Magnetism & Electromagnetism

By: Dr Rosemizi Abd Rahim

Click here to watch the magnetism and electromagnetism animation video

http://rmz4567.blogspot.my/2013/02/electrical-engineering.html
Learning Outcomes

• At the end of the chapter, students should be able to:
  – understand the theory of magnetic and electromagnetic
  – understand the law of electromagnetic induction.
Introduction to Magnetism

Basic Magnetism

• Effects of magnetism known as early as 800 BC by the Greeks.
• Certain stones called "magnetite or iron oxide (Fe2O3)" attracted, pieces of iron.
Introduction to Magnetism

Magnetism

• magnets do not come in separate charges
• Any magnetic/magnetized object has a North and South pole

• If you break a magnet in half, each piece will have a North and a South end
Introduction to Magnetism

Magnetic field

- Magnetic field lines – 3D lines which tiny bar magnets lie along. Magnetic field lines run from N to S.
- A compass can be used to map out the magnetic field.
- Field forms closed “flux lines” around the magnet (lines of magnetic flux never intersect)
Introduction to Magnetism

Magnetic field

- The strength of the magnetic field is greater where the lines are closer together and weaker where they are farther apart.
- Field is strongest in regions of dense field lines.
- Field is weakest in regions of sparse field lines.

The density of field lines indicates the strength of the field.
Introduction to Magnetism

Magnetism

- Magnetism is a basic force of attraction and repulsion in nature that is created, by moving charges.
- A magnet is an object, which has a magnetic field that causes a push or pulling action.
- Similar to electric charges, unlike poles attract, while like poles repel.

![Diagram of magnetic poles attracting and repelling](image)
Introduction to Magnetism

Magnetism

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Introduction to Magnetism

Magnetic flux

• Magnetic flux is measurement of the quantity of magnetism, the description of how certain materials relate to magnetic fields.
• Specifically, it describes the strength and extent of the object's interaction with the field.
• Magnetic lines of force (flux) are assumed to be continuous loops.
• Magnetic flux measured in Webers (Wb)
• Symbol $\Phi$
Introduction to Magnetism

The Earth is a Magnet

• A magnetic compass aligns itself along the magnetic field lines (produced by the Earth in the absence of a stronger field)
Introduction to Magnetism

The Earth is a Magnet

- The North pole of the compass points to the Earth magnetic South pole (generally toward geographic north) and vice-versa
Introduction to Magnetism

Magnetism

- Magnetism can be transferred or induced into other materials, this is known as Magnetic Induction

- The induction of magnetism into a material can be permanent or temporary
Introduction to Magnetism

Magnetism

- Magnetic materials (ferromagnetic): iron, steel, cobalt, nickel and some of their alloys.

- Non magnetic materials: water, wood, air, quartz.

- In an un-magnetised state, the molecular magnets lie in random manner, hence there is no resultant external magnetism exhibited by the iron bar.
Introduction to Magnetism

**Magnetism**

- When the iron bar is placed in a magnetic field or under the influence of a magnetising force, then these molecular magnets start turning their axes and orientate themselves more or less along a straight lines.
Introduction to Magnetism

Magnetism

- When the iron bar is placed in a very strong magnetic field, all these molecular magnets orientate themselves along a straight lines (saturated).
Introduction to Electromagnetism

• A simple electromagnet can be made by coiling some wire around a steel nail, and connecting a battery to it.

• A magnetic field is produced when an electric current flows through a coil of wire.

• We can make an electromagnet stronger by doing these things:
  • wrapping the coil around an iron core
  • adding more turns to the coil
  • increasing the current flowing through the coil.
Introduction to Electromagnetism

Using Electromagnets

• Many objects around you contain electromagnets. They are found in electric motors and loudspeakers.

• Very large and powerful electromagnets are used as lifting magnets in scrap yards to pick up, then drop, old cars and other scrap iron and steel.

