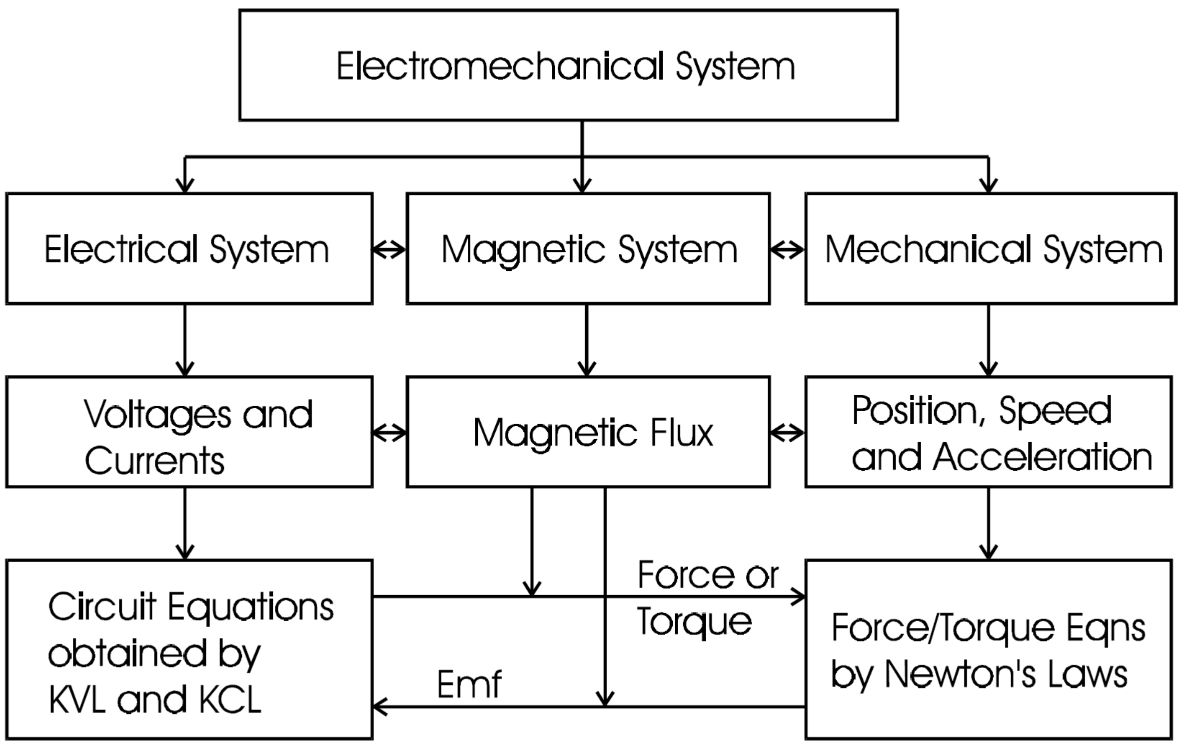
Electromechanical Energy Conversion

Prepared by: Dr. Surinder Jassar

Energy Conversion

- Various devices can convert electrical energy to mechanical energy and vice versa
    1. Motors and Generators – continuous energy conversion equipment. These devices operate in rotating mode.
    2. Actuators (solenoids, relays, electromagnets) – translational force (linear motion)
    3. Transducers (measurement and control) – these devices transform the signals of different forms (microphones, speakers etc.)
- Magnetic field is used as a medium for energy conversion as the permeability of ferromagnetic materials are much larger than the permittivity of dielectric materials



Energy Conversion

- Principle of conservation of energy
- In an Electromechanical energy conversion device, the total input energy is equal to the sum of the following three components:
  - Energy dissipated (as a loss in the resistor)
  - Energy stored (in the magnetic field)
  - Useful output energy

field loss (core loss)

I^2R loss (Elect. loss)

Electrical energy i/p from a source = Mech. energy o/p + Increase in stored energy in the coupling magnetic field + energy loss

Energy Conversion

- Motor - the electromechanical energy conversion takes place from electrical energy to mechanical energy
- Generator - the conversion takes place from mechanical energy to electrical energy
- In the electrical machines, conversion of energy from electrical to mechanical ~~to~~ or from mechanical to electrical results the following two electromagnetic phenomena:
    1. When a conductor moves in a magnetic field, an EMF (voltage) is induced in the conductor : principle of operation for a Generator
    2. When a current carrying conductor is placed in a magnetic field, a mechanical force acts on the conductor : principle of operation for a Motor
- These two effects occur simultaneously whenever energy conversion takes place from electrical to mechanical or vice versa

