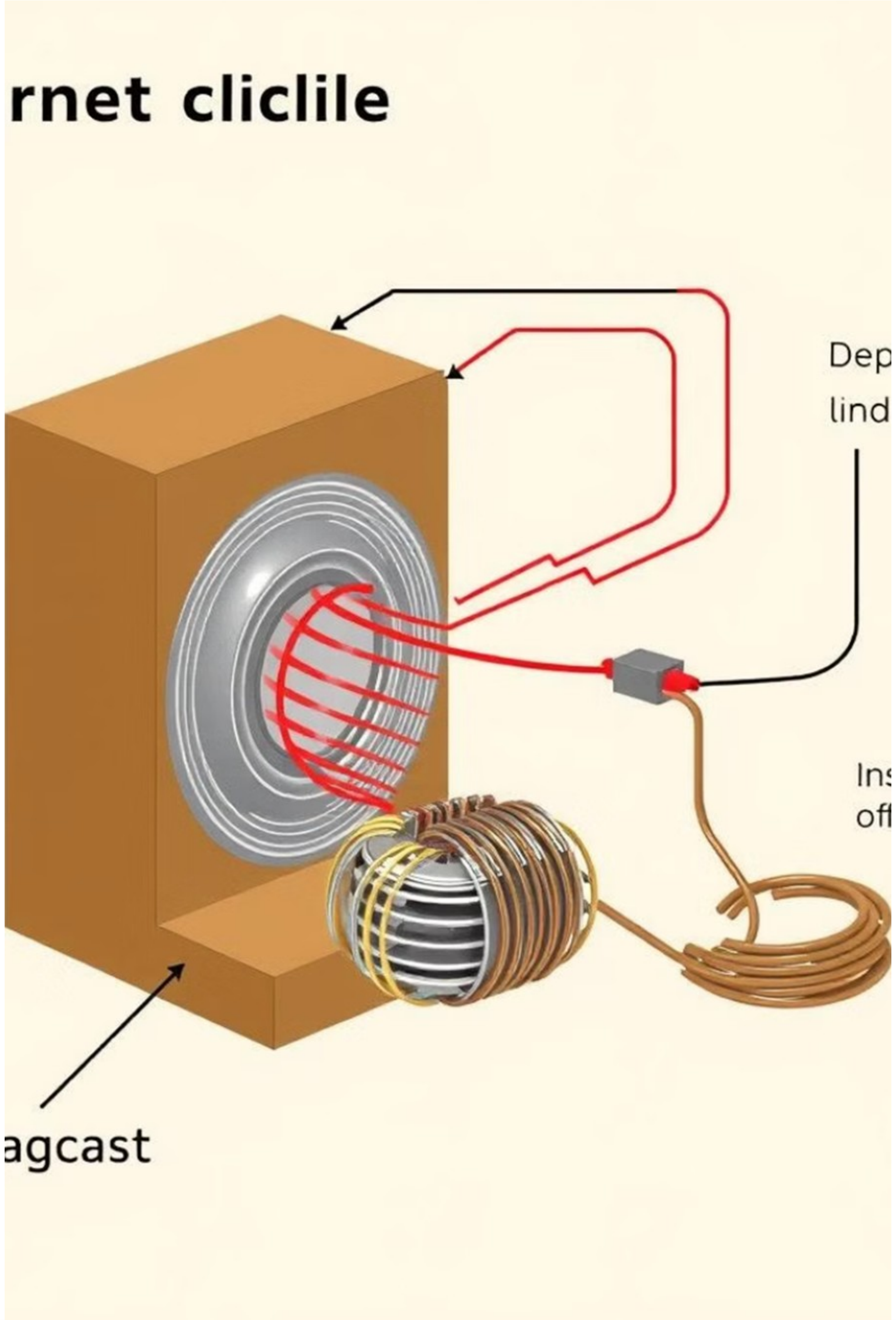
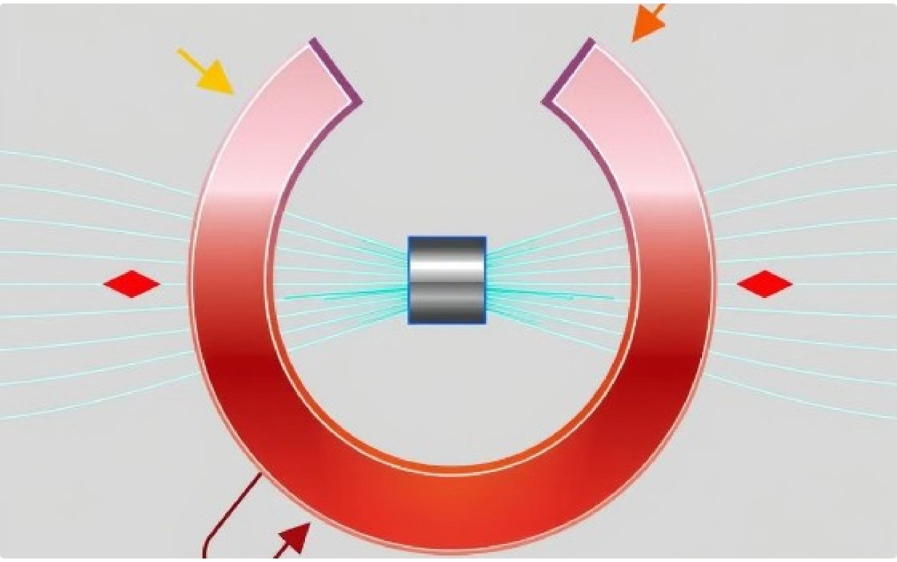
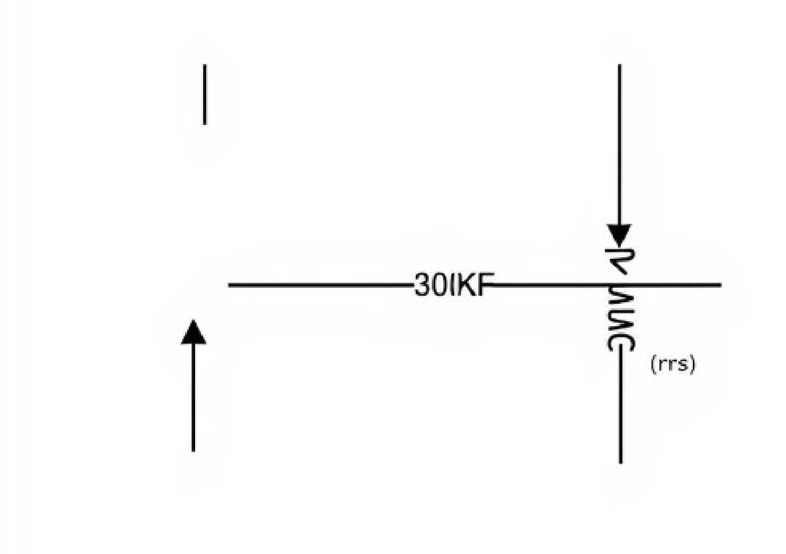
Plan

