EEE 363
ELECTRIC MACHINES

Class Schedule : MW 1:00 PM – 2:40 PM

Instructor : Dr. Shohana Rahman Deeba
Department of Electrical and Computer Engineering
Office: SAC-1010B
Email: shohana.deeba@northsouth.edu

Acknowledgement: Dr. Mithulan Nadarajah
The University of Queensland, Australia

Electric Machines

- A machine uses power to apply forces and control movements to perform an intended action
- Electric machine is a general term for machines using electromagnetic forces e.g. motors, generators etc.
- Transfers one form of energy to another

Classifications

- Stationary e.g. Transformers
- Rotating e.g. Motors and Generators

Major Types of Electric Machines

- Rotating Machines
  - Generators
    - AC generators
      (Alternators, Doubly-Fed-Induction-Generators)
    - DC generators
  - Motors
    - AC Motors
      (Synchronous motors, Induction motors)
    - DC Motors

INTRODUCTION TO MAGNETIC CIRCUITS LECTURE-1

Text Book: Charles I Hubert

Magnetic Circuit

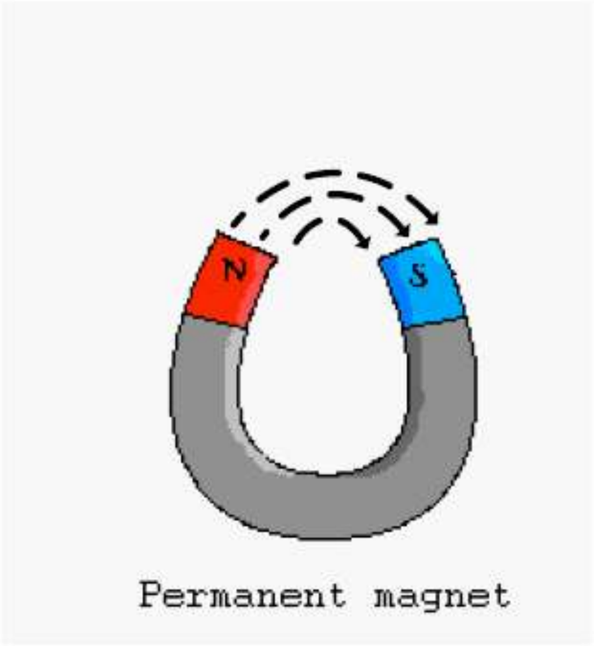
- Most electric machines convert energy by use of magnetic field. e.g.
  - Synchronous Generators
  - Induction Motors
  - DC Machines

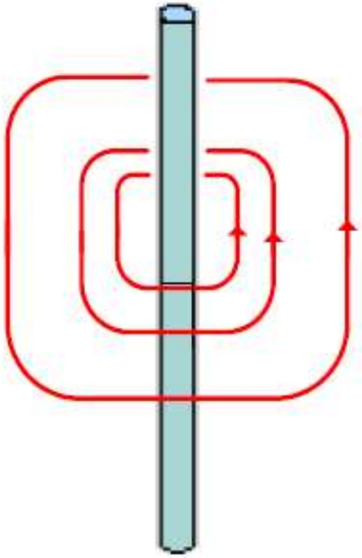
- Need to understand basic magnetic circuit concepts
  - Especially analogy to electric circuits

- Application of magnetic circuit concepts to determine the magnetic fields in practical devices fundamental in determination of equivalent circuits for AC machines

Magnetic Circuit

Source of Magnetic Fields/Flux





Current carrying wire

Magnetic Circuit

Source of Magnetic Fields

- Permanent Magnetic
  - North pole is the pole from which the field lines emanate, and the south pole is the end to which the field lines return
- Current carrying wire
  - If a wire is grasped with the thumb pointing in the (conventional) current direction, the fingers encircle the wire in the direction of the magnetic field

Ampere's Law

- The line integral of the magnetic field intensity around a closed path is equal to the algebraic sum of the currents flowing through the area enclosed by the path.

$$\oint \mathbf{H} \cdot d\mathbf{l} = I$$

- H – Magnetic field intensity [amperes/metre] [A/m] - measure of magnetic field strength

- I – Current producing magnetic field

Ampere's Law

- Magnetic field intensity produced by coil of N turns

$$\oint \mathbf{H}_c \cdot \mathbf{dl} = N I$$

- NI – magneto motive force
  Units – ampere.turns
  Dimension – amperes
- Presence of magnetic field will produce lines of *magnetic flux* with density

$$B = \mu H \qquad [\text{Tesla}] \text{ or } [\text{Wb/m}^2]$$

  – Distribution and strength of magnetic field will depend upon path taken by flux produced by magneto-motive force (MMF)

