EE3303 ELECTRICAL MACHINES I

Electromechanical energy conversion

CONTENTS

Laws of Magnetism

Law 1 : Like poles repel and unlike poles attract.

Law 2 : The force 'F' exerted by one pole over the other is,

- Directly proportional to the product of pole strength 'M1, M2'.
- Inversely proportional to the square of the distance between the poles 'd'
- Directly proportional to the nature of the surrounding medium 'K'.

$$F \infty \frac{M_1 M_2}{d^2} \text{ (N)}$$

$$F = \frac{K M_1 M_2}{d^2} \text{ (N)}$$

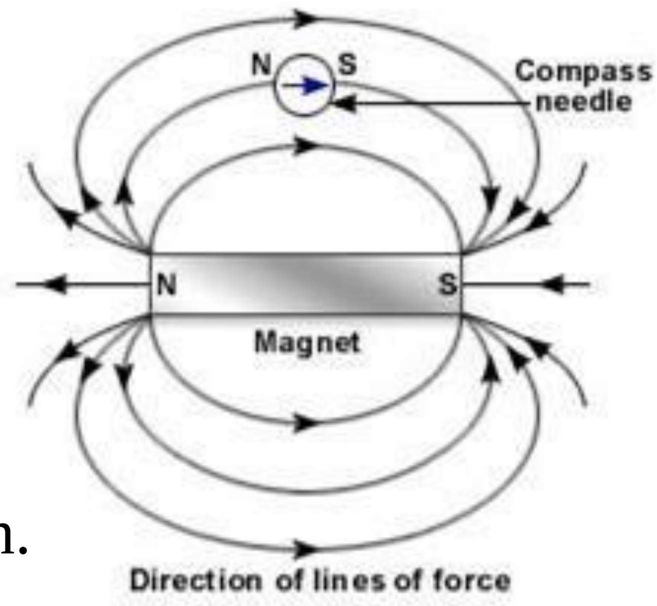
IMPORTANT DEFINITIONS

Magnetic Field : Region around the magnet where magnetic influence is experienced.

Magnetic Lines of Force : Imaginary lines around the magnet.

Properties of Magnetic Lines of Force :

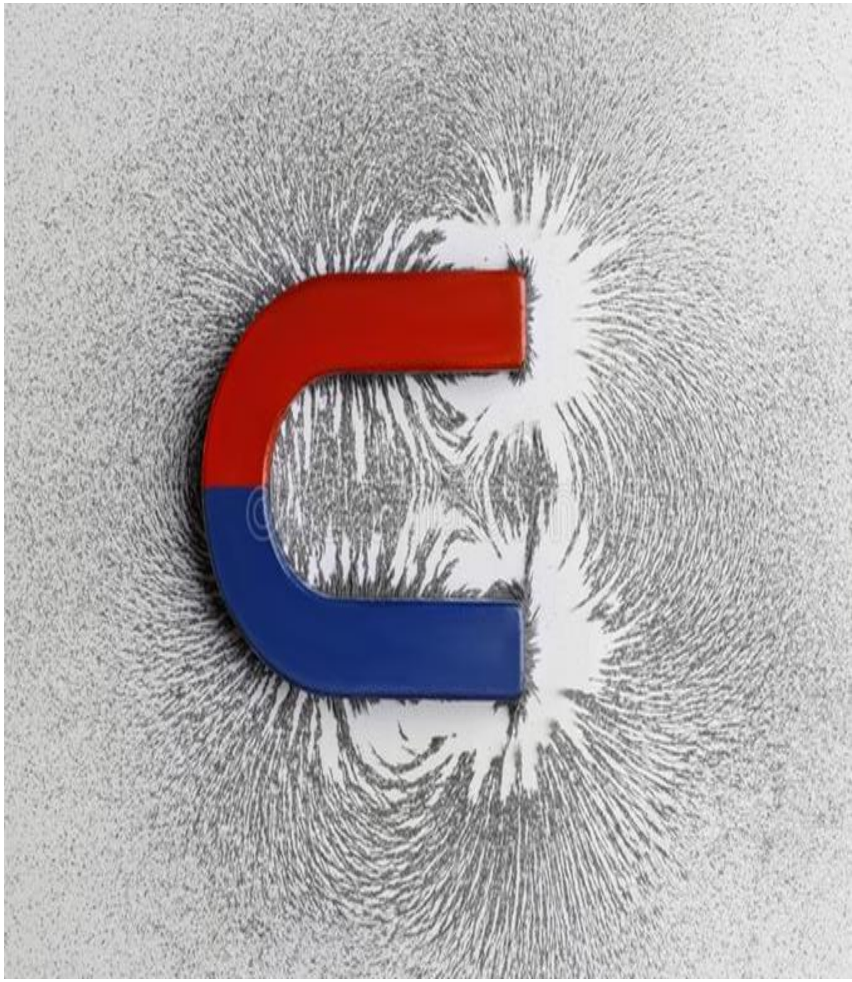
1. Travels from North to South pole.
2. Each line forms closed loop.
3. Lines never intersect.
4. Lines travel parallel to each other.
5. Lines always tries to contract in length.
6. Lines prefer the path with least opposition.



IMPORTANT DEFINITIONS

Magnetic Flux : Total number of lines of force. Symbol is Φ. Unit is weber (W).

i.e, 1 weber = 10^8 lines of force.



Magnetic Flux Density: Flux per unit area. Denoted as B. Unit is weber/ square meter.

B= Φ / A (Wb/m^2)

Magnetic Field Intensity: Measure of strengthness or weakness of the region around the magnet.

(or) The force experienced by unit north pole when placed in a magnetic field. Denoted as H. Unit is ampere/ meter (A/m) or newton/ weber (N/Wb) or ampere turns per meter (AT/m)

H= NI / L

IMPORTANT DEFINITIONS

Permeability: Ability or ease to force the magnetic flux in ι medium. Unit is Henry/ meter (H/m).

Absolute Permeability : $\mu = \frac{Magnetic\ field\ Density,B}{Magnetic\ field\ Intensity,H}$(H/m)

(Or) $\mu = \mu_o\ \mu_r$ (H/m)

Permeability of Free Space or Vacuum:

$\mu_o = \frac{Magnetic\ field\ Density,B}{Magnetic\ field\ Intensity,H} = 4\pi\ \times\ 10^{-7}$ (H/m)

[since μ_r=1 for free space]