• They are better than magnets because the magnetism can be turned off and on.
Introduction to Electromagnetism

- A moving electric field creates a magnetic field that rotates around it
- A moving magnetic field creates an electric field that rotates around it
- The **Right Hand Rule** helps describe this
The Right Hand Rule

- First define positive electric current as flowing from the positive (+) end of a battery, through an electric circuit, and back into the negative (-) end.
- Next define a magnetic field as always pointing away from a North pole and towards a South pole.
- Curl your fingers in the direction of the rotating field.
The Right Hand Rule

• Extend your thumb. It now points in the direction of the other field.

• If your fingers are curling along with a rotating electric field, your thumb will point in the direction of the magnetic field and vice versa.
The Right Hand Rule

Representing Currents

- Wire carrying current out of page

- Wire carrying current into page
The Right Hand Rule

The magnetic field of two wires

• Wire carrying current out of page

• Wire carrying current into page
The Right Hand Rule

The magnetic field of two wires

- Wire carrying current out of page

- Wire carrying current into page
The Right Hand Rule

The magnetic field of two wires

- Both of the wire carrying current out of page
The Right Hand Rule

The magnetic field of a coil

- The overall field around a coil is the sum of the fields around each individual wire
The Right Hand Rule

The magnetic field of a solenoid

- The magnetic field around a solenoid resembles that of a bar magnet.
- Inside the solenoid the field lines are parallel to one another. We say it is a uniform field.
The Electromagnetism

- By the Right Hand Rule, a coil of wire with current flowing in it will create a magnetic field
- The strength of the magnetic field depends on
  - The amount of current in a wire – More current means stronger magnetic field
  - The number of turns in the coil – More turns means stronger magnetic field
  - The material in the coil – Magnetic materials like iron and steel make the magnetic field stronger
- In other word, the magnetic field only exists when electric current is flowing
The Electromagnetism

- The lines of flux, formed by current flow through the conductor, combine to produce a larger and stronger magnetic field.
- The center of the coil is known as the core. In this simple electromagnet the core is air.
The Electromagnetism

- Iron is a better conductor of flux than air. The air core of an electromagnet can be replaced by a piece of soft iron.
- When a piece of iron is placed in the center of the coil more lines of flux can flow and the magnetic field is strengthened.
The Electromagnetism

Magnetic field - wire coil

• Notice that a carrying-current coil of wire will produce a perpendicular field
The Electromagnetism

Magnetic field - wire coil
Flux $\Phi$ can be increased by increasing the current $I$.

$\propto \Phi \quad I$
Flux \( \Phi \) can be increased by increasing the number of turns \( N \).
Magnetic Field

Flux $\Phi$ can be increased by increasing the cross-section area of coil $A$. **(Diagram showing magnetic field lines and coil)**
Magnetic Field

Flux $\Phi$ can be increased by increasing the cross-section area of coil $A$. 
Magnetic Field

Flux $\Phi$ is decreased by increasing the length of coil $l$.

$\Phi \propto \frac{1}{l}$
Therefore we can write an equation for flux $\Phi$ as,

$$\Phi \propto \frac{NIA}{l}$$

or

$$\Phi = \frac{\mu_0 NIA}{l}$$
Where $\mu_0$ is vacuum or non-magnetic material permeability

$$\Phi = \frac{\mu_0 NIA}{l}$$

$\mu_0 = 4\pi \times 10^{-7}$ H/m
Magnetic Field: Coil

- Placing a ferrous material inside the coil increases the magnetic field
- Acts to concentrate the field also notice field lines are parallel inside ferrous element
- ‘flux density’ has increased
Magnetic Field

By placing a magnetic material inside the coil,

\[ \Phi = \mu N I A \]

Where \( \mu \) is the permeability of the magnetic material (core).
Magnetic Field

By placing a magnetic material inside the coil,

\[ \Phi = \frac{\mu NI A}{l} \]

Where \( \mu \) is the permeability of the magnetic material (core).
Flux Density

\[ B = \frac{\Phi}{A} \]

- Flux density measured in Teslas (T)
Permeability

- Permeability $\mu$ is a measure of the ease by which a magnetic flux can pass through a material (Wb/Am)
- Permeability of free space $\mu_o = 4\pi \times 10^{-7}$ (Wb/Am)
- Relative permeability:

$$\mu_r = \frac{\mu}{\mu_o}$$
Reluctance

• Reluctance: “resistance” to flow of magnetic flux

\[ R = \frac{l}{\mu A} \] (At/Wb)

Associated with “magnetic circuit” – flux equivalent to current
Ampere’s Law

The relationship between current and magnetic field intensity can be obtained by using Ampere’s Law.