Ferromagnetism

- When iron, iron alloys or other special materials situated in magnetic field, *flux density* produced within metal much greater than corresponding value in free space
- FERROMAGNETISM
  - Property of producing higher flux densities (than free space)
- Flux density in free space
  $B = \mu_o H$, μ_o – permeability of free space, $4\pi \times 10^{-7}$ [Wb/A.m]
- Flux density in ferromagnetic material
  $B = 400000\mu_o H$, $= \mu_r \mu_o H$ μ_r – relative permeability

Ferromagnetism

- Property of ferromagnetism occurs when spacing of atoms just right for “magnetic moments” of all adjacent atoms to add and cause spontaneous magnetisation
- Regions of high local flux density called “domains”
- Without application of external field, all soft ferromagnetic materials produce no external field
- When magnetising force provided, (by external coil), domains change directions of magnetisation, enhancing levels of flux beyond that in free space

Magnetic Circuits

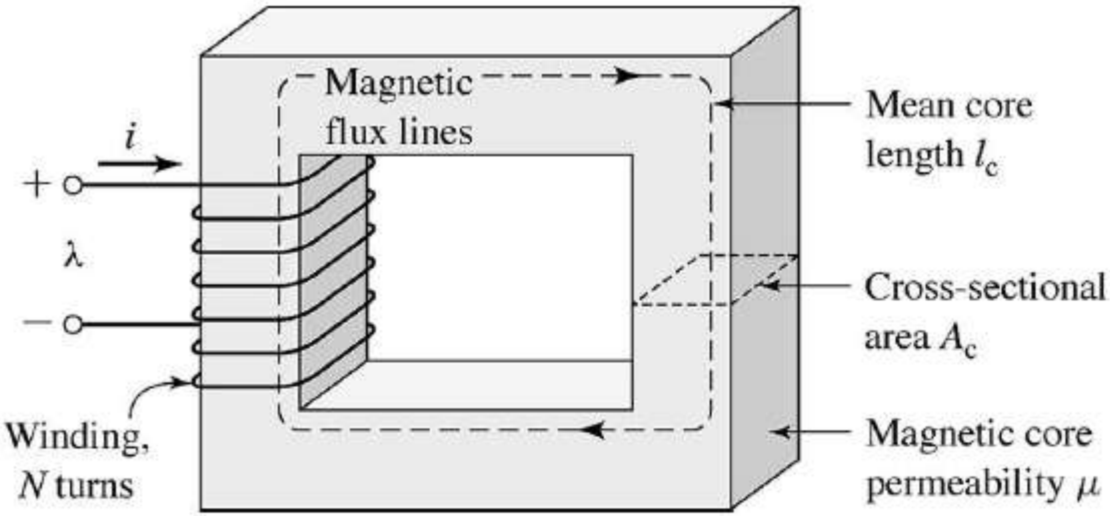
- A magnetic circuit then consists of magnetic structure built mainly of high permeability material.
  - Magnetic flux confined to paths presented by high permeability material
  - Similar to confinement of electric current to conductors in electric circuit

Magnetic Flux

$$\phi = \int_S B.dS$$

- Magnetic flux, Φ, [webers] or [Wb]
  – sum across a surface of density of magnetic flux passing through it (at perpendicular)
- Important concept when flux density uniform across surface through piece of magnetic material

Magnetic Circuits



Magnetic motive force (MMF), produces magnetic field

Magnetic field, H_c, approximately constant

Produces magnetic flux, Φ, within the material

– Dependent upon permeability of material

Magnetic Flux

- For magnetic circuit shown previously
  - $\phi = B_c A_c \quad = \mu H_c A_c$
- From Amperes Law – $NI = H_c L_c$
  - $\phi = \mu A_c (NI/L_c)$
  - $\phi [L_c/(\mu A_c)] = NI = \mathcal{F}$
- This can be re-written as
  - $R\phi = NI = F$,

    Where R = reluctance of the magnetic circuit in (A-t)/Wb.