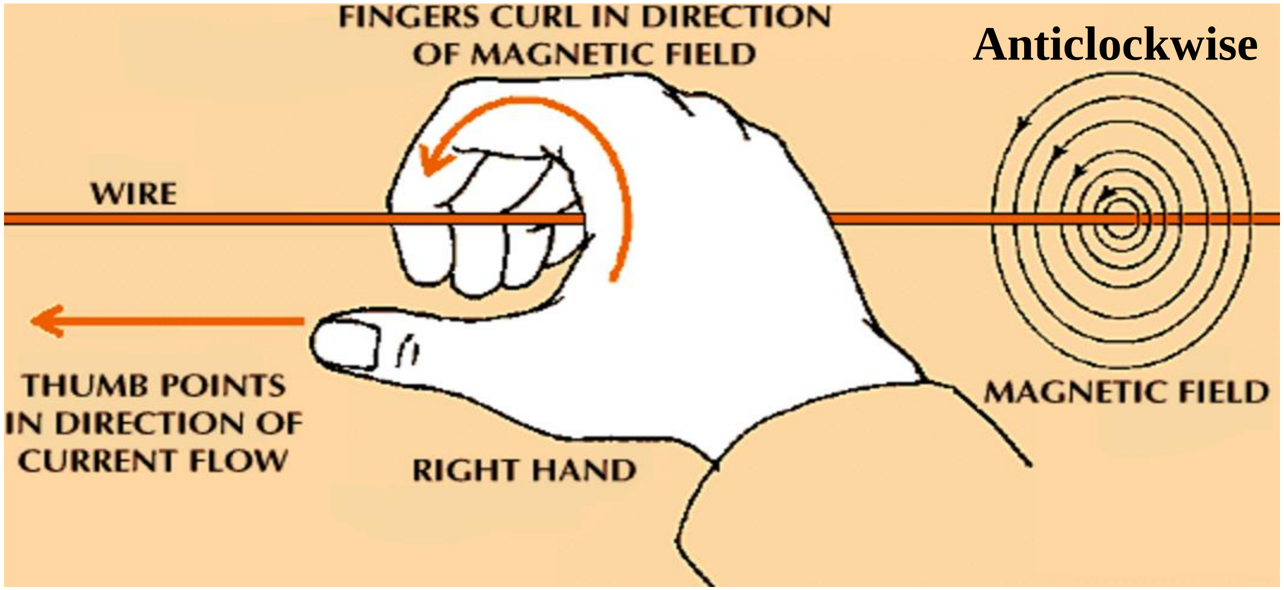
Relative Permeability:

$\mu_r = \frac{\mu}{\mu_o}$ (H/m)

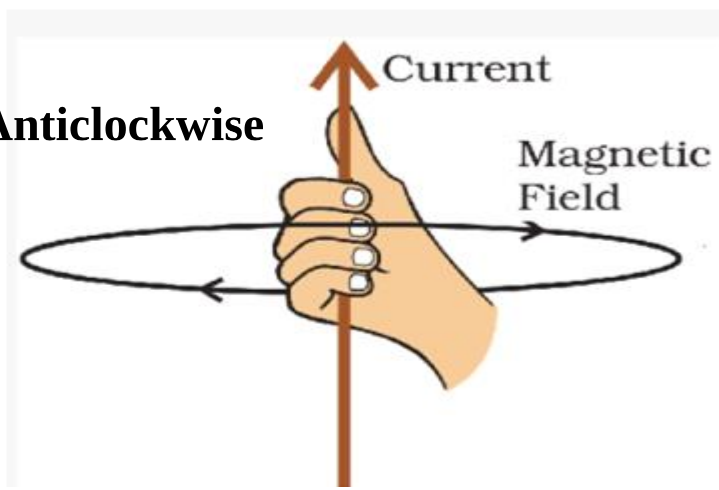
S.No	Electrical Circuit	Magnetic Circuit
1	**EMF:** Force required for the flow of electrons. emf = iR (volt)	**MMF:** Force required for the flow of flux. mmf = NI (or) mmf= SΦ (AT)
2	**Resistance, R:** Resistance offered to the flow of electrons or current. R (ohm or Ω)	**Reluctance, S:** Resistance offered to the flow of flux. S(AT/Wb)
3	**Conductance, G:** Reciprocal of resistance. G (mho or ℧)	**Permeance, P:** Reciprocal of reluctance. P (Wb/AT)

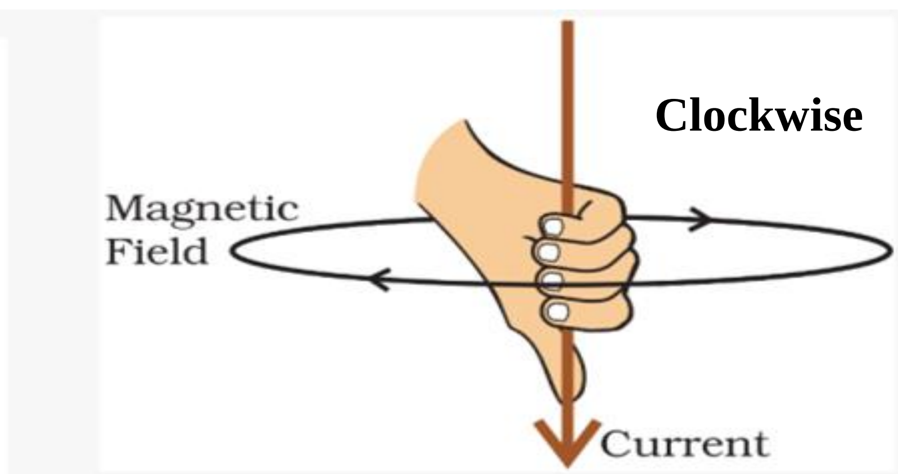
Rules and Laws

Right Hand Thumb Rule:



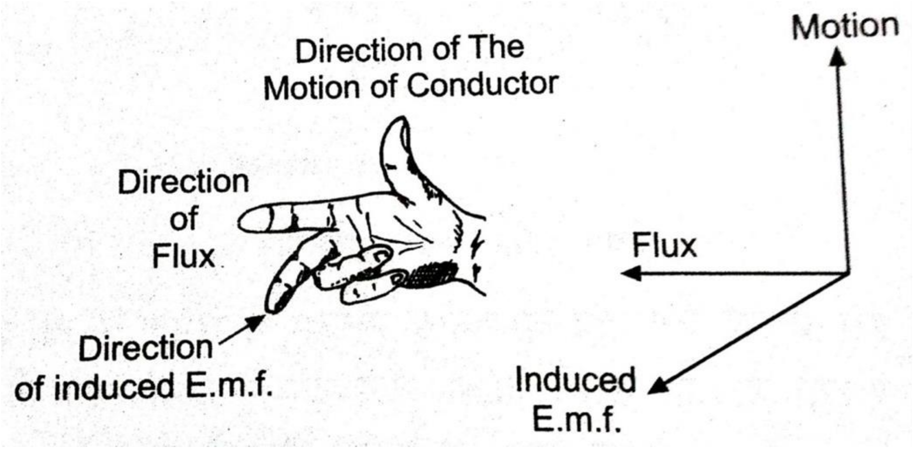
Anticlockwise



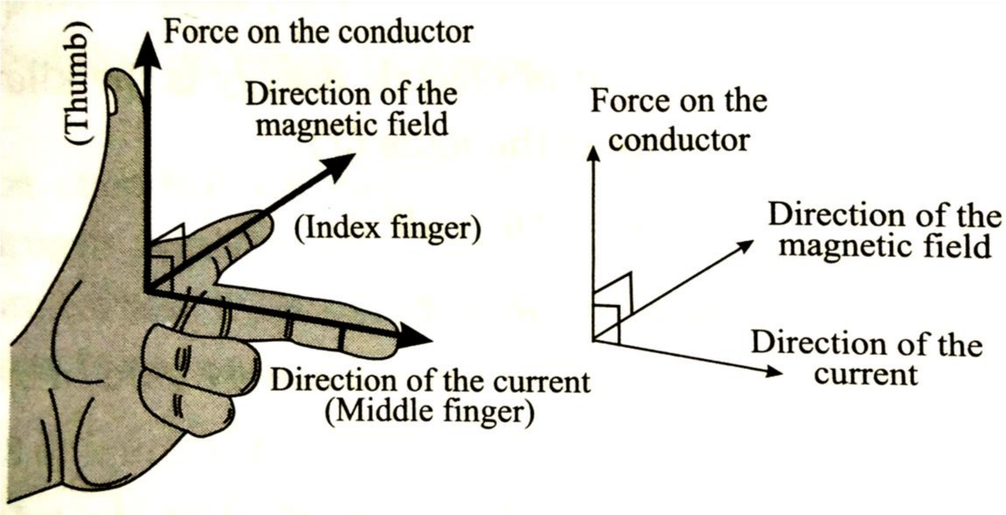


Rules and Laws

Flemmings Right Hand Rule:

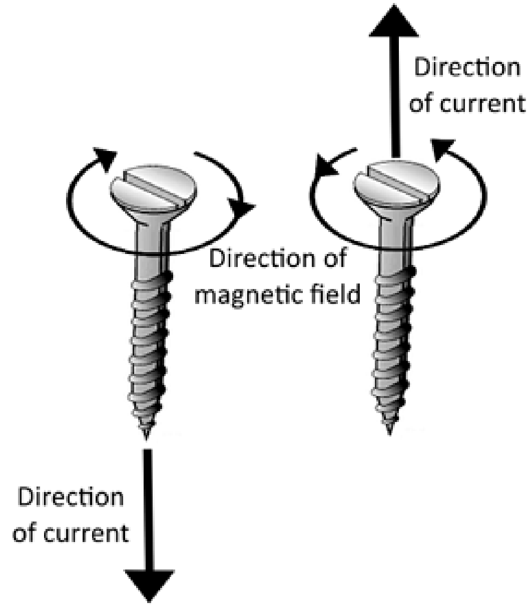


Flemmings Left Hand Rule:



Rules and Laws

Corkscrew Rule:



End Rule:

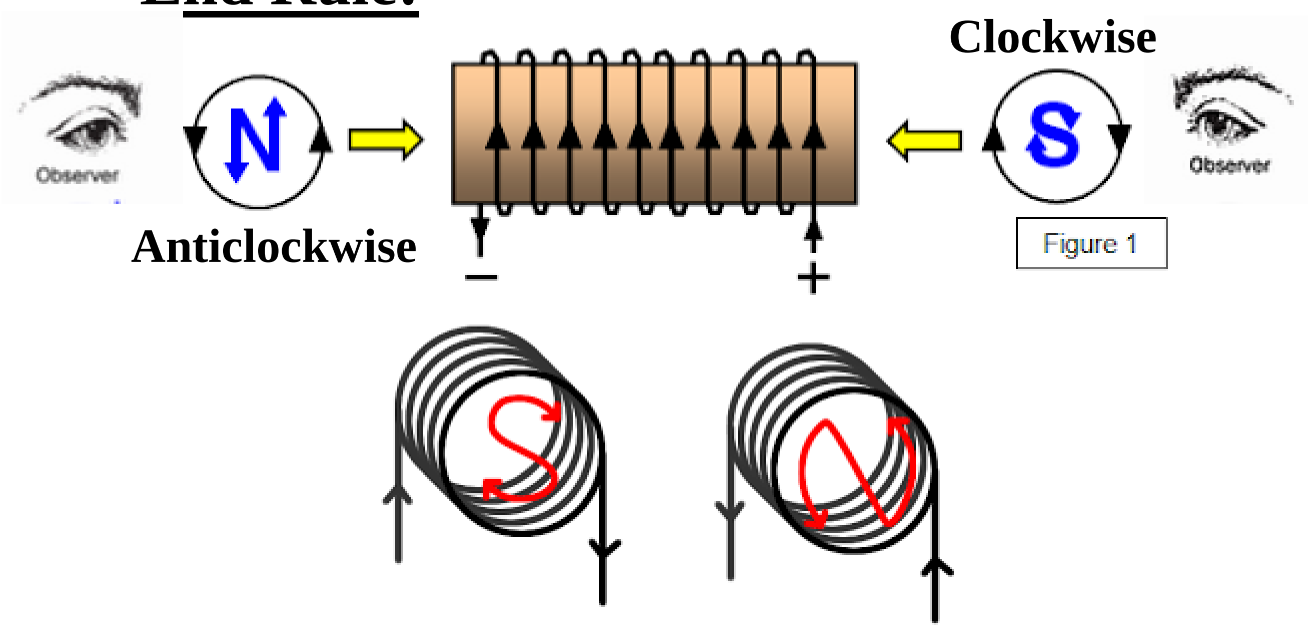


Figure 1

Rules and Laws

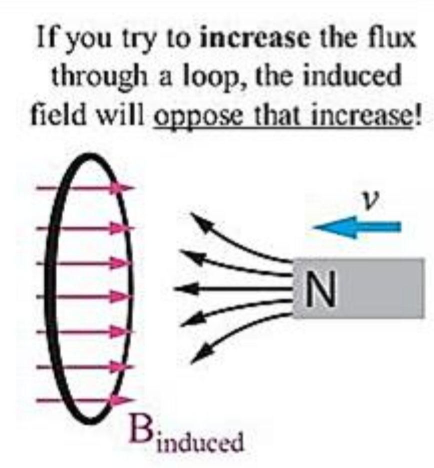
Faraday's Law of Electromagnetic Induction:

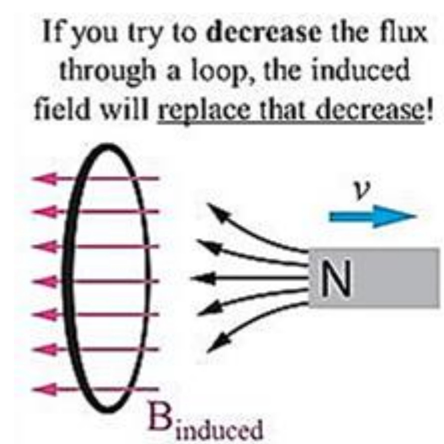
First law Whenever magnetic flux linked with a circuit changes, an emf is induced in it which lasts, so long as change in flux continuous. **(1/2)**