Ampere’s Law states that the line integral of the magnetic field intensity, $H$ around a closed path is equal to the total current linked by the contour.

\[ \oint H \cdot dl = \sum i \]

$H$: the magnetic field intensity at a point on the contour
$dl$: the incremental length at that point

If $\theta$: the angle between vectors $H$ and $dl$ then

\[ \oint Hdl \cos \theta = \sum i \]
Ampere’s Law

Consider a rectangular core with N winding

\[ \sum i = Ni \]

\[ dl = l_c \]

\[ \therefore Hl_c = Ni \]

Therefore

\[ H = \frac{Ni}{l_c} \]

H - magnetic field intensity
Relationship between B-H

The magnetic field intensity, H produces a magnetic flux density, B everywhere it exists.

\[ B = \mu H \left( \frac{\text{weber}}{m^2} \right) \text{ or Tesla} \]

\[ B = \mu_r \mu_0 H \left( \frac{\text{wb}}{m^2} \right) \text{ or T} \]

- \( \mu \) - Permeability of the medium
- \( \mu_0 \) - Permeability of free space, \( 4\pi \times 10^{-7} \ \text{wb/A.t.m} \)
- \( \mu_r = \frac{\mu}{\mu_0} \) - Relative permeability of the medium

For free space or electrical conductor (Al or Cu) or insulators, \( \mu_r \) is unity

The \( H \)-field is defined as a modification of \( B \) due to magnetic fields produced by material media
Magnetic Equivalent Circuit

Assumption:
• All fluxes are confined to the core
• The fluxes are uniformly distributed in the core

The flux outside the toroid (called leakage flux), is so small (can be neglected)

Use Ampere’s Law,

\[ \oint H \cdot dl = Ni \]

\[ Hl = Ni \]

\[ H \cdot 2\pi r = Ni \]

\[ F = \text{Magnetomotive force (mmf)} \]
Magnetic Equivalent Circuit

\[ B = \mu H \]

\[ H = \frac{Ni}{l} \left( \frac{At}{m} \right) \]

\[ B = \frac{\mu Ni}{l} (T) \]

Where:

- \( N \) – no of turns of coil
- \( i \) – current in the coil
- \( H \) – magnetic field intensity
- \( l \) – mean length of the core
Magnetomotive Force, $F$

- Coil generates magnetic field in ferrous torroid
- Driving force $F$ needed to overcome torroid reluctance $R$

- Magnetic equivalent of ohms law

\[ \Phi = \frac{F}{R} \quad \text{(T)} \]
Magnetomotive Force

- The MMF is generated by the coil
- Strength related to number of turns and current, measured in Ampere turns (At)

\[ F = NI \]

\[ \Phi = \frac{NI}{R} \]
Field Intensity

- The longer the magnetic path the greater the MMF required to drive the flux
- Magnetomotive force per unit length is known as the "magnetizing force" $H$

$$H = \frac{F}{l} \text{ (At/m)}$$

- Magnetizing force and flux density related by:

$$B = \mu H \text{ (T)}$$
Magnetomotive Force

• Electric circuit: \( \text{Emf} = V = I \times R \)