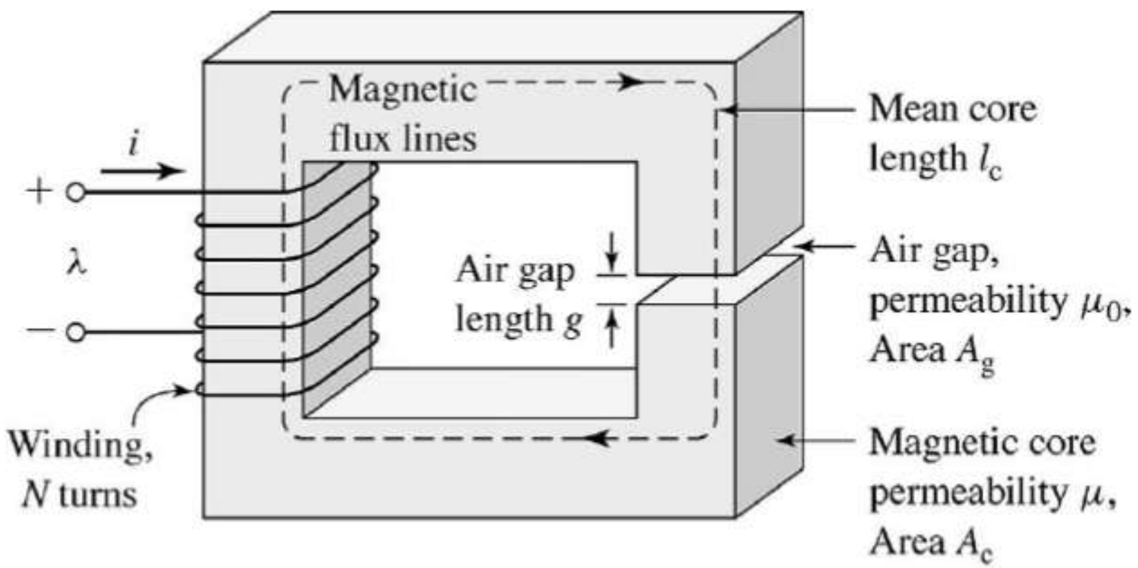
Electric – Magnetic Circuits

Electric Circuit	Magnetic Circuit
I – current (A)	Φ – flux (Wb)
V – emf (V)	*F* – MMF (A-t)
R – resistance (Ω)	*R* – reluctance (A-t/Wb)
Σ – conductivity (S/m)	μ - permeability (H/m)

Electric – Magnetic Circuits

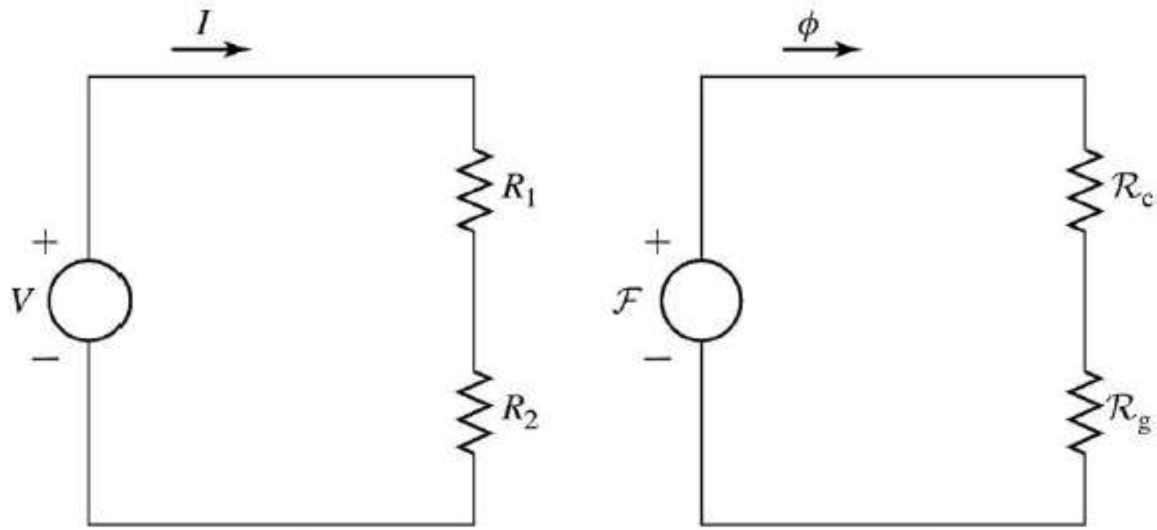
A magnetic circuit is an arrangement of Ferromagnetic materials called a **core** that forms a path to contain and guide the magnetic flux in a specific direction. The core shape in the Figure is used in a Transformer.