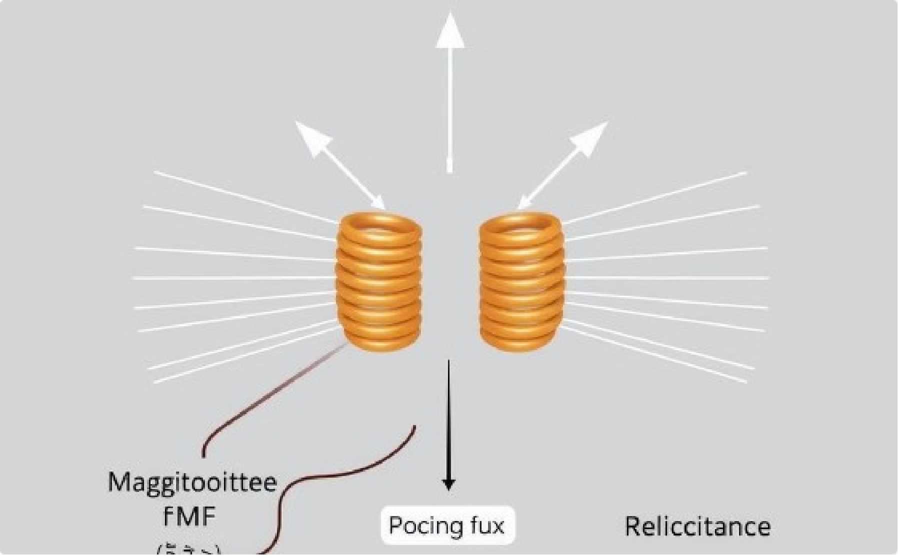
1. Introduction to Magnetic Circuits
2. Magnetic Materials and Properties
3. Magnetic Field and Flux
4. Reluctance and Magnetic Resistance
5. Magnetomotive Force (MMF)
6. Electromagnetic Induction Basics
7. Self-Induction and Mutual Induction
8. Applications of Electromagnetic Induction
9. Losses in Magnetic Circuits
10. Conclusion and Summary