Energy Conversion

- Motoring – electric current flows through the conductors placed in the magnetic field due to which a force is produced on each conductor. The conductors are placed on a rotor, which is free to move. An electromagnetic torque is produced → o/p of the motor on the rotor so that the rotor starts rotating at some speed. The torque produced on the rotor is transferred to a shaft of the rotor and hence it can drive a mechanical load. Since the conductors are rotating in a magnetic field, thus as EMF is also induced in each conductor
  ↳ back emf / counter emf

Electrical energy input from the source	=	mechanical energy output	+	increase in stored energy in coupling medium	+	energy loss

hydro
steam
diesel engine
turbine

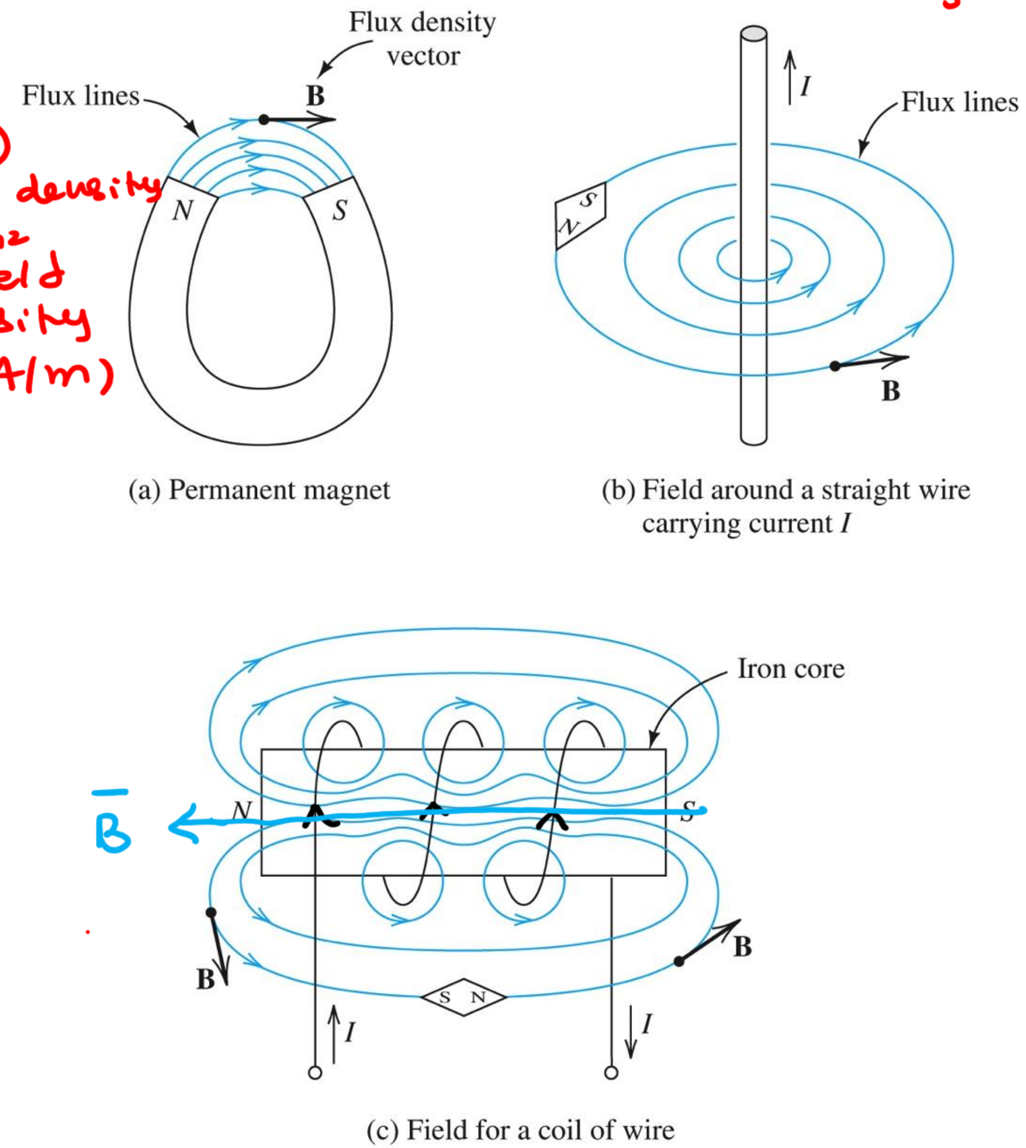
- Generating - the rotor is driven by a prime mover. An EMF is induced in the rotor → o/p of the generator conductors due to which a current will flow and deliver electric power to the load. The current flowing through the conductors will interact with the magnetic field to produce a reaction torque, which will tend to oppose the torque developed by the prime mover
  counter torque

