



Electrical Engineering Department

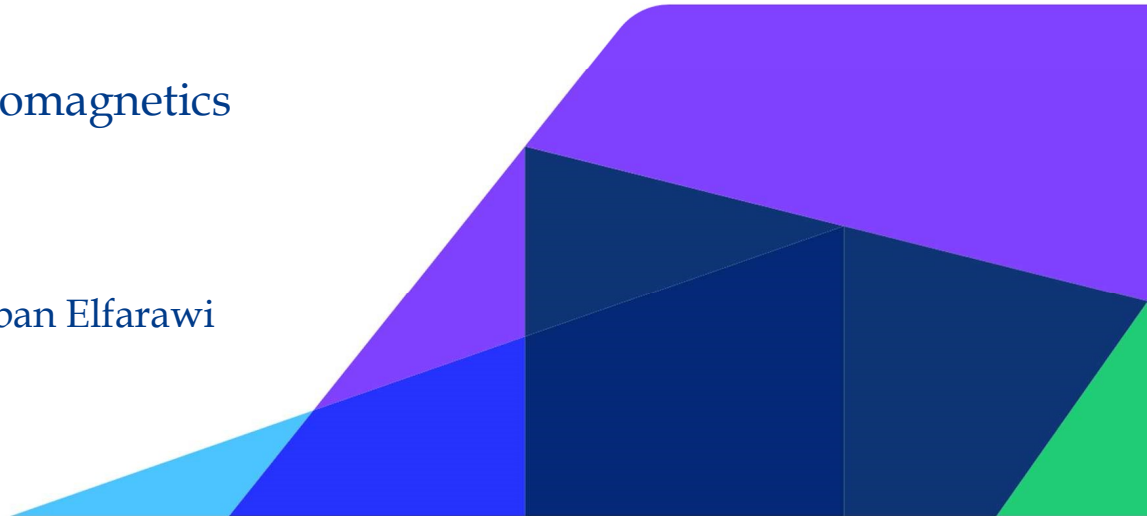
EEN 315: Electric Machines

Introduction

Chapter 1. Electromagnetics

Semester: 481 (2026)

Instructor: Mr. Shaaban Elfarawi





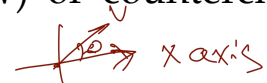
Electrical Machines

Almost all electric machines rotate about an axis, called the shaft of the machine. Because of the rotational nature of machinery, it is important to have a basic understanding of rotational motion. The concepts of distance, velocity, acceleration, Newton's law, and power as they apply to rotating machinery are briefly explained.

A three-dimensional vector is required to completely describe the rotation of an object in space. However, machines normally turn on a fixed shaft, so their rotation is restricted to one angular dimension. Relative to a given end of the machine's shaft, the direction of rotation can be described as either clockwise (CW) or counterclockwise (CCW).

Angular Position θ

$$V_m \sin(\omega t + \theta)$$



The angular position θ of an object *is the angle at which it is oriented, measured from some arbitrary reference point*. Angular position is usually measured in radians or degrees.

$$\omega = 2\pi f$$

Electrical Machines

ω



Angular Velocity ω

Angular velocity (or speed) *is the rate of change in angular position with respect to time*. It is assumed positive if the rotation is in a counterclockwise direction. Angular velocity is the rotational analog of the concept of velocity on a line.

Angular Acceleration α

Angular acceleration *is the rate of change in angular velocity with respect to time*. It is assumed positive if the angular velocity is increasing in an algebraic sense.

Torque τ

The torque on an object *is defined as the product of the force applied to the object and the smallest distance between the line of action of the force and the objects axis of rotation*.

Work W

For linear motion, work *is the application of a force through a distance*.

Power P

Power *is the rate of doing work, or the increase in work per unit time*.

Magnetic Field



Magnetic fields from electricity

- A static distribution of charges produces an electric field
- Charges in *motion* (an electrical current) produce a magnetic field
 - electric current is an example of charges (electrons)



Electromagnets

- Arranging wire in a coil and running a current through it produces a magnetic field that looks a lot like a bar magnet
 - called an electromagnet
 - putting a real magnet inside, can push the magnet back and forth depending on current direction: called a solenoid

Electromagnetism



- Electricity and magnetism are different facets of *electromagnetism*
 - a moving electric charge produces magnetic fields
 - changing magnetic fields move electric charges
- This connection was explained by Faraday, Maxwell
- Einstein saw electricity and magnetism as frame-dependent facets of *unified* electromagnetic force

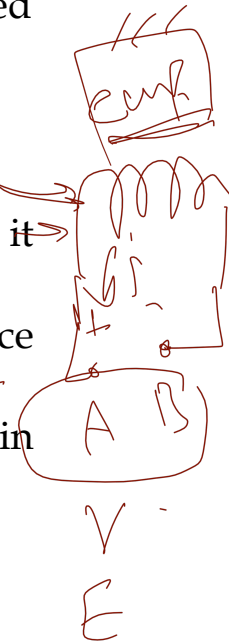
The Magnetic Field



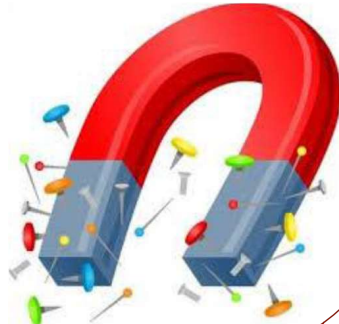
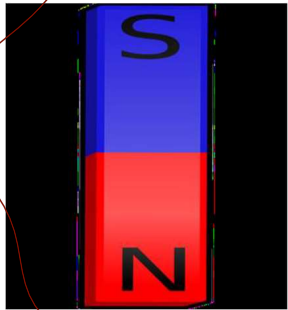
Magnetic fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators, and transformers.