Introduction to Magnetic Circuits







Magnetic Flux Flow

Magnetic circuits provide controlled pathways for magnetic flux, much like electrical circuits guide the flow of current.

Electrical Circuit Analogy

The concept of a magnetic circuit draws parallels with its electrical counterpart.

Magnetic Circuit Components

Just as voltage drives current through a resistive path in an electrical circuit, MMF propels magnetic flux through a circuit with magnetic reluctance.

Electrical Circuit

• Voltage (V) drives current (I) • Resistance (R) opposes current flow • Ohm's Law: $V = IR$

Magnetic Circuit

• MMF (F) drives magnetic flux (Φ) • Reluctance (R) opposes flux flow • Hopkinson's Law: $F = \Phi R$

Applications

• Transformers • Electric motors • Inductors • Electromagnetic relays

Magnetic Materials and Properties

The behavior of magnetic circuits is profoundly influenced by the materials used in their construction. Ferromagnetic materials, such as iron, nickel, and cobalt, are the workhorses of magnetic circuits due to their strong attraction to magnetic fields and ability to enhance magnetic flux.

Paramagnetic materials exhibit weak attraction to magnetic fields, while diamagnetic materials slightly repel them. The key properties that define a material's magnetic behavior include permeability (μ), which measures how easily magnetic flux passes through the material, and saturation, the point at which increasing MMF no longer significantly increases magnetic flux.

1

Ferromagnetic Materials

Strongly attracted to magnets, high permeability, used in transformer cores and motor components.

2

Paramagnetic Materials

Weakly attracted to magnetic fields, slightly enhance magnetic flux, examples include aluminum and platinum.

3

Diamagnetic Materials

Weakly repel magnetic fields, slightly reduce magnetic flux, examples include copper and gold.

4

Magnetic Saturation

The point where further increase in magnetic field strength produces little to no increase in magnetization, crucial in core design.

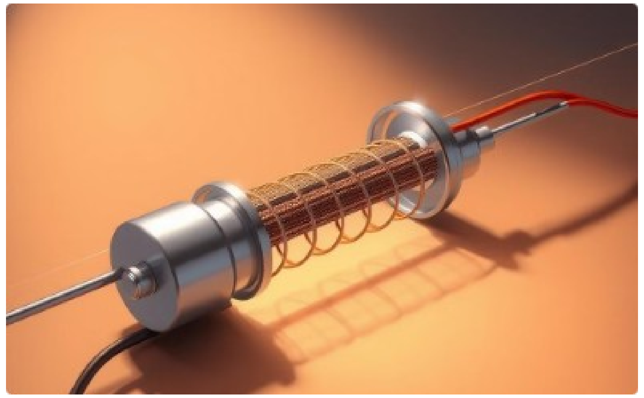
Magnetic Field and Flux

Understanding magnetic fields and flux is crucial for grasping the behavior of magnetic circuits. The magnetic field (B) represents the magnetic influence at a point in space and is measured in teslas (T). This field can be visualized as lines of force emanating from magnetic poles, with their density indicating field strength.