A magnetic circuit with an air gap



Electric – Magnetic Circuits

Equivalent circuit (with air-gap)



$$I = \frac{V}{(R_1 + R_2)}$$

(a)

$$\phi = \frac{\mathcal{F}}{(\mathcal{R}_c + \mathcal{R}_g)}$$

(b)

Laws of Electromagnetic Induction

First **Law** of **Faraday's Electromagnetic Induction** states that whenever a conductor are placed in a varying magnetic field, emf are **induced** which is called **induced** emf, if the conductor circuit are closed current are also **induced** which is called **induced** current.

Faraday's second law: **Faraday's second law of electromagnetic induction** states that, the magnitude of **induced** emf is equal to the rate of change of flux linkages with the coil. The flux linkages is the product of number of turns and the flux associated with the coil.

In accordance to Lenz's law: the voltage generated in each coil will be induced in a direction that opposes the action that caused it.

Faraday’s Law

A time-varying magnetic field induces an electromotive force that produces a current in a closed circuit. This current flows in a direction such that it produces a magnetic field that tends to oppose the changing magnetic flux of the original time varying field.

- Mathematically

$$emf = d\lambda/dt$$

  - λ - total flux linkages of closed path = N ϕ

$$emf = dN\Phi/dt$$

- Produced by:
  - Time varying flux linking stationary path – transformer
  - Relative motion between steady flux and stationary path – synchronous generator under no-load conditions
  - A combination of previous two cases – induction

A Simple Inductor

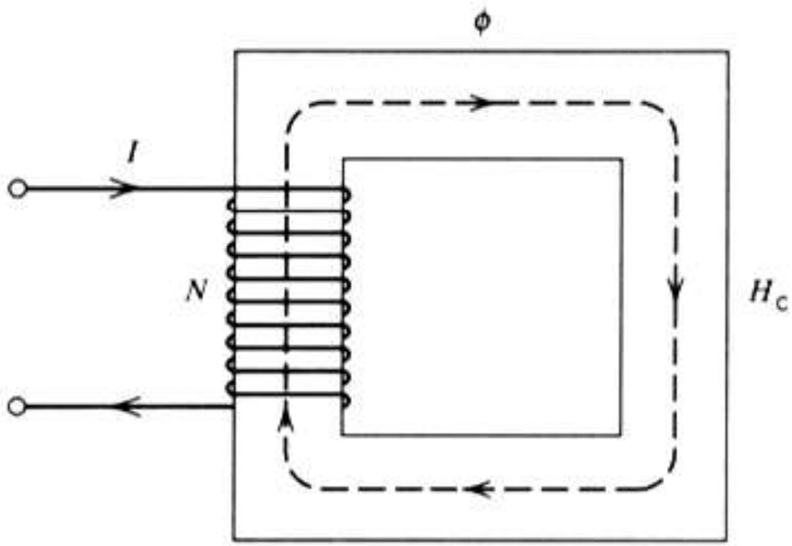


FIGURE 4.1 A magnetic circuit.

If coil connected to voltage source, *v*, current *i* will flow.