Four basic principles describe how magnetic fields are used in these devices:

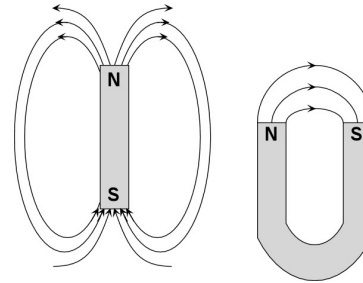
1. A current-carrying wire produces a magnetic field in the area around it.
2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis of transformer action).
3. A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of motor action).
4. A moving wire in the presence of a magnetic field has a voltage induced in it. (This is the basis of generator action).



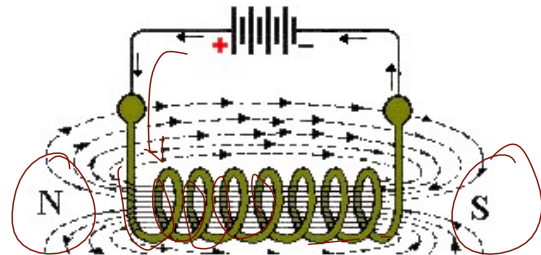
Magnetic Field Sources



Permanent magnet



Magnetic Field lines



Electromagnet

Important terms



1. **Magnetic field**: The region around a magnet where its poles exhibit a force of attraction or repulsion.
2. **Magnetic flux (ϕ)**: The amount of magnetic lines of force set-up in a magnetic circuit. Its unit is weber (Wb). It is analogous to electric current I in electric circuit.
3. **The magnetic flux density** at a point is the flux per unit area at right angles to the flux at that point. It is, generally, represented by letter 'B'. Its unit is Wb/m² or Tesla.
4. **Permeability**: The ability of a material to conduct magnetic lines of force through. It is generally represented by μ . The greater the permeability of a material, the greater is its conductivity for the magnetic lines of force and vice-versa.
5. **Magnetic field intensity**: The force acting on a unit north pole (1 Wb) when placed at a point in the magnetic field. It is denoted by H . In magnetic circuits, it is defined as mmf per unit length of the magnetic path. It is denoted by H .

$$\mu = \mu_0 \mu_r$$
$$\mu_0 = 4\pi \times 10^{-7}$$

Important terms

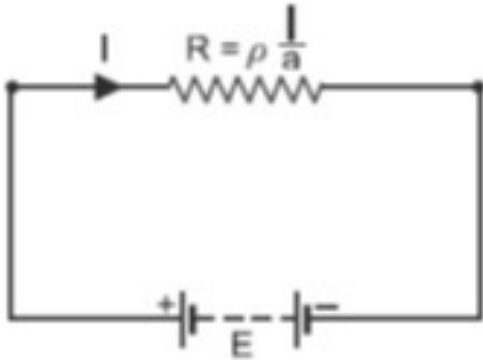


6. **Magneto-motive force (mmf)**: The magnetic pressure which sets-up or tends to set-up magnetic flux in a magnetic circuit. As per work law it may be defined as The work done in moving a unit magnetic pole (1 Wb) once round the magnetic circuit.
7. **Reluctance (S)**: The opposition offered to the magnetic flux by a magnetic circuit. It depends upon length (l), area of cross-section (a) and permeability ($\mu = \mu_0 \mu_r$) of the material that makes up the magnetic circuit.
$$S = \frac{\mu l}{a}$$
8. **Permeance**: It is a measure of the ease with which flux can be set-up in the material. It is just reciprocal of reluctance of the material and is measured in Wb/AT or henry.
$$\frac{1}{S}$$
9. **Reluctivity**: It is specific reluctance and analogous to resistivity in electric circuit.
$$\frac{l}{\mu a}$$