Magnetic flux (Φ), measured in webers (Wb), quantifies the total magnetic field passing through a given area. The concentration of this flux in an area is described by the magnetic flux density (B), also measured in teslas. This relationship is expressed as $B = \Phi/A$, where A is the cross-sectional area.

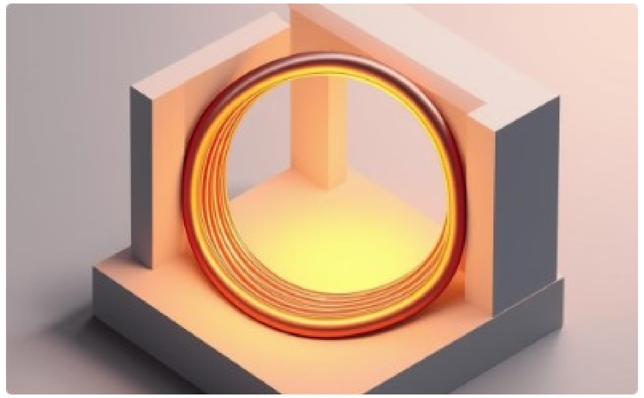
Quantity	Symbol	Unit	Description
Magnetic Field	H	A/m	Magnetic field strength
Magnetic Flux	Φ	Wb	Total magnetic field through an area
Magnetic Flux Density	B	T	Flux per unit area
Permeability	μ	H/m	Material's ability to support magnetic field

Reluctance and Magnetic Resistance



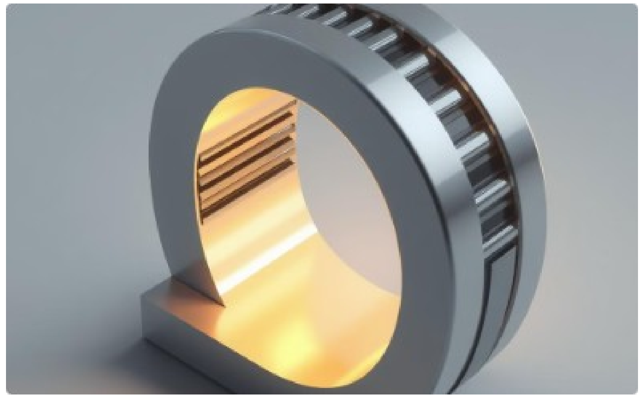
Material Selection

Choose materials with high permeability to minimize reluctance.



Path Length Optimization

Minimize the length of the magnetic path to reduce reluctance.



Cross-sectional Area Design

Increase the cross-sectional area where possible to lower reluctance.

Air Gap Consideration

Minimize air gaps, as they significantly increase the overall circuit reluctance.

Reluctance (R_m) in a magnetic circuit is analogous to resistance in an electrical circuit. It represents the opposition to magnetic flux flow and is a crucial parameter in designing efficient magnetic devices. The reluctance of a magnetic path is given by the formula: $R_m = l / (\mu \cdot A)$, where l is the length of the path, μ is the permeability of the material, and A is the cross-sectional area.

Magnetomotive Force (MMF)

Magnetomotive Force (MMF) is the driving force behind magnetic flux in a circuit, analogous to voltage in an electrical circuit. It represents the total magnetic driving force produced by a coil or permanent magnet. For a coil, MMF is calculated using the formula: $\text{MMF} = N \cdot I$, where N is the number of turns in the coil, and I is the current flowing through it.

MMF plays a crucial role in various electromagnetic devices. In transformers, it drives flux through the core, enabling power transfer between windings. In electric motors, MMF creates the rotating magnetic field that produces torque. The relationship between MMF, flux, and reluctance is expressed by Hopkinson's Law: $\text{MMF} = \Phi \cdot R_m$, where Φ is the magnetic flux and R_m is the reluctance of the magnetic circuit.

Transformers

MMF drives flux through the core, enabling voltage transformation.

Electric Motors

MMF creates rotating magnetic fields for torque production.

Electromagnets

MMF determines the strength of the magnetic field generated.

Relays

MMF actuates the magnetic switch in electromagnetic relays.