Mechanical energy input from the source	=	Electrical energy output	+	increase in stored energy in coupling medium	+	energy loss

Magnetic Field

electromagnet

- Magnetic field
  - flux, Φ (Wb)
  - magnetic flux density $\bar{B}$ (Wb/m²)
  - magnetic field intensity $\bar{H}$ (A/m)
  - lines of flux form closed paths
  - compass is used to determine the direction of the flux lines at any point

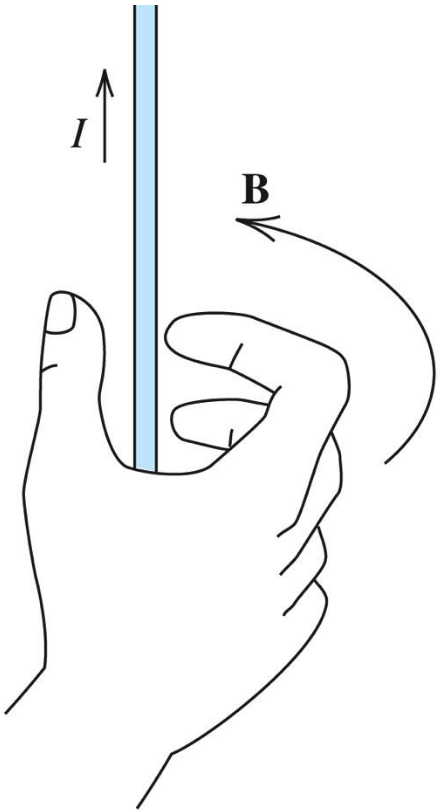


(a) Permanent magnet

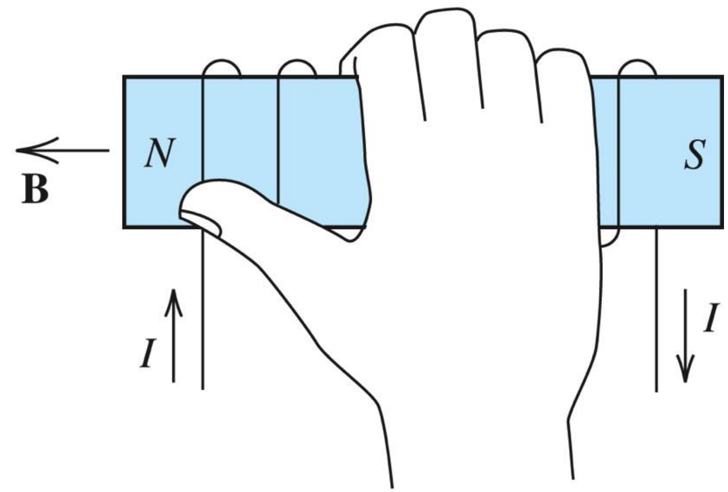
(b) Field around a straight wire carrying current I

(c) Field for a coil of wire

Magnetic Field – Right Hand Rule



(a) If a wire is grasped with the thumb pointing in the current direction, the fingers encircle the wire in the direction of the magnetic field



(b) If a coil is grasped with the fingers pointing in the current direction, the thumb points in the direction of the magnetic field inside the coil

Magnetic Field - Force [Motor action]