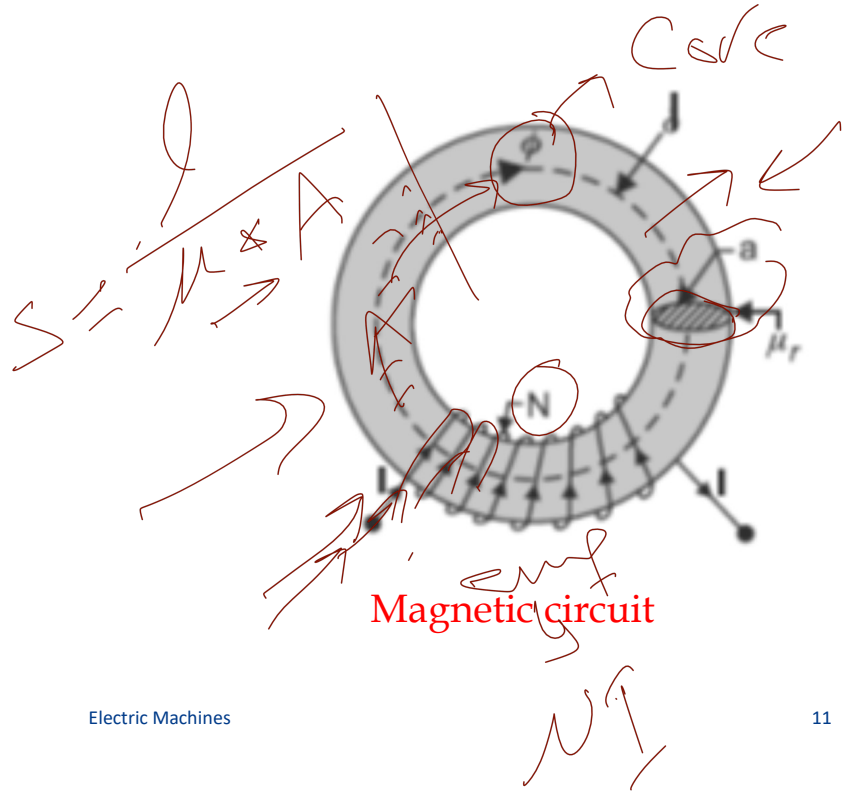
Electric and magnetic circuits



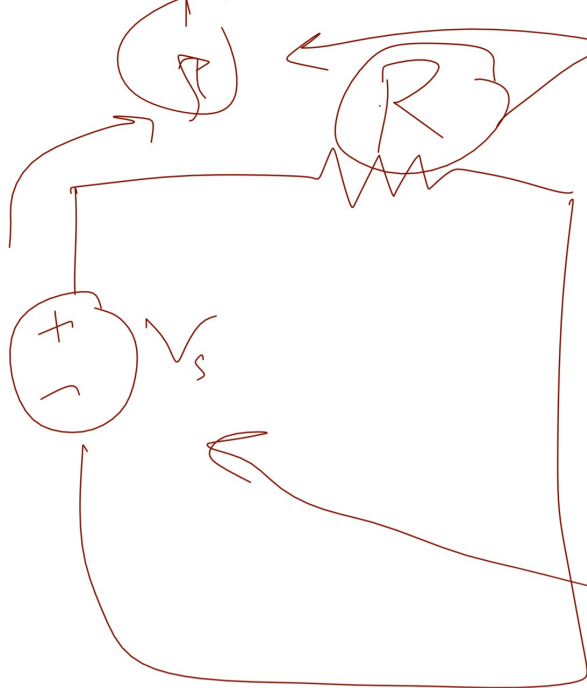
Although magnetic and electric circuits have many points of similarity but still they are not analogous in all respects.



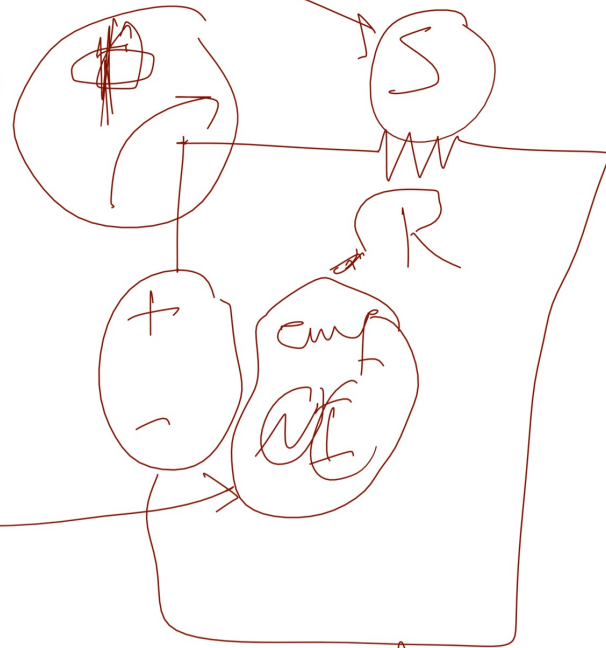
Electrical circuit



Magnetic circuit



Electrical
circuit



magnetic
circuit

Electric and magnetic circuits



A comparison of the two circuits is given below:

similarities	
1. The closed path for magnetic flux is called magnetic circuit. 2. Flux = mmf/reluctance. 3. Flux ϕ in Wb. 4. mmf in AT. 5. Reluctance $S = 1 / a \mu = 1/a\mu_0\mu_r$ AT/Wb 6. Permanence = 1 / reluctance 7. Permeability, μ 8. Reluctivity 9. Flux density $B = \phi/a$ Wb/m² 10. Magnetic intensity, $H =$	1. The closed path for electrical current is called electric circuit. 2. Current = emf/ resistance 3. Current, I in ampere 4. emf, in V 5. Resistance, $R = \delta(1/a) \Omega$ 6. Conductance = 1/resistance 7. Conductivity 8. Resistivity 9. Current density, $j = I/a$ A/m² 10. Electrical intensity, $E = V/d$





Ampere-turn Calculations

Flux produces

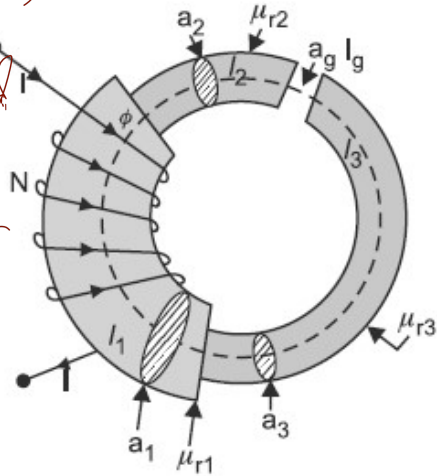
$$\phi = \frac{\text{m.m.f.}}{\text{reluctance}} = \frac{NI}{l/a \mu_0 \mu_r}$$

$$NI = \frac{\phi l}{a \mu_0 \mu_r} = \frac{B l}{\mu_0 \mu_r} = Hl$$

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

$$NI = Hl$$

$$= \frac{B l}{\mu}$$



or

Series Magnetic Circuit

A circuit that has number of parts of different dimensions and different materials