• Magnetic circuit:

\[
\text{mmf} = F = \Phi \times \frac{R}{\mu A} = H \times I
\]

\[
= (B \times A) \times \frac{I}{\mu A}
\]

\[
= B \times \frac{I}{\mu} = H \times I
\]
Example

- Find the value of $I$ needed to develop a magnetic flux of $4 \times 10^{-4}$ Wb
- The permeability of the material is $1.818 \times 10^{-3}$ Wb/Am
- Flux density

$$B = \frac{\Phi}{A} = \frac{4 \times 10^{-4}}{2 \times 10^{-3}} = 0.2 \, T$$

$$H = \frac{B}{\mu} = \frac{0.2}{1.818 \times 10^{-3}} = 110 \, At / m$$

A = $2 \times 10^{-3}$ m$^2$
N = 400 turns
l = 0.16 m
Example

\[ F = NI = Hl \]

\[ I = \frac{Hl}{N} = \frac{110 \times 0.16}{400} = 44 \text{ mA} \]

\[ A = 2 \times 10^{-3} \text{ m}^2 \]

\[ N = 400 \text{ turns} \]

\[ l = 0.16 \text{ m} \]
Example

\[ \mathbf{F} = NI = Hl = \Phi \times R \]

\[ R = \frac{l}{\mu A} \]

\[ = \frac{0.16}{1.818 \times 10^{-3} \times 2 \times 10^{-3}} \]

\[ = 44004.4 \]
Example

\[ F = NI = HI = \Phi x R \]

\[ = \Phi x R \]

\[ = 4 \times 10^{-4} \times 44004.4 \]

\[ = 17.6 \]

\[ I = \frac{F}{N} = \frac{17.6}{400} = 44 \text{ mA} \]
Example 2

- Find the flux if the flux density is 1.0 T
- The current in the coil
- The magnetic field strength in the air gap and in the magnetic core ($\mu_r = 70,000$)
Example 2

\[ A_c = A_g = 9 \times 10^{-4} \, m^2 \]
\[ l_g = 0.0005m \]
\[ l_c = 0.3m \]

\[ \Phi = BA = 1.0 \times 9 \times 10^{-4} = 9 \times 10^{-4} \, Wb \]

\[ F = \Phi R_c + \Phi R_g = F_c + F_g \]

To find current need to find MMF – use ohm’s law equivalent!
Circuit Analogy
Example 2

Air Gap:

\[ R_g = \frac{I_c}{\mu_o A_g} = \frac{5 \times 10^{-4}}{(4\pi \times 10^{-7})(9 \times 10^{-4})} \]

\[ = 4.42 \times 10^5 \text{ At/Wb} \]

\[ F_g = \Phi R_g = 9 \times 10^{-4} \times 4.42 \times 10^5 = 397.9 \text{ At} \]

Core:

\[ R_c = \frac{I_c}{\mu_r \mu_o A_c} = \frac{0.3}{(7 \times 10^4)(4\pi \times 10^{-7})(9 \times 10^{-4})} \]

\[ = 3789.4 \text{ At/Wb} \]

\[ F_c = \Phi R_c = 9 \times 10^{-4} \times 3789.4 = 3.41 \text{ At} \]
Example 2

\[ F = F_c + F_g \]

\[ 3.41 + 397.9 = 401.31 \, At \]

\[ I = \frac{F}{N} = \frac{401.31}{500} = 0.8 \, A \]
Example 2

\[ H_c = \frac{B}{\mu_r \mu_o} = \frac{1}{(7 \times 10^4)(4\pi \times 10^{-7})} = 11.37 \text{At/m} \]

\[ H_g = \frac{B}{\mu_o} = \frac{1}{(4\pi \times 10^{-7})} = 7.96 \times 10^5 \text{At/m} \]
Leakage Flux and Fringing

- It is found that it is impossible to confine all the flux to the iron path only. Some of the flux leaks through air surrounding the iron ring.
- Spreading of lines of flux at the edges of the air-gap. Reduces the flux density in the air-gap.