Force on a charge moving in a magnetic field

$$\bar{F} = \bar{f} = q(\bar{u} \times \bar{B})$$

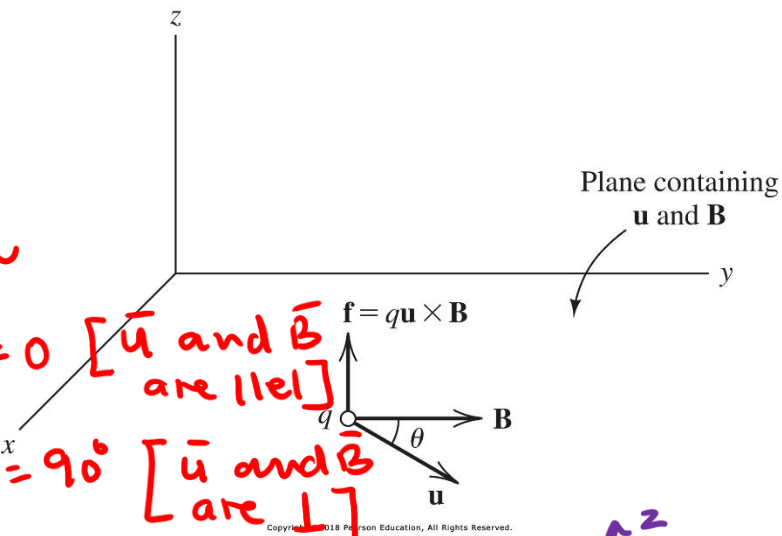
direction of $\bar{F}$ is $\perp$ to both $\bar{u}$ and $\bar{B}$

$$|\bar{F}| = quB \sin\theta$$

θ: angle b/w $\bar{u}$ and $\bar{B}$

$|\bar{F}| = 0 \rightarrow \theta = 0$ [$\bar{u}$ and $\bar{B}$ are ∥el]

$|\bar{F}| = quB \rightarrow \theta = 90^\circ$ [$\bar{u}$ and $\bar{B}$ are $\perp$]



Force on a current carrying conductor (wire)

$$\bar{F} = I(\bar{l} \times \bar{B})$$

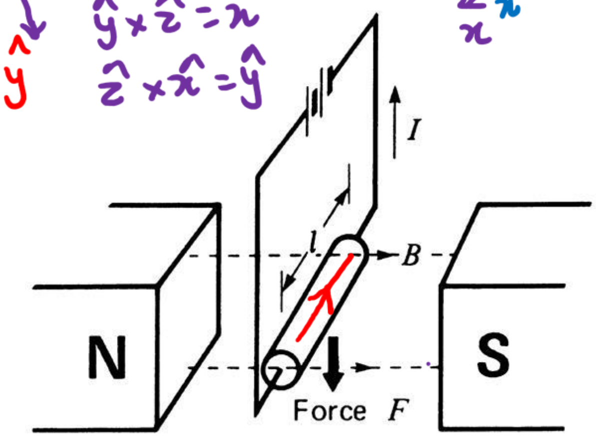
$\bar{l}$: direction of I

$$= I[-\hat{x}l \times \hat{y}B] = -\hat{z}IlB$$

$\hat{x} \times \hat{y} = \hat{z}$

$\hat{y} \times \hat{z} = \hat{x}$

$\hat{z} \times \hat{x} = \hat{y}$



Magnetic Field – Induced Voltage

(Generator Action)