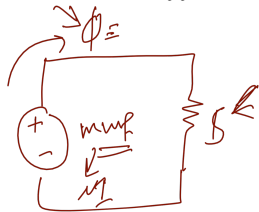
$$V = IR$$

$$\Rightarrow I = \frac{V}{R}$$

$$\text{mmf} = \phi S$$

$$\Rightarrow \phi = \frac{\text{mmf}}{S}$$

8/29/2026



$$S = \frac{l}{\mu A}$$

$$\phi = \frac{NI}{\frac{l}{\mu A}} = \frac{NI \mu A}{l}$$

Electric Machines



Ampere-turn Calculations

Total reluctance of the magnetic circuit

$$S = S_1 + S_2 + S_3 + S_g$$

$$= \frac{l_1}{a_1 \mu_0 \mu_{r1}} + \frac{l_2}{a_2 \mu_0 \mu_{r2}} + \frac{l_3}{a_3 \mu_0 \mu_{r3}} + \frac{l_g}{a_g \mu_0}$$

Total mmf = ϕS

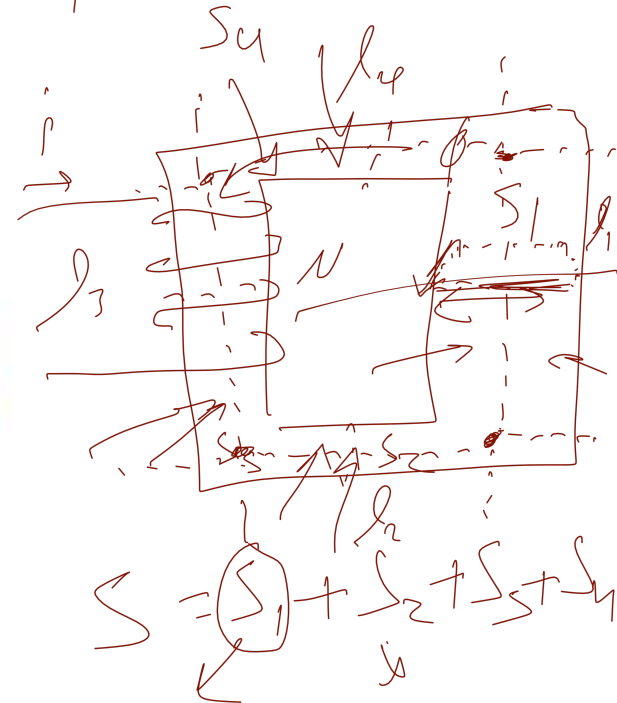
$$= \phi \left(\frac{l_1}{a_1 \mu_0 \mu_{r1}} + \frac{l_2}{a_2 \mu_0 \mu_{r2}} + \frac{l_3}{a_3 \mu_0 \mu_{r3}} + \frac{l_g}{a_g \mu_0} \right)$$

$$= \frac{B_1 l_1}{\mu_0 \mu_{r1}} + \frac{B_2 l_2}{\mu_0 \mu_{r2}} + \frac{B_3 l_3}{\mu_0 \mu_{r3}} + \frac{B_g l_g}{\mu_0}$$

$$= H_1 l_1 + H_2 l_2 + H_3 l_3 + H_g l_g$$

$$B = \frac{\phi}{A}$$

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

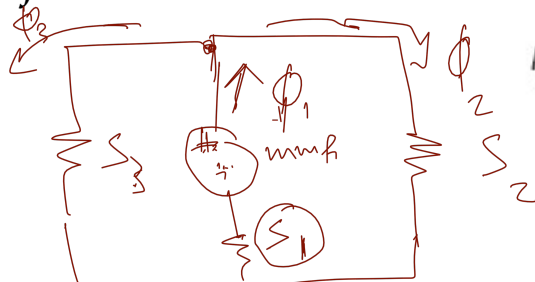


$$S = S_1 + S_2 + S_3 + S_4$$

Ampere-turn Calculations

Parallel Magnetic Circuit

A circuit that has two or more paths for magnetic flux as shown in the figure.



It is clear that $\Phi_1 = \Phi_2 + \Phi_3$

The two magnetic paths **ADCB** and **AFEB** are in parallel. The ATs required for this parallel circuit is equal to the ATs required for any one of the paths.