Leakage coefficient \( \lambda = \frac{\text{Total flux produced}}{\text{Useful flux available}} \)
Fleming’s Left Hand Rule
Force on a current-carrying conductor

- It is found that whenever a current-carrying conductor is placed in a magnetic field, it experiences a force which acts in a direction perpendicular both to the direction of the current and the field.
Force on a current-carrying conductor

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Force on a current-carrying conductor

- Hence, the combined effect is to strengthen the magnetic field on the left hand side and weaken it on the right hand side,
Force on a current-carrying conductor

- Hence, the combined effect is to strengthen the magnetic field on the left hand side and weaken it on the right hand side, thus giving the distribution shown below.
Force on a current-carrying conductor

- This distorted flux acts like stretched elastic cords bend out of the straight, the line of the flux try to return to the shortest paths, thereby exerting a force $F$ urging the conductor out of the way.

On the left hand side, the two fields in the same direction

On the right hand side, the two fields in the opposition
Faraday’s Law

First Law

Whenever the magnetic flux linked with a coil changes, an emf (voltage) is always induced in it.

Or

Whenever a conductor cuts magnetic flux, an emf (voltage) is induced in that conductor.
Faraday’s Law

Second Law

The magnitude of the induced emf (voltage) is equal to the rate of change of flux-linkages.

If a magnetic flux, $\Phi$, in a coil is changing in time (n turns), hence a voltage, $e_{ab}$ is induced

$$ e = \frac{d\lambda}{dt} $$

where $\lambda = N\phi$

$$ e = \frac{d(N\phi)}{dt} = \frac{Nd\phi}{dt} $$

$e = $ induced voltage

$N = $ no of turns in coil

$d\Phi = $ change of flux in coil

$dt = $ time interval
Voltage Induced from a time changing magnetic field
Lenz’s Law

• Lenz’s law states that the polarity of the induced voltage is such that the voltage would produce a current that opposes the change in flux linkages responsible for inducing that emf.

• If the loop is closed, \( a \) connected to \( b \), the current would flow in the direction to produce the flux inside the coil opposing the original flux change.

• The direction (polarity) of induced emf (voltage) can be determined by applying Lenz’s Law.

• Lenz’s law is equivalent to Newton’s law.
Lenz’s Law
Self Inductance, $L$

From Faraday’s Law:

$$e = N \frac{d\phi}{dt}$$

By substituting

$$\phi = \frac{\mu NIA}{l}$$
Self Inductance, L

\[ e = N \frac{d}{dt} \left( \frac{\mu N A}{l} \right) \]

Rearrange the equation, yield

\[ e = \frac{\mu N^2 A}{l} \frac{di}{dt} \]
Self Inductance, $L$

\[ e = \frac{\mu N^2 A}{l} \frac{di}{dt} \]

or

\[ e = L \frac{di}{dt} \]

where

\[ L = \frac{\mu N^2 A}{l} \]
Mutual Inductance, $M$

From Faraday’s Law:

$$e_2 = N_2 \frac{d\phi}{dt}$$

Substituting

$$\Phi = \frac{\mu N_1 i_1 A}{l}$$
Mutual Inductance, M

\[ e_2 = N_2 \frac{d}{dt} \left( \frac{\mu N_1 i_1 A}{l} \right) \]

\[ e_2 = \mu N_2 N_1 \left( \frac{A}{l} \right) \frac{di_1}{dt} \]
Mutual Inductance, $M$

\[
e_2 = \mu N_2 N_1 \left( \frac{A}{l} \right) \frac{di_1}{dt}
\]

or

\[
e_2 = M \frac{di_1}{dt}
\]

where

\[
M = \mu N_2 N_1 \left( \frac{A}{l} \right)
\]
Mutual Inductance, $M$

$$M = \mu N_2 N_1 \left( \frac{A}{l} \right)$$

For $M^2$,

$$M^2 = \mu^2 N_2^2 N_1^2 \left( \frac{A}{l} \right)^2$$

$$M^2 = \mu N_1^2 \left( \frac{A}{l} \right) \times \mu N_2^2 \left( \frac{A}{l} \right) = L_1 \times L_2$$
Mutual Inductance, $M$

\[ M^2 = L_1 \times L_2 \]

\[ M = \sqrt{(L_1 \times L_2)} \]

or

\[ M = k\sqrt{(L_1 \times L_2)} \]