Current will produce magnetic flux, Φ

Total flux linkages of the coil containing N turns $\lambda = N\Phi$

Inductance

- For simple coil

$$\Phi = Ni/\mathcal{R} = Ni \div (L_c/\mu A_c)$$

- Self inductance of coil defined as

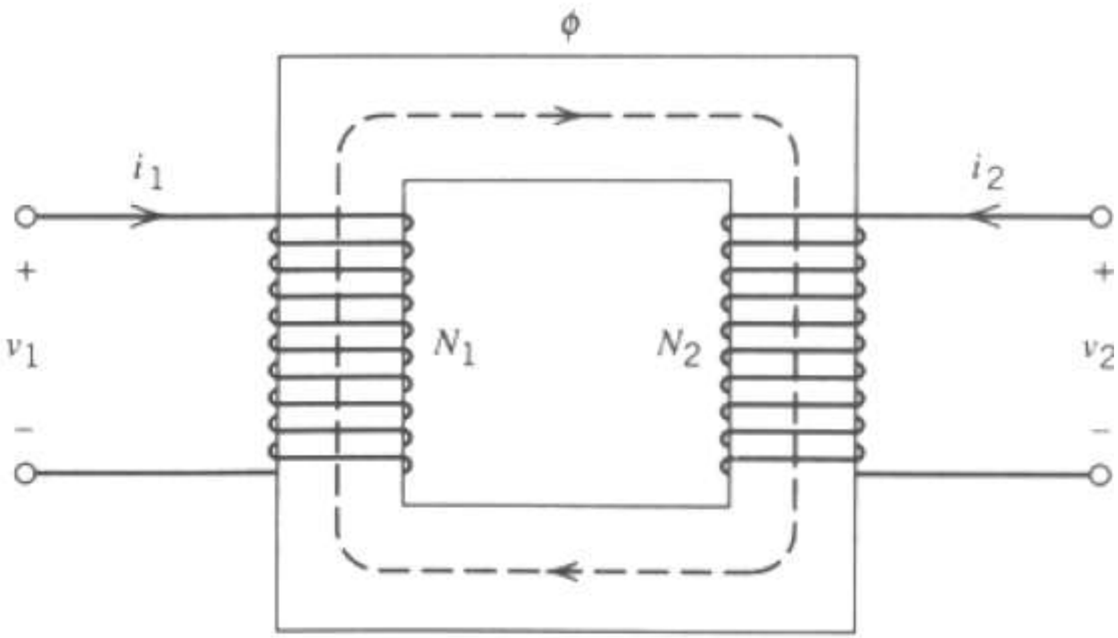
$$L = \frac{\text{total flux linkage of the coil}}{\text{current producing the flux}} = \frac{\lambda}{i}$$

- This can be re-written as

$$L = \frac{\lambda}{i} = \frac{N^2 \mu A}{l}$$

- Implies inductance is a property of the coil energized

Mutual Inductance



Mutual Inductance

- Flux produced by coil 1 will link coil 2.
- Define mutual inductance as

$$L_{21} = \frac{\text{total flux linking coil 2}}{\text{current flowing through coil 1}} = \frac{\lambda_{21}}{i_1}$$

- Assume no "leakage" of flux, so that all flux generated by coil 1 reaches coil 2

Mutual Inductance

$$\lambda_{21} = N_2\phi_{21} = N_2\phi, \quad \phi = \frac{N_1 i_1}{\Re} = \frac{N_1 i_1}{\left(l/_{\mu A} \right)}$$

$$\therefore \lambda_{21} = N_2\phi = \frac{N_1 N_2 i_1}{\Re}, \quad L_{21} = \frac{\lambda_{21}}{i_1} = \frac{N_1 N_2}{\Re}$$

Mutual Inductance

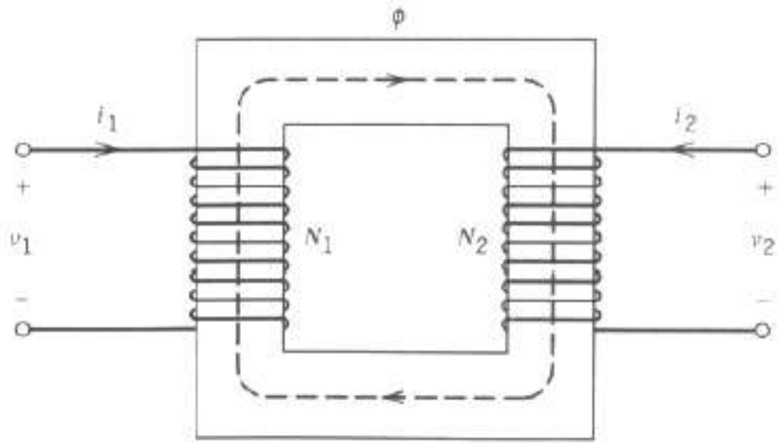


FIGURE 4.7 Mutual inductance.

- If coil 2 excited first and coil 1 left un-energized flux produced by coil 2 will link coil 1

$$L_{12} = \frac{\text{total flux linking coil 1}}{\text{current flowing through coil 2}} = \frac{\lambda_{12}}{i_2}$$

Mutual Inductance

$$\lambda_{12} = N_1\phi_{12} = N_1\phi, \quad \phi = \frac{N_2 i_2}{\Re} = \frac{N_2 i_2}{\left({l}/{\mu A} \right)}$$

$$\therefore \lambda_{12} = N_1\phi = \frac{N_1 N_2 i_2}{\Re}, \quad L_{12} = \frac{\lambda_{12}}{i_2} = \frac{N_1 N_2}{\Re}$$