If S_1 = reluctance of path BA i.e., $l_1/a_1 \mu_0 \mu_{r1}$

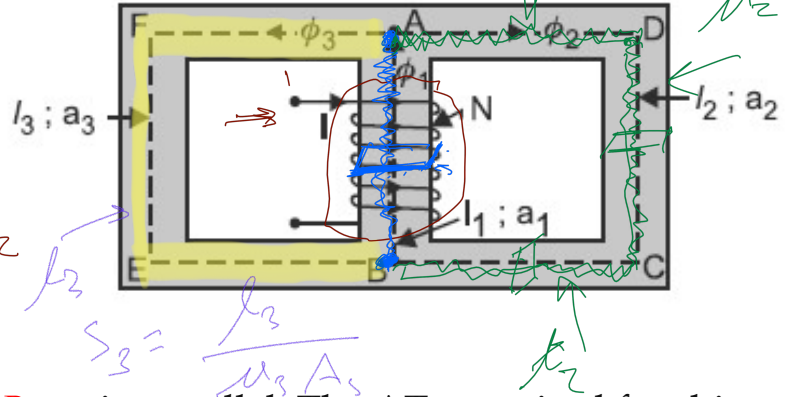
S_2 = reluctance of path ADCB i.e., $l_2/a_2 \mu_0 \mu_{r2}$

S_3 = reluctance of path AFEB i.e., $l_3/a_3 \mu_0 \mu_{r3}$

$$\sum I = \frac{l_1}{\mu_r A_1}$$

$$\sum_2 = \frac{l_2}{\mu_2 A_2}$$

$$\sum_3 = \frac{l_3}{\mu_3 A_3}$$



$$\mu = \mu_0 \mu_r$$



Ampere-turn Calculations

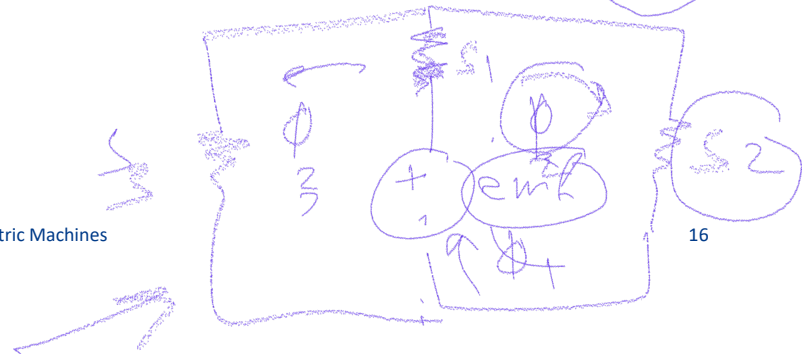
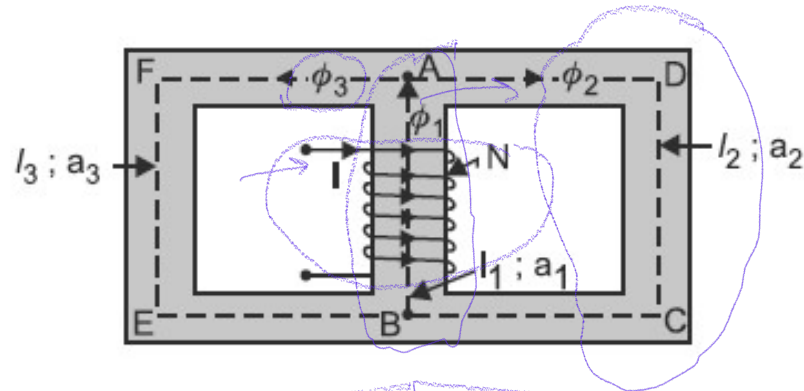
Parallel Magnetic Circuit

∴ Total mmf required = mmf required for path BA + mmf required path $ADCB$ or path $AFEB$.

i.e., Total mmf or

$$AT = \phi_1 S_1 + \phi_2 S_2 = \phi_1 S_1 + \phi_3 S_3$$

$$emf = NI$$





Leakage flux

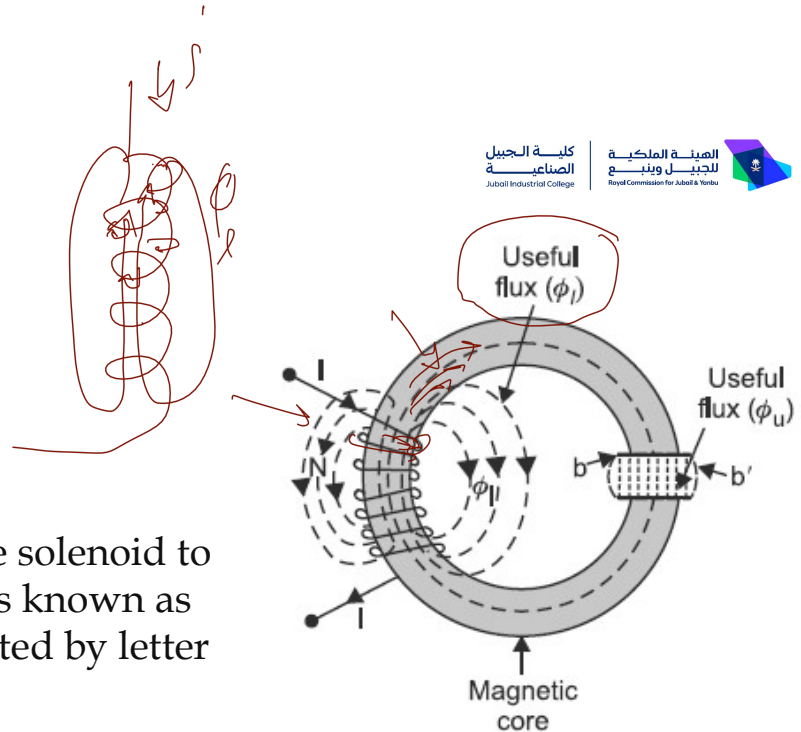
It is the magnetic flux which does not follow the intended path in a magnetic circuit.