$k =$ coupling coefficient ($0 \text{ --- } 1$)
Dot Convention

Aiding fluxes are produced by currents entering like marked terminals.
Hysteresis Loss

- Hysteresis loop
  Uniform distribution
  \[ H = \frac{Ni}{l} \]

- From Faraday's law

\[
e = \frac{d\lambda}{dt} = N \frac{d\Phi}{dt} = NA \frac{dB}{dt}
\]

\[ \rightarrow B = \int_{-\infty}^{t} \frac{e}{NA} dt, \]

Where \( A \) is the cross section area
Hysteresis Loss

- Field energy

Input power:

\[ p = e \cdot i = i \frac{d\lambda}{dt} = iNA \frac{dB}{dt} = HlA \frac{dB}{dt} \]

\[ \rightarrow pdt = lA \cdot HdB = V_{core} \cdot HdB \]

Input energy from \( t_1 \) to \( t_2 \)

\[ W = \int_{t_1}^{t_2} pdt = V_{core} \int_{B_1}^{B_2} HdB \]

where \( V_{core} \) is the volume of the core
Hysteresis Loss

• One cycle energy loss

\[ W_{cycle} = V_{core} \int H dB = V_{core} \cdot A_{BH} \]

where is the closed area of B-H hysteresis loop

• Hysteresis power loss

\[ P_h = \frac{W_{cycle}}{T} = V_{core} \cdot A_{BH} \cdot f \]

where \( f \) is the operating frequency and \( T \) is the period
Hysteresis Loss

• Empirical equation

\[ p_h = K_h B_{\text{max}}^n f \quad [\text{W/m}^3] \]

- Empirical equation

\( p_h \) – hysteresis power loss per unit volume

\( K_h, n \) – constants, depending on core material, available in various design handbook (\( n = 1.5 \sim 2.5 \))

\( B_{\text{max}} \) – maximum flux density

Summary: Hysteresis loss is proportional to \( f \) and \( A_{BH} \)
Magnetic saturation & hysteresis in ac magnetic field

Applied field is reduced; the magnetism reduced thru diff. curve since iron tends to retains magnetized state - hence produced permanent magnet, Residual Flux, \( \phi_{res} \)

Magnetism increase as magnetic field magnetized unmagnetized iron

Iron becomes magnetically saturated

AC increased in negative direction, magnetic field reversed, the iron reversely magnetized until saturated again

If continue apply ac current, curve continue to follow S-shaped curve (hysteresis curve)

The area enclosed by hysteresis curve is energy loss per unit volume per cycle – heats the iron and is one reason why electric machines become hot. Therefore, it is required to select magnetic materials that have a narrow hysteresis loop.
Eddy Current Loss

- Eddy current
  Along the closed path, apply Faraday's law
  \[ e = \frac{d\lambda}{dt} = N \frac{d\Phi}{dt} = N A \frac{dB}{dt} , \]
  where \( A \) is the closed area
  Changes in \( B \rightarrow \Phi, BA \) changes

  \[ \rightarrow \text{induce emf along the closed path} \]
  \[ \rightarrow \text{produce circulating circuit (eddy current) in the core} \]

- Eddy current loss
  \[ p = \frac{e^2}{R} , \]
  where \( R \) is the equivalent resistance along the closed path
Eddy Current Loss

• How to reduce Eddy current loss
i) Use high resistivity core material
e.g. silicon steel, ferrite core (semiconductor)
 ii) Use laminated core
    To decrease the area closed by closed path
    
\[ p = \frac{e^2}{R} \propto A^2 \]

Lamination thickness
0.5~5mm for machines, transformers at line frequency
0.01~0.5mm for high frequency devices
Core Loss

Hysteresis loss + eddy current loss = Core loss

- Core Loss

\[ P_c = P_h + P_e \]

where \( P_h \) = hysteresis loss

\[ P_e = \text{eddy current loss} \]