Second law The emf induced in loop or closed circuit is directly proportional to the rate of change of magnetic flux linked with the loop

i.e. $e \propto \frac{(-)\, d\phi}{dt}$ or $e = -N \frac{d\phi}{dt}$

where, N = number of turns in the coil. Negative sign indicates the Lenz's law. **(1/2)**



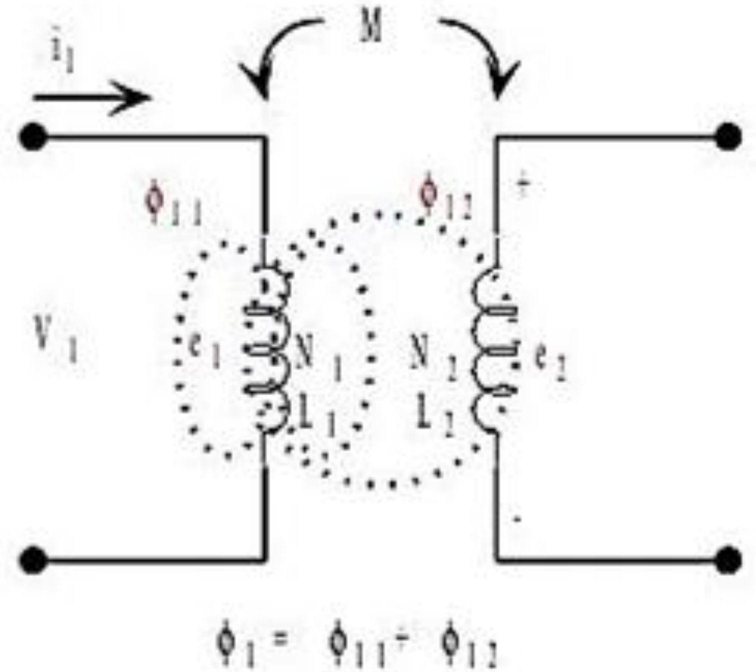


Lenz's Law

The *induced B field* in a loop of wire will **oppose the change in magnetic flux** through the loop.

ELECTROMAGNETIC INDUCTION
(Statically Induced Emf)

Definition: Emf induction in the coil without any physical movement.
Example : Transformer
Principle : Faraday's law of electromagnetic induction



- The induced emf, e, in a coil is proportional to the rate of the change of the magnetic flux passing through it due to its own current. This emf is termed as **Self Induced EMF**
- The induced emf e_2 is proportional to the rate of change of current through coil 1 and this proportionality constant is called the mutual inductance, M

Self Inductances L_1 and L_2 are

$$L_1 = \frac{N_1 \Phi_1}{I_1} \quad \text{and} \quad L_2 = \frac{N_2 \Phi_2}{I_2}$$

Mutual Inductance M

$$M = \frac{N_2 \Phi_{12}}{I_1} = \frac{N_1 \Phi_{21}}{I_2}$$

where $\Phi_{12} = k\,\Phi_1$; $\Phi_{21} = k\,\Phi_2$ and

k is the coupling coeficient

$$L_1 L_2 = \frac{M^2}{k^2} \quad \text{or} \quad k = \frac{M}{\sqrt{L_1 L_2}}$$

ELECTROMAGNETIC INDUCTION
(Dynamically Induced Emf)

Definition : Emf induction in the coil with physical movement.

Example : Generators and Motors

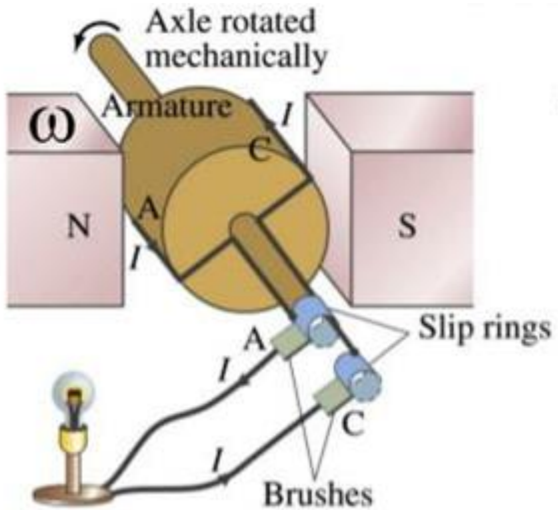
Principle : Faraday’s law of electromagnetic induction, Flemmings left hand rule

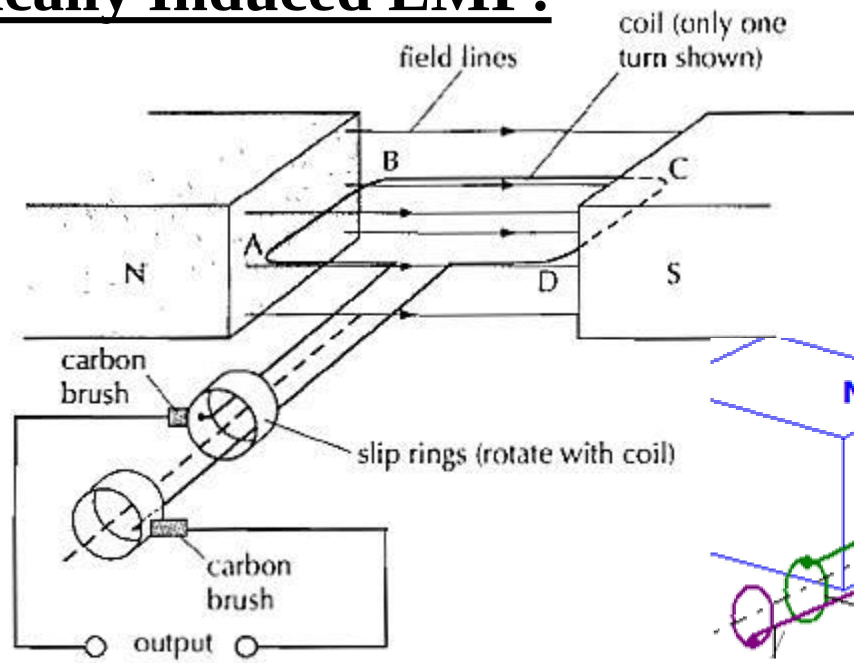
<u>Direction of Dynamically Induced EMF:</u>

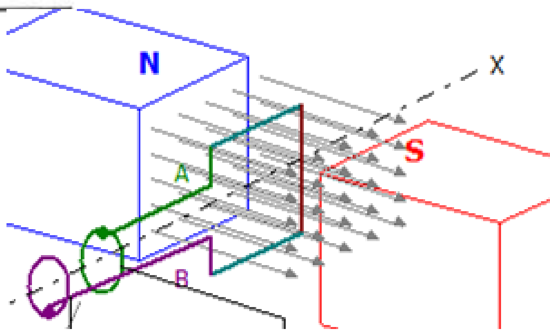
1. Flemming’s right hand rule
2. Flemming’s left hand rule
3. Lenz’s Laws