Total flux produced $\phi = \phi_{\mu} + \phi_l$

The ratio of total flux (ϕ) produced by the solenoid to the useful flux (ϕ_{μ}) set-up in the air gap is known as *leakage co-efficient*. It is generally represented by letter ' λ '.

Leakage co-efficient,

$$\lambda = \phi / \phi_{\mu}$$





Example 1

An iron ring of 400 cm mean circumference is made from round iron of cross-section 20 cm² as shown in the figure. Its permeability is 500. If it is wound with 400 turns, what current would be required to produce a flux of 0.001 Wb?

Solution:

The magnetic circuit is shown in the figure

Mean length of magnetic path,

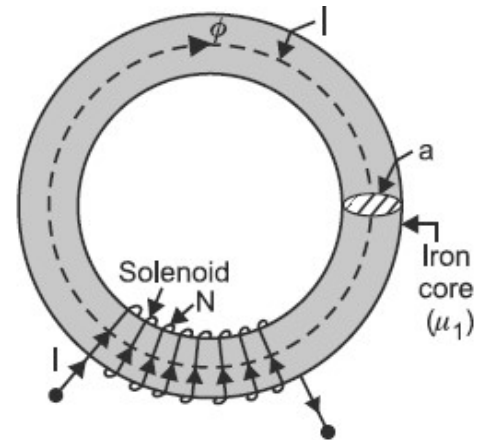
$$l_m = 400 \text{ cm} = 4 \text{ m}$$

Area of X-section of iron ring,

$$a = 20 \times 10^{-4} \text{ m}^2$$

Absolute permeability,

$$\mu_0 = 4\pi \times 10^{-7}$$



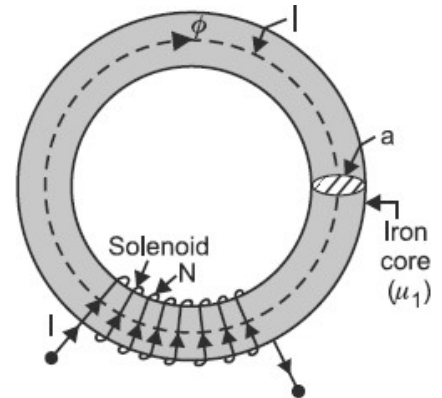
Solution:

Now mmf = (flux) × (reluctance)

$$NI = \phi \times \frac{l_m}{a\mu_0\mu_r}$$

$$400 \times I = 0.001 \times \frac{4}{20 \times 10^{-4} \times 4\pi \times 10^{-7} \times 500}$$

$$\text{Current, } I = \frac{0.001 \times 4}{20 \times 10^{-4} \times 4\pi \times 10^{-7} \times 500 \times 400} = 7.958 \text{ (Ans.)}$$





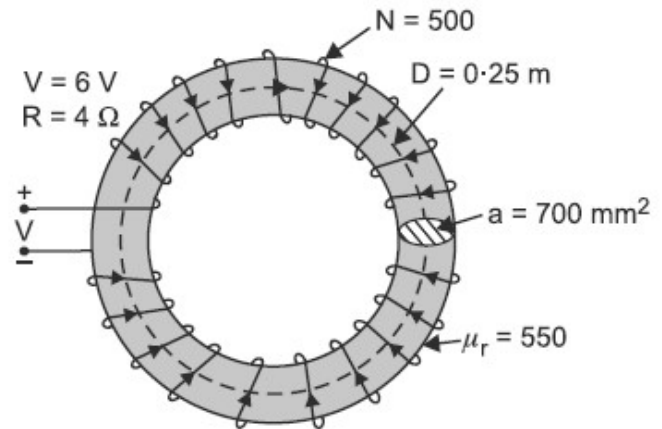
Example 2

A coil of insulated wire of 500 turns and of resistance 4Ω is closely wound on iron ring as shown in the figure. The ring has a mean diameter of 0.25 m and a uniform cross-sectional area of 700 mm^2 . Calculate the total flux in the ring when a DC supply of 6 V is applied to the ends of the winding. Assume a relative permeability of 550 .

Solution:

Mean length of iron ring,
 $l = \pi D = \pi \times 0.25 = 0.25\pi \text{ m}$

Area of cross-section,
 $a = 700 \text{ mm}^2 = 700 \times 10^{-6} \text{ m}^2$



Solution:

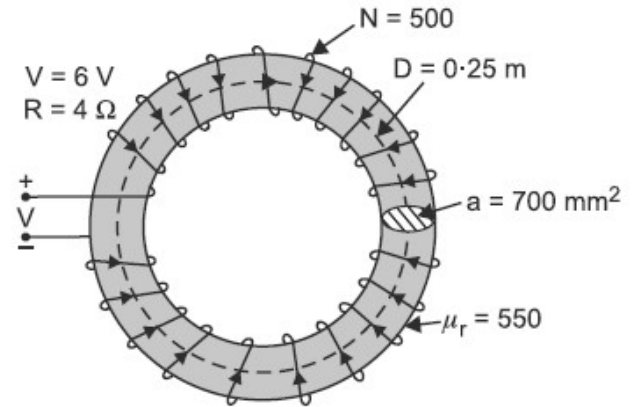


Current flowing through the coil,

$$I = \frac{\text{Voltage applied across coil}}{\text{Resistance of coil}}$$
$$= \frac{6}{5} = 1.5 \text{ A}$$

Total flux in the ring, $\phi = \frac{NI}{l / a \mu_0 \mu_r} = \frac{NI \times a \mu_0 \mu_r}{l}$

$$= \frac{500 \times 1.5 \times 700 \times 10^{-6} \times 4\pi \times 10^{-7} \times 550}{0.25 \pi} = 0.462 \text{ mWb}$$





Example 3

A coil of 1000 turns is wound on a laminated core of steel having a cross-section of 5 cm². The core has an air gap of 2 mm cut at right angle. What value of current is required to have an air gap flux density of 0.5 T? Permeability of steel may be taken as infinity. Determine the coil inductance.