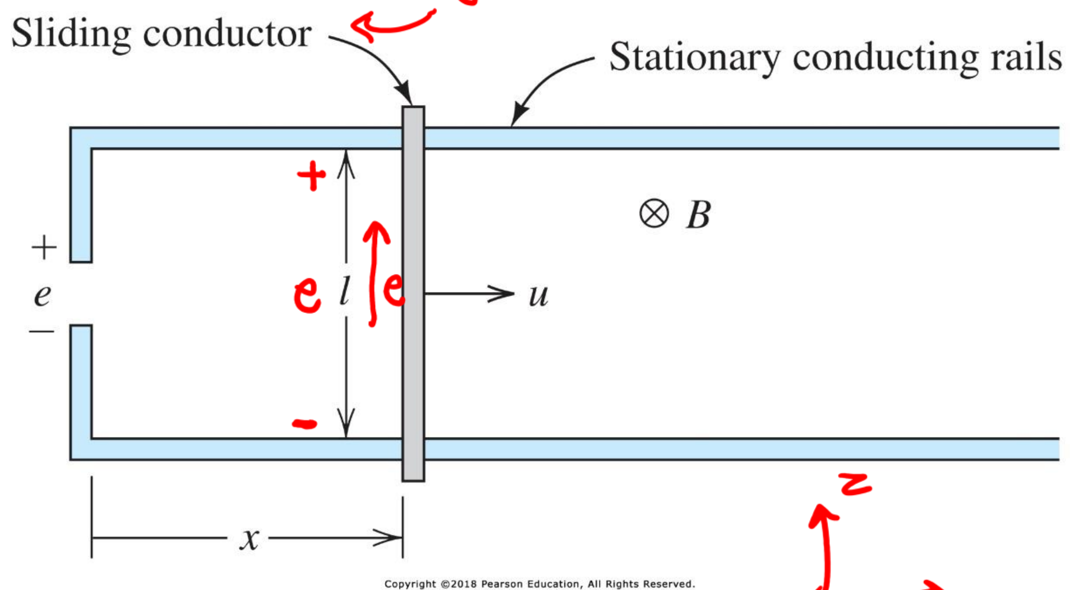
⊙ out of the page
⊗ into the page

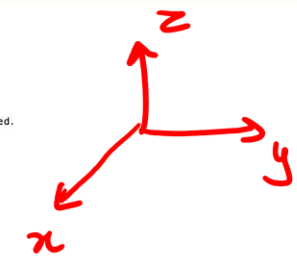
$\hat{x}$ $\hat{y}$ $\hat{z}$

$e = l(\bar{u} \times \bar{B})$

$= l(\hat{y}u \times -\hat{x}B)$

$e = +\hat{z}\,ulB$





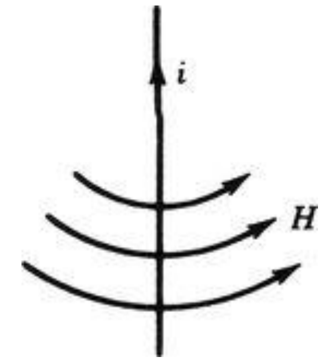
$$e = Blu$$

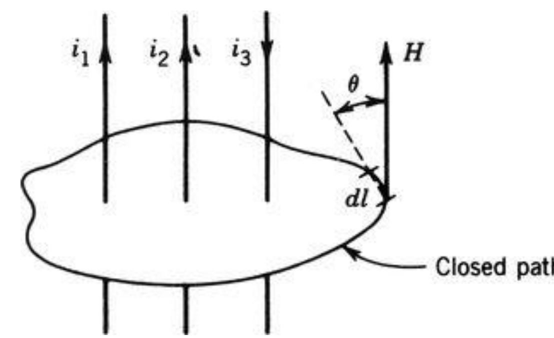
Magnetic Circuits – Ampere's Law

Magnetic field Intensity, H (A/m)

$$\oint_l \bar{H} \cdot d\bar{l} = \Sigma i = i_1 + i_2 - i_3$$

closed path





Magnetic flux Density, B (Wb/m^2 or T)

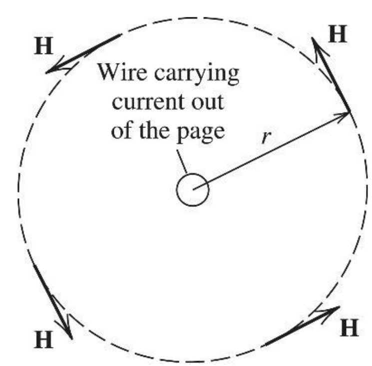
$$\bar{B} = \mu \bar{H}$$

permeability → material property

Magnetic flux, ϕ (Wb)