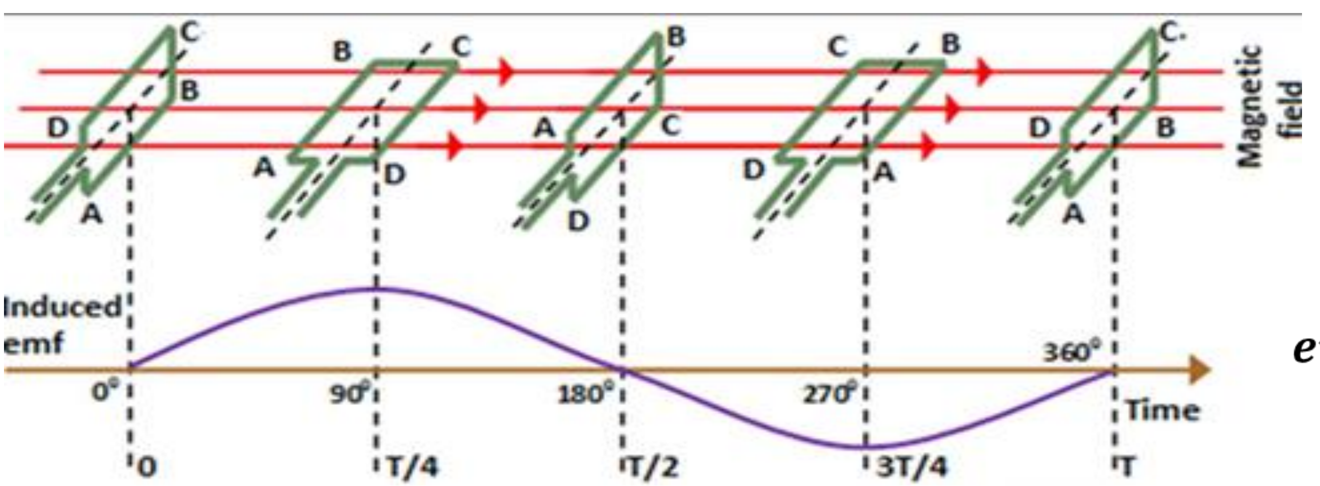
ELECTROMAGNETIC INDUCTION
(Dynamically Induced Emf)

Magnitude of Dynamically Induced EMF:









$$e \propto \frac{(-)\,d\phi}{dt} \quad \text{or} \quad e = -N\frac{d\phi}{dt}$$

$$emf, e = B\,l\,v\,sin\theta \quad \text{(volt)}$$

CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic Materials

Magnetic Materials Based on Relative Permeability

Linear

1. Diamagnetic ($\mu_r \leq 1$)

- Magnetic moment opposite to applied field.
- Dipoles align in the direction of applied field
- Poor magnetization

2. Paramagnetic ($\mu_r \geq 1$)

- Magnetic moment is in the direction of applied field.
- Dipoles align in the direction of applied field
- Dipoles get back to original position when external field is removed.

Non-Linear (μ_r>>1)

1. Ferromagnetic

- Magnetic moment is in the direction of applied field.
- Dipoles align in the direction of applied field
- Dipoles will not get back to original position when external field is removed.
- Iron, Nickel, Cobalt

2. Ferrimagnetic

- Nickel ferrite, Nickel-Zinc ferrite

Magnetic Materials Based on Hysteresis Loop Area

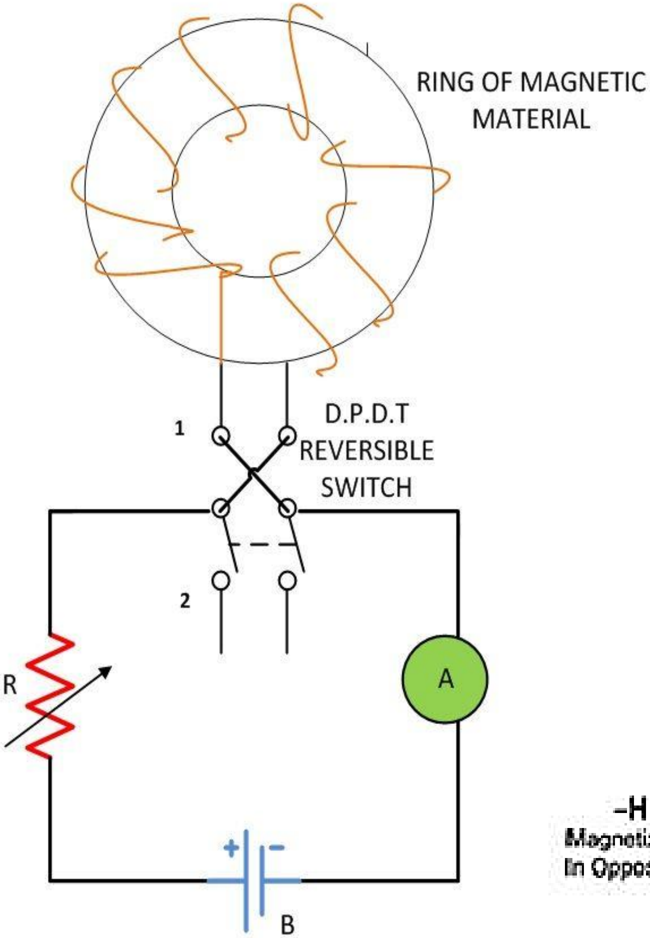
Soft Magnetic Materials

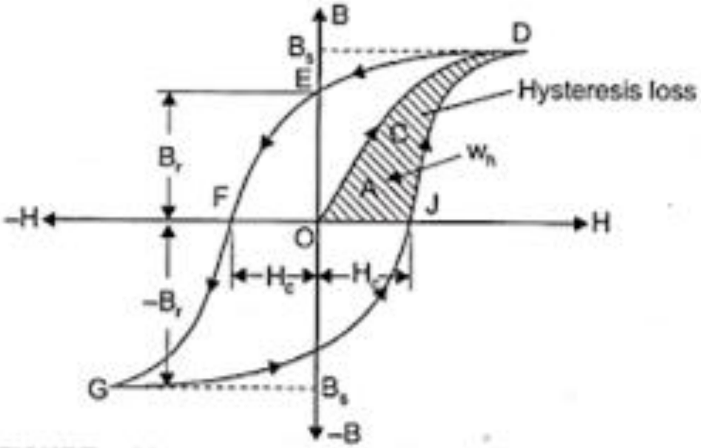
- High saturation magnetization, permeability, resistivity, susceptibility
- Low coercivity, core loss
- Small hysteresis area
- Transformers, generators, motors
- Ferrites, Alloys of iron.