Solution:

Here, $N = 1000$ turns; $a = 5 \text{ cm}^2 = 5 \times 10^{-4} \text{ m}^2$;

$l_g = 2 \text{ mm} = 2 \times 10^{-3} \text{ m}$; $B = 0.5 \text{ T}$; $\mu_r = \infty$

Total ampere-turns required,

$$AT = \frac{B}{\mu_0} l_g + \frac{B}{\mu_0 \mu_r} l_i = \frac{0.5}{4\pi \times 10^{-7}} \times 2 \times 10^{-3} + 0 = 796$$

Solution:



$$\left(\text{As } \mu_r = \infty; \frac{B}{\mu_0 \mu_r} \times l_i = 0 \right)$$

Current required, $I = \frac{AT}{l} = \frac{796}{1000} = 0.796 \text{ A (Ans.)}$

Inductance of coil, $L = \frac{N\phi}{I} = \frac{N \times B \times a}{I} = \frac{1000 \times 0.5 \times 5 \times 10^{-4}}{0.796}$
 $= 0.314 \text{ H (Ans.)}$



Exercise 1

A flux density of 1.2 Wb/m^2 is required in 2 mm air gap of an electro-magnet having an iron path 1 meter long. Calculate the magnetizing force and current required if the electro magnet has 1273 turns. Assume relative permeability of iron to be 1500.

Solution:

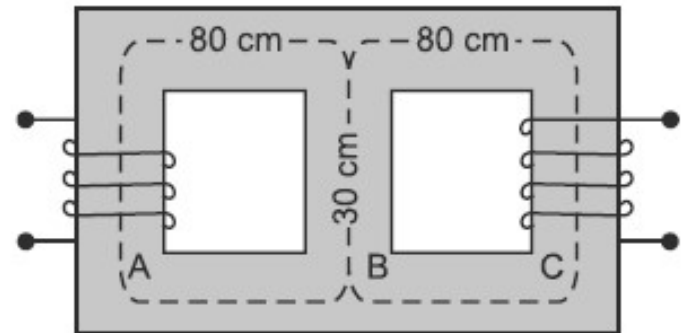
Solution:



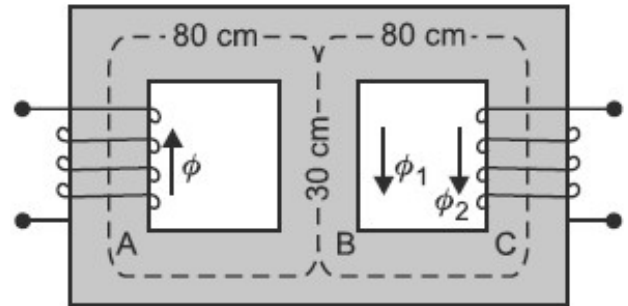


Exercise 2

A magnetic core made of hardened sheet steel has the dimensions as shown in the figure. The cross section everywhere is 25 cm^2 . The flux in branches A and B is 3500 mWb , but that in the branch C is zero. Find the required ampere-turns for coil A and for coil C. Relative permeability of sheet steel is 1000.



Solution:





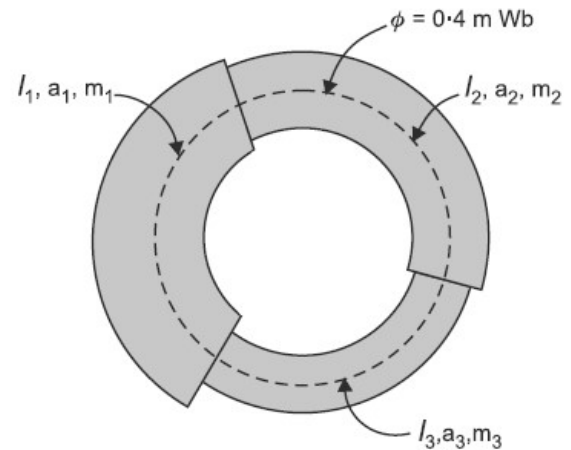
Exercise 3

An iron ring is made up of three parts;
 $l_1 = 10 \text{ cm}$, $a_1 = 5 \text{ cm}^2$, $\mu_1 = 2670$;

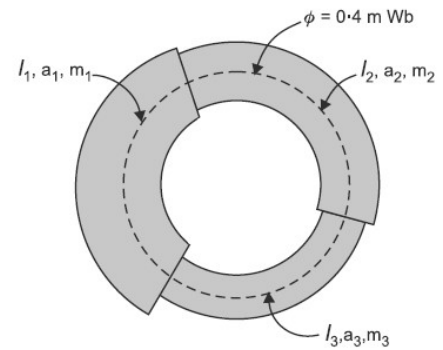
$l_2 = 8 \text{ cm}$, $a_2 = 3 \text{ cm}^2$, $\mu_2 = 1050$;

$l_3 = 6 \text{ cm}$, $a_3 = 2.5 \text{ cm}^2$, $\mu_3 = 600$.