Electromagnetic Induction Basics

Electromagnetic induction, discovered by Michael Faraday in 1831, is the phenomenon where a changing magnetic field induces an electromotive force (EMF) in a conductor. This principle forms the basis for numerous electrical devices and power generation systems. Faraday's Law of Induction quantifies this relationship, stating that the induced EMF is proportional to the rate of change of magnetic flux through a circuit.

The formula for Faraday's Law is: $EMF = -d\Phi/dt$, where Φ is the magnetic flux and t is time. The negative sign represents Lenz's Law, which states that the direction of induced current opposes the change in flux that caused it. This opposition is crucial for energy conservation in electromagnetic systems.

1

Changing Magnetic Field

A varying magnetic field is created, either by moving a magnet or changing current in a nearby coil.

2

Flux Linkage

The changing magnetic flux cuts through a conductor or coil in the vicinity.

3

EMF Induction

An electromotive force is induced in the conductor, proportional to the rate of flux change.

4

Current Flow

If the conductor forms a closed circuit, the induced EMF causes current to flow, opposing the flux change.

Self-Induction and Mutual Induction

Self-induction occurs when a changing current in a coil induces an EMF within the same coil. This property is quantified by inductance (L), measured in henries (H). The induced EMF opposes the change in current, following the formula: $EMF = -L(dI/dt)$. Self-inductance is crucial in many electrical components, particularly in inductors used for energy storage and filtering in circuits.

Mutual induction, on the other hand, involves the interaction between two separate coils. When current changes in one coil (primary), it induces an EMF in the nearby coil (secondary). This principle is fundamental to transformer operation, where energy is transferred between coils without direct electrical connection. The degree of coupling between coils is described by the mutual inductance (M), also measured in henries.

Self-Induction

• Occurs in a single coil • EMF proportional to rate of current change • Key in inductor design • Affects circuit time constants

Mutual Induction

• Involves two or more coils • Basis for transformer operation • Depends on coil geometry and proximity • Crucial for wireless power transfer

Applications

• Transformers • Inductors in filters • Wireless charging systems • Induction motors

Applications of Electromagnetic Induction

Electromagnetic induction finds widespread application in modern technology. Transformers, essential components of power distribution systems, use mutual induction to step voltages up or down. They consist of primary and secondary coils wound around a common core, allowing efficient power transfer and voltage conversion without direct electrical connection.

Electric generators harness electromagnetic induction to convert mechanical energy into electrical energy. By rotating a coil within a magnetic field or vice versa, they induce an alternating EMF, forming the basis of power generation in plants worldwide. Inductors, another key application, store energy in their magnetic fields and are crucial for filtering and tuning in electronic circuits.

Transformers

Use mutual induction to change voltage levels in power distribution systems, enabling efficient long-distance power transmission.

Electric Generators

Convert mechanical energy to electrical energy through rotating magnetic fields, powering everything from large power plants to small portable generators.

Inductors

Store energy in magnetic fields, used for filtering in power supplies, radio frequency circuits, and as chokes in various electronic applications.

Induction Heating

Utilizes eddy currents induced in conductive materials to generate heat, used in industrial processes and cooking applications.

Losses in Magnetic Circuits and Optimization

Magnetic circuits, while efficient, are not without losses. Two primary sources of loss are hysteresis and eddy currents. Hysteresis loss occurs due to the energy required to repeatedly magnetize and demagnetize the core material, proportional to the area of the material's hysteresis loop. Eddy current losses result from circulating currents induced within the core material itself, generating heat and reducing efficiency.

To minimize these losses, engineers employ various techniques. Laminated cores, made of thin insulated sheets, significantly reduce eddy currents by limiting their path. Using materials with narrow hysteresis loops, such as silicon steel, helps minimize hysteresis losses. Additionally, proper core design, including optimizing cross-sectional area and magnetic path length, can further enhance efficiency.

1

Material Selection

Choose low-loss materials like silicon steel or ferrites to minimize hysteresis.

2

Lamination

Use thin, insulated laminations to reduce eddy current paths and losses.

3

Core Geometry

Optimize core shape and size to balance flux density and minimize overall losses.

4

Frequency Consideration

Select appropriate materials and designs based on operating frequency to minimize losses.

Used literatures

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