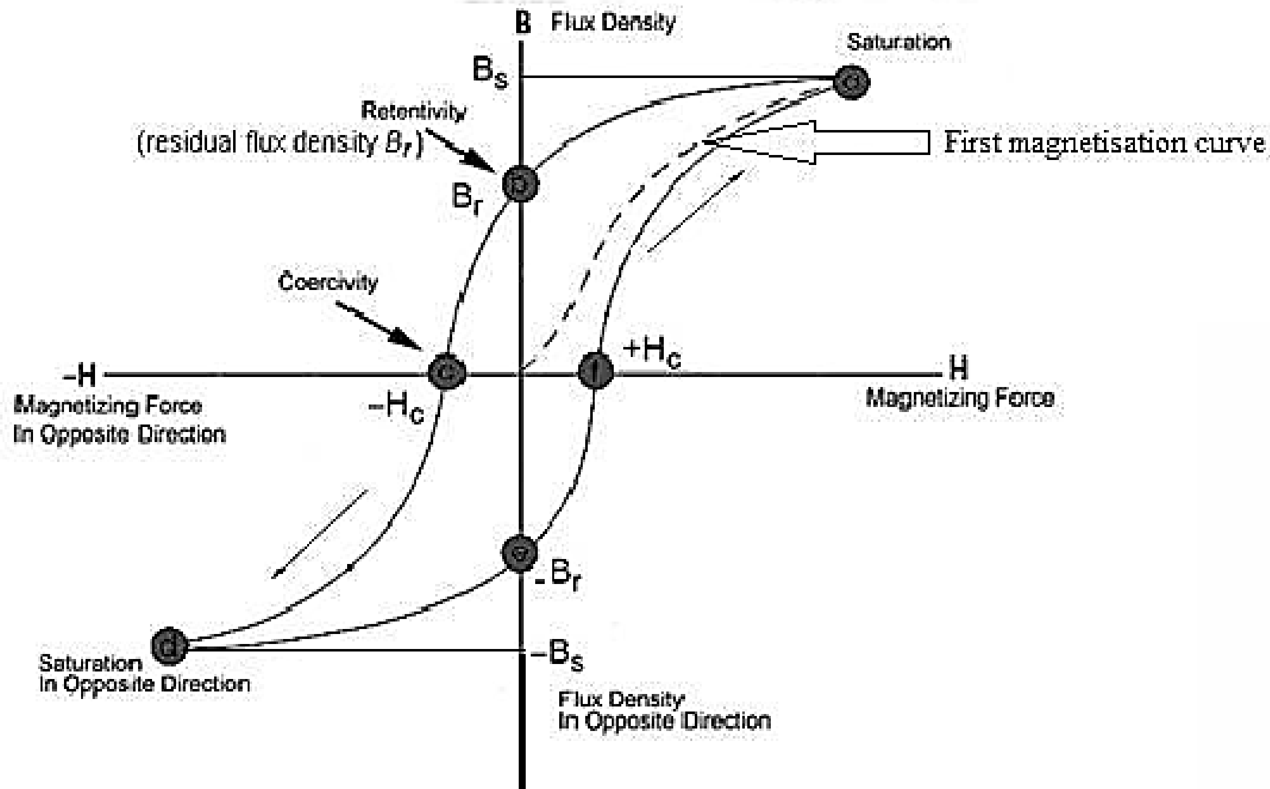
Hard Magnetic Materials

- High saturation magnetization.
- Low coercivity and susceptibility.
- Large hysteresis area.
- High curie temperature.
- Manufacture of permanent magnets.
- Alnico, Nickel, Cobalt.

HYSTERESIS LOOP

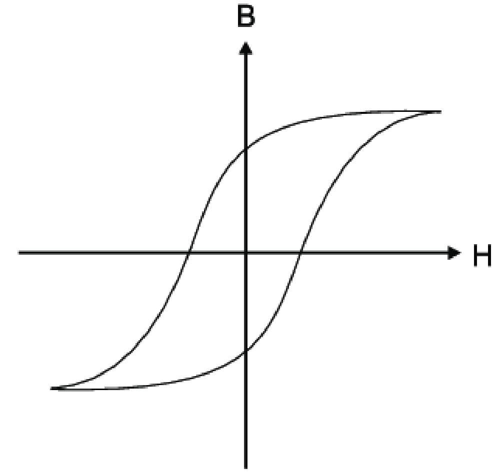




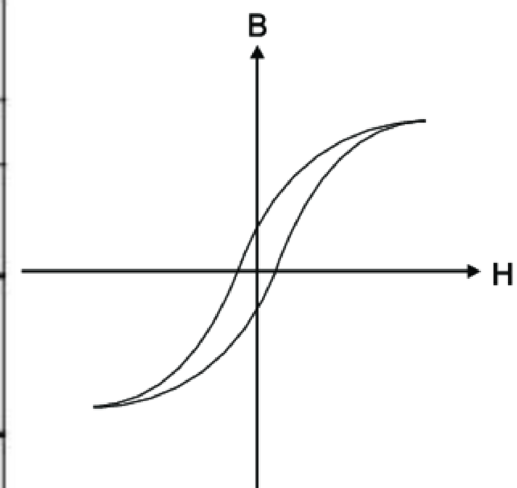


HYSTERESIS LOOP

S. No	*Hard Magnetic Materials*	*Soft Magnetic Materials*
1.	Cannot be easily magnetized	Can be easily magnetized.
2.	It can be produced by heating and sudden cooling	It can be produced by heating and slow cooling.
3.	Domain wall does not move easily and require large value of H for magnetization.	Domain wall move easily and requires small value of H for magnetization.
4.	Hysteresis loop area is large Susceptibility and Permeability values are small.	Hysteresis loop area is small Susceptibility and Permeability values are high.
5.	Retentivity and Coercivity are large	Retentivity and Coercivity are small.
6.	High eddy current loss	Low eddy current loss
7.	Impurities and defects will be more	No impurities and defects
8.	**Examples:** Alnico, Chromium steel, tungsten steel, carbon steel.	**Examples:** Iron-silicon alloy, Ferrous nickel alloy, Ferrites Garnets.
9.	**Uses:** Permanent magnets, DC magnets.	**Uses:** Electro magnets, computer data storage. Transformer core.



Hard Magnetic Materials



Soft Magnetic Materials

HYSTERESIS LOSS

Definition : Due to repeated magnetization and demagnetization a disturbance in the domain alignment results in storage of energy. The loss of energy in the circuit appears as heat known as hysteresis loss.

Elimination : Using narrow silicon steel core materials

Formula : $P_h = K_h (B_m)^{1.6} f V$ (watt)

Where,

P_h is Hysteresis loss in watts

K_h is hysteresis loss constant

B_m is the magnetic flux density in weber per square meter

f is the frequency in hertz

V is the volume of the material in cubic meter

EDDY CURRENT LOSS

Definition : By Faraday's law of electromagnetic induction the emf gets induced not only in the conductor but also in the core that carries the conductor or coil. This emf in the core produces a current known as eddy current which opposes its cause that is the main flux by Lenz's law. This reduction in main flux is eddy current loss.