It is wound with a 250 turns coil. Calculate current required to produce flux of 0.4 mWb.



Solution:



AC Excitation in Magnetic Circuits

AC Excitation



To magnetize the magnetic circuits of electrical devices such as transformers, AC rotating machines, an electromagnetic relays, etc., an AC supply is used. The magnetization of magnetic circuits is called their *excitation*.

The magnetic circuits are *never excited by DC supply*, because in case of DC excitation the steady state current is determined by the impressed voltage and resistance of the circuit. The inductance of the coil comes into picture only during transient period i.e., *when the current is building-up or decaying during switching (ON or OFF) instants*.

The magnetic flux in the magnetic circuit adjusts itself in accordance with this steady value of current so that the relationship imposed by magnetization (B - H) curve is satisfied.

As a result for most of the magnetic circuits the flux is determined by *the impressed voltage and frequency*.

For all practical purposes the parameters of the magnetic circuit are considered to be constant.

AC Excitation



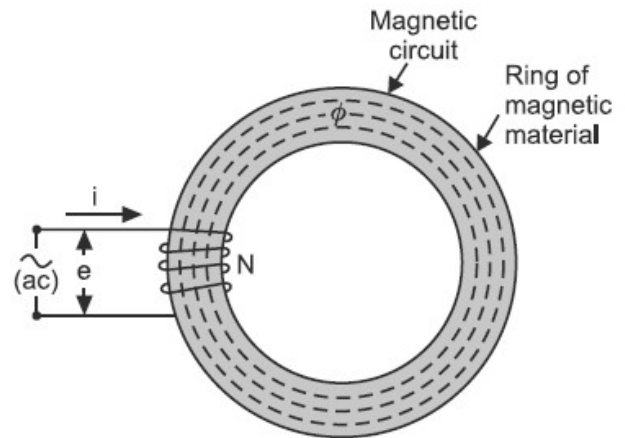
The reactive effect of the alternatively flux setup by the exciting current can be shown as per Faraday's laws i.e.,

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

Consider a magnetic core which is excited by a coil (winding) having N turns and carrying a current of i ampere as shown in the figure.

A magnetic flux is set-up by the exciting current i . Let the magnetic flux ϕ varies sinusoidally with respect to time t , then its instantaneous value is

$$\phi = \phi_m \sin \omega t = \phi_m \sin 2\pi ft$$





AC Excitation

$$\phi = \phi_m \sin \omega t = \phi_m \sin 2\pi ft$$

ϕ_m is the maximum value of the alternating flux

f is the supply frequency

The induced *emf* in the coil is

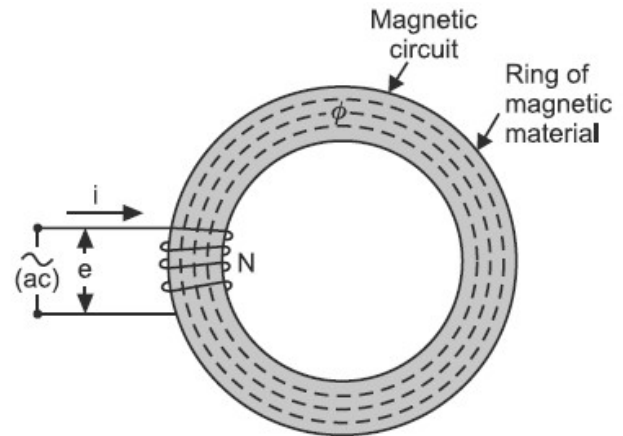
$$\begin{aligned} e &= N \frac{d\phi}{dt} = N \frac{d}{dt} (\phi_m \sin 2\pi ft) \\ &= 2\pi f N \phi_m \cos 2\pi ft = 2\pi f N \phi_m \sin \left(2\pi ft + \frac{\pi}{2} \right) \end{aligned}$$

The value of the induced emf will be maximum when

$$\cos 2\pi ft = 1$$

$$E_m = 2\pi f N \phi_m$$

$$E_{rms} = \frac{E_m}{\sqrt{2}} = \frac{2\pi f N \phi_m}{\sqrt{2}} = 4.44 f N \phi_m$$





Example 4

For the AC excited magnetic circuit shown in the figure. Calculate the excitation current and induced *emf* of the coil to produce a core flux of **$0.6 \sin 314 t$** mWb.

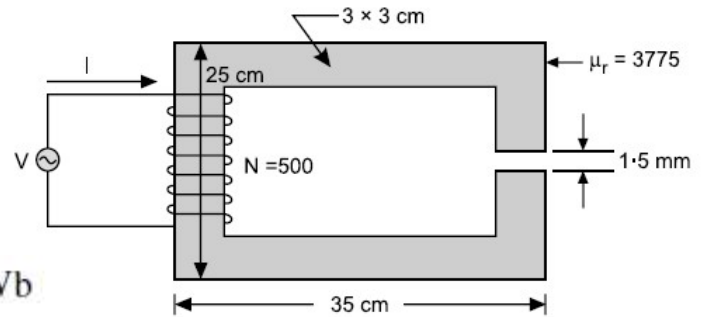
Solution:

$$\phi = \phi_m \sin \omega t = 0.6 \sin 314 t \text{ mWb}$$