$$\Phi = B \times \text{Area}$$

cross-sectional area

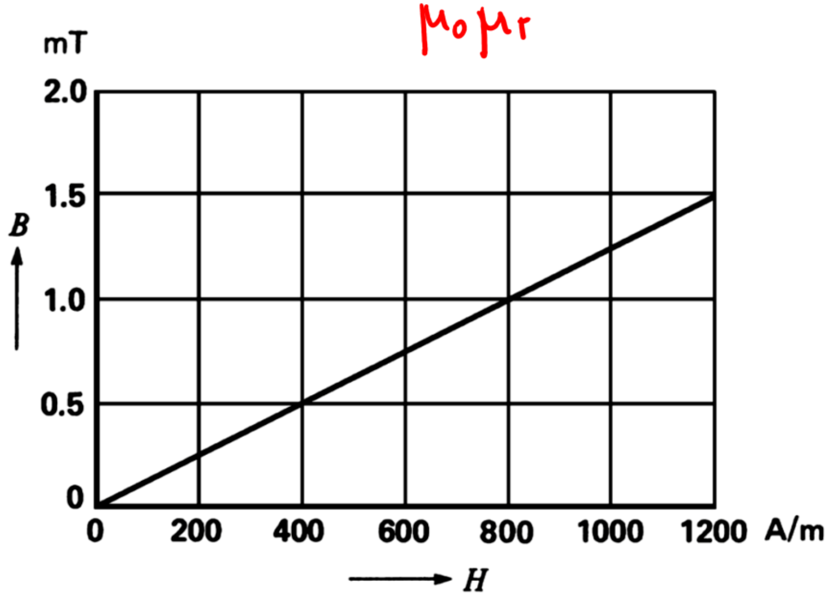


Magnetic Circuits – Flux Density

$B = \mu H$

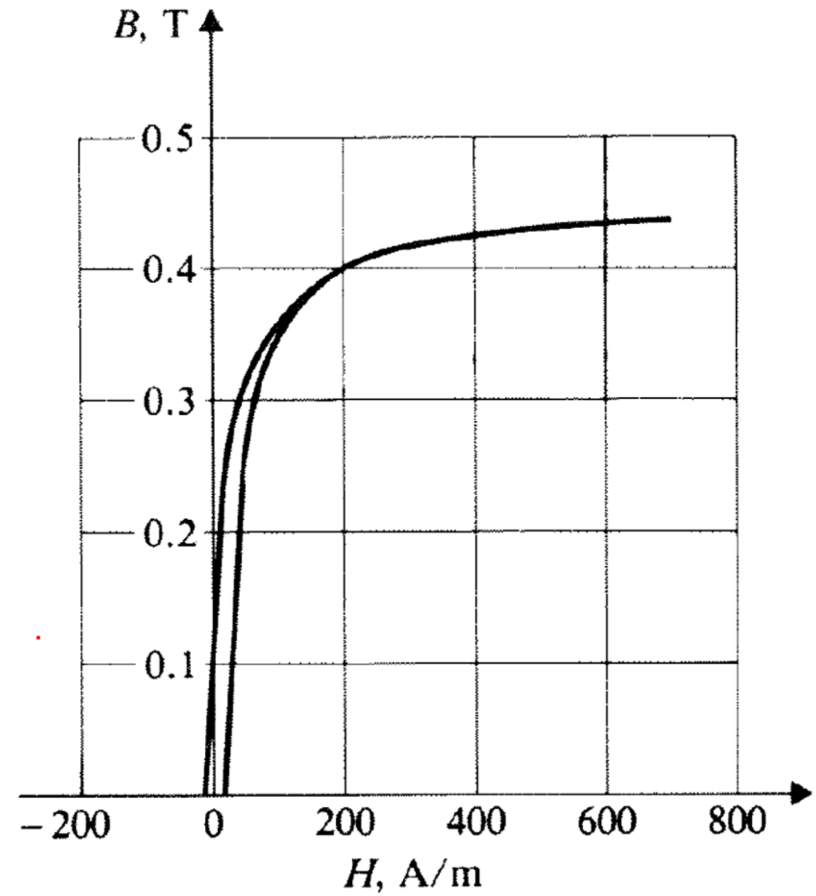
$\downarrow$

$\mu_0 \mu_r$



Vacuum → free space ($\mu_r = 1$)

$B = \mu_0 \mu_r H$



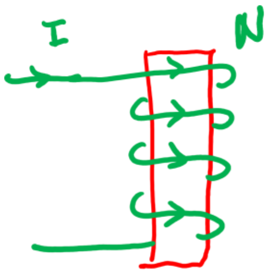
B-H loop for a typical ferrite material.

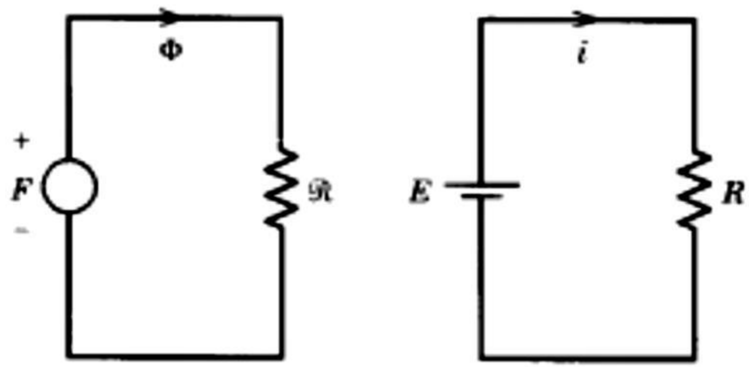
Ferrite Material

Magnetic Circuits

- Magnetic circuit is the path followed by the flux in a magnetic material
- Magnetic circuit form an integral part of the rotating electrical machines and transformers