Elimination : reducing the thickness of the laminations

Formula : $P_e = K_e (B_m)^2 f^2 t^2 \ V \ (\text{watt})$

Where,

P_e is Hysteresis loss in watts

K_e is hysteresis loss constant

B_m is the magnetic flux density in weber per square meter

f is the frequency in hertz

V is the volume of the material in cubic meter

t is the thickness of the material in square meters

ENERGY STORED IN MAGNETIC FIELD

By using the formula of self induced emf using Faraday's law of electromagnetic induction,

$$\therefore \quad e = -L\frac{dI}{dt}$$

$$\Rightarrow \quad dI = \frac{e}{L}\,dt$$

Small amount of work done *i.e.*,

$$dW = eI\,dt$$

Total work done

$$W = \int eI\,dt$$

$$= \int_0^I LI\,dI = \frac{1}{2}$$

This work done will be stored in th magnetic energy in inductor,

$$W = \frac{1}{2}LI^2.$$

$$W = \frac{1}{2}LI^2$$

$$\text{Energy density} \quad (u) = \frac{\text{total energy stored}}{\text{volume}}$$

$$u = \frac{\left(\frac{1}{2}\right)LI^2}{Al} = \frac{\frac{1}{2}(LI)\,I}{Al}$$

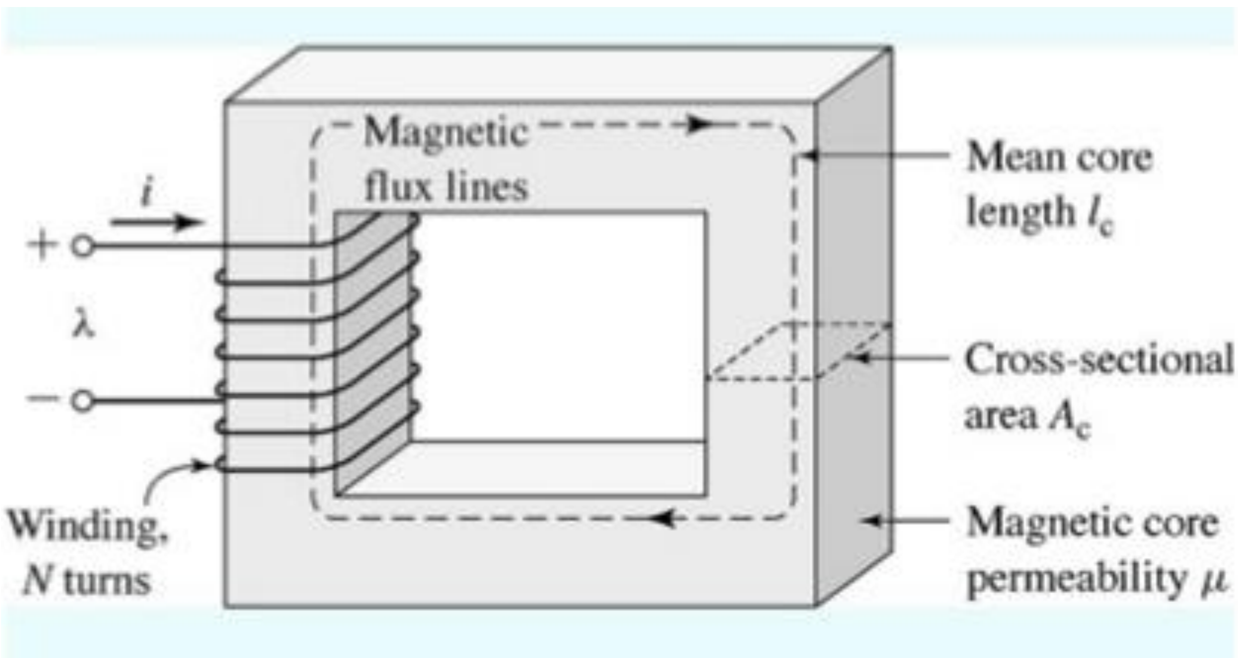
$$\text{Flux} = NBA = LI$$

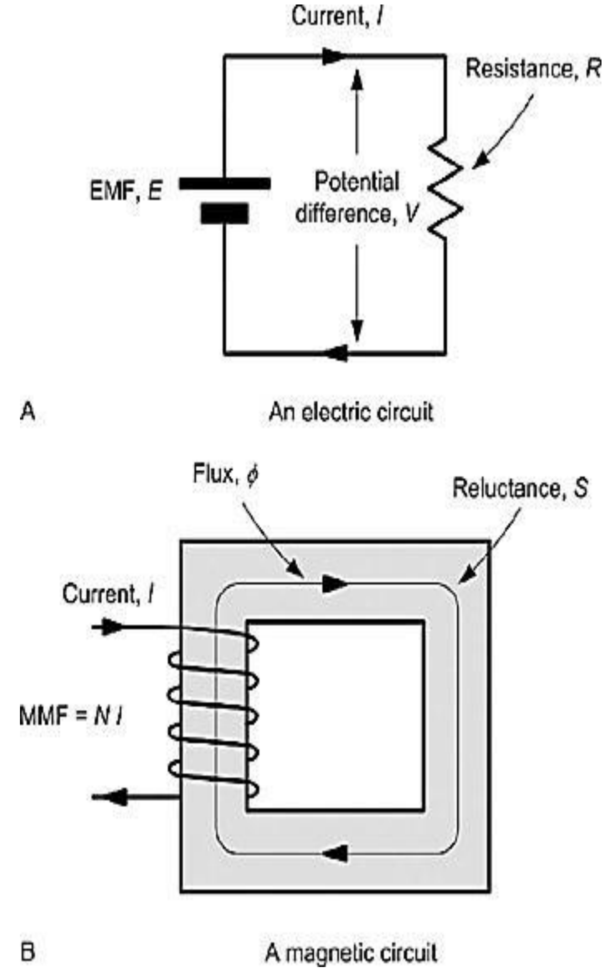
$$\text{and} \quad B = \frac{\mu_0 NI}{l} \Rightarrow I = \frac{Bl}{\mu_0 N}$$

$$\therefore \quad u = \frac{\frac{1}{2}(NBA).\frac{Bl}{\mu_0 N}}{Al} = \frac{B^2}{2\mu_0}$$

MAGNETIC CIRCUITS

Definition **:** Closed path traced by magnetic lines of force or flux





<u>MMF:</u> Force required for the flow of flux.

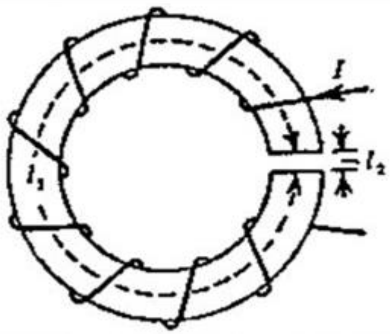
mmf = NI (or) mmf= SΦ (AT)

<u>Reluctance, S:</u> Resistance offered to the flow of flux.