Magnetic Circuits





(a) (b)

$\mathcal{F} = NI$

↳ Ampere-turns

	Electric Circuit	Magnetic Circuit
Driving force	emf (E or V)	mmf ($\mathcal{F}$)
Produces	Current (i=E/R)	Flux ($\Phi = \mathcal{F}/\mathcal{R}$)
Limited by	Resistance ($R = l/\sigma A$)	Reluctance ($\mathcal{R} = \frac{l}{\mu A}$)

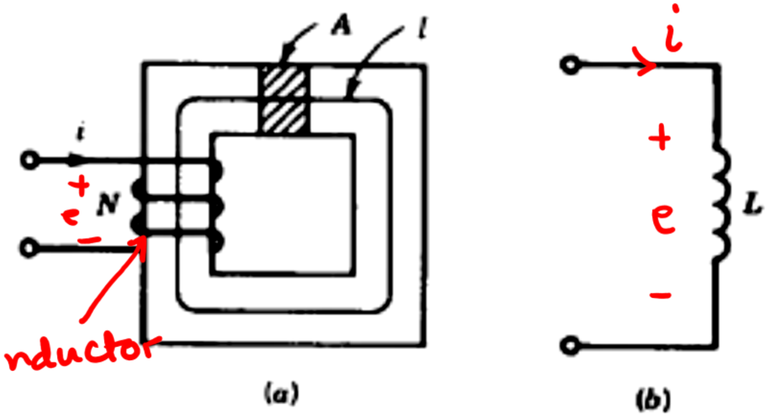
$R = \rho \frac{L}{A}$

$R = \frac{1}{\sigma} \frac{L}{A}$

Inductance

- Assume
  - The flux of ϕ through the core
  - Very close winding turns
- Linkage flux

$$\lambda = N\phi$$



- Inductance

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

$$L = N\frac{d\phi}{di}$$

$$L = \frac{\lambda}{i} = \frac{N\phi}{i}$$

Henry

$$e = L\frac{di}{dt}$$

Inductance of an inductor

- Alternate expression

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} = \frac{NBA}{i} = \frac{N\mu HA}{i} = \frac{N\mu\frac{Ni}{l}A}{i} = \frac{N^2\mu A}{l} = \frac{N^2}{\frac{l}{\mu A}} = \frac{N^2}{\mathcal{R}}$$

Faraday's Law

- A voltage is induced in a coil whenever its flux linkages are changing

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

  - Linear Flux

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

  - Sinusoidal Flux

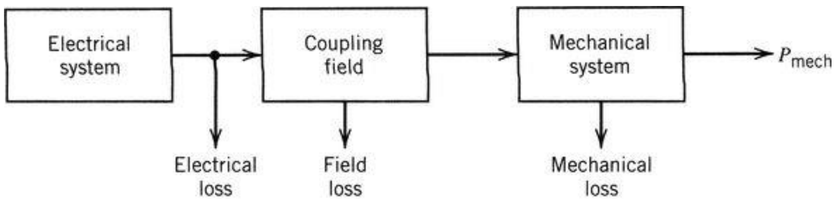
$$e = N\frac{d\phi}{dt} = N\frac{d(\phi_m sin\omega t)}{dt} = N\phi_m \omega cos\omega \mathrm{t} = E_m cos\omega \mathrm{t}$$

- Inductance

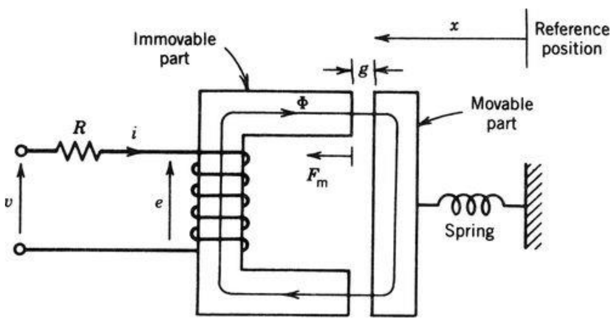
$$e = \frac{d\lambda}{dt} = \frac{d(Li)}{dt} = L\frac{di}{dt}$$

Electromagnetic Force – Linear Systems

- Energy Conversion



- Air Gap



Electromagnetic Force – Example