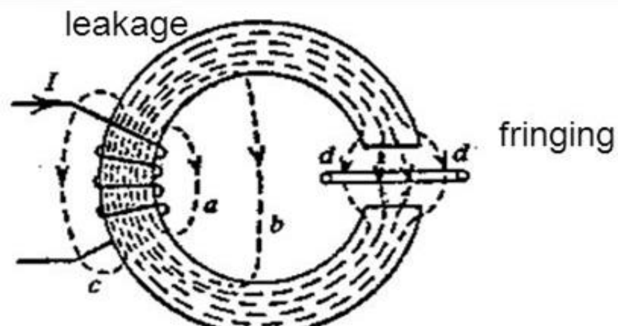
$S = \frac{NI}{\Phi}$; (or) $S = \frac{l}{\mu_o \, \mu_r A}$ (AT/Wb)

<u>Permeance, P:</u> Reciprocal of reluctance. $P = \frac{1}{S}$ (Wb/AT)

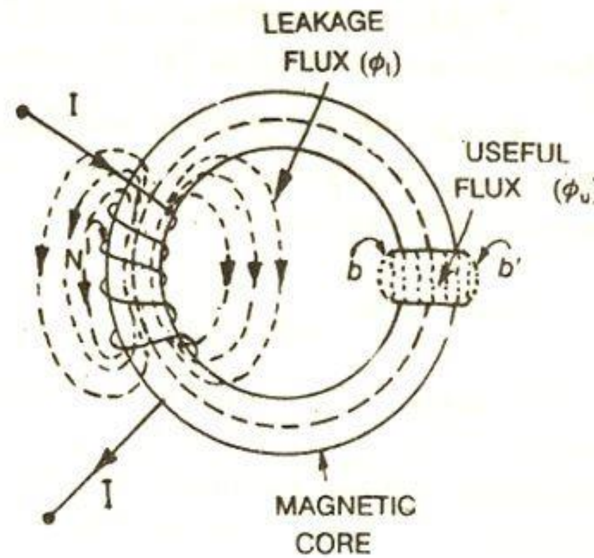
IMPORTANT TERMS IN MAGNETIC CIRCUITS



Magnetic circuit with air-gap

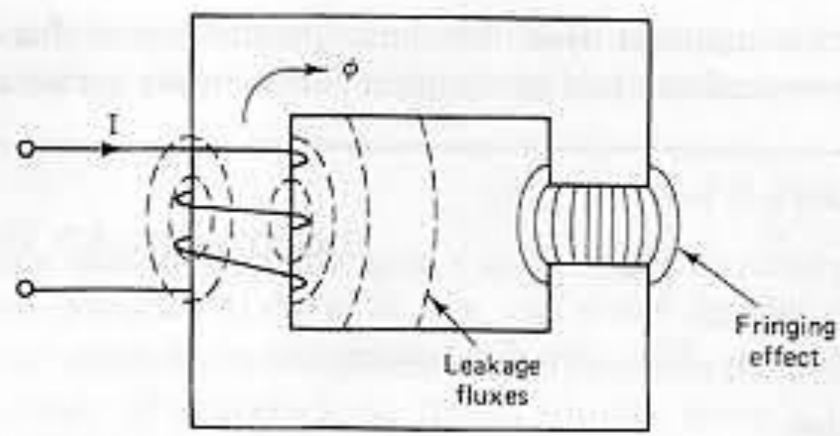


Leakages and fringing of flux



Some fluxes are leakage via paths a, b and c . Path d is shown to be expanded due to fringing. Thus the usable flux is less than the total flux produced, hence

$$Leakage\ factor = \frac{total\ flux}{usable\ flux}$$



$$\text{Stacking Factor} = \frac{\text{Net cross sectional area occupied by magnetic material}}{\text{Gross cross sectional area}}$$

AC EXCITION IN MAGNETIC CIRCUITS

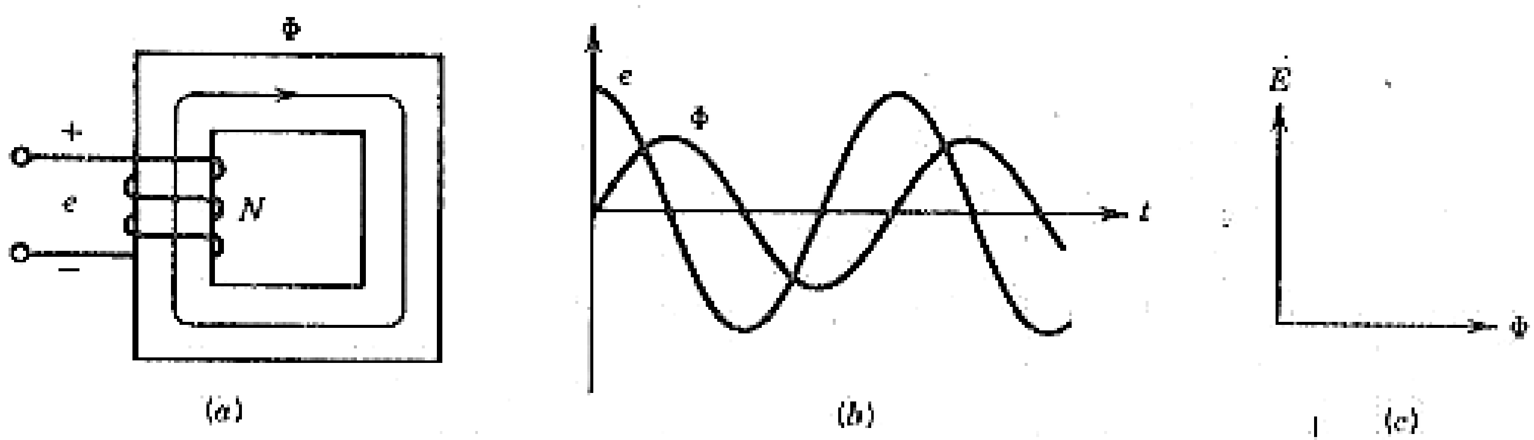


FIGURE 1.17 Sinusoidal excitation of a core. (a) Coil–core assembly. (b) Waveforms. (c) Phasor diagram.

$$\Phi(t) = \Phi_{max} \sin \omega t$$

where Φ_{max} is the amplitude of the core flux

$\omega = 2\pi f$ is the angular frequency

f is the frequency

AC EXCITION IN MAGNETIC CIRCUITS

From Faraday's law, the voltage induced in the N-turn coil is

$$e(t) = N\frac{d\Phi}{dt} \tag{1.38}$$

$$= N\Phi_{\max}\omega\cos\omega t$$

$$= E_{\max}\cos\omega t \tag{1.39}$$

Note that if the flux changes sinusoidally (Eq. 1.37), the induced voltage changes cosinusoidally (Eq. 1.39). The waveforms of e and Φ are shown in Fig. 1.17b, and their phasor representation is shown in Fig. 1.17c. The root-mean-square (rms) value of the induced voltage is

$$E_{\text{rms}} = \frac{E_{\max}}{\sqrt{2}}$$

$$= \frac{N\omega\Phi_{\max}}{\sqrt{2}}$$

$$= 4.44Nf\Phi_{\max} \tag{1.40}$$

This is an important equation and will be referred to frequently in the theory of ac machines.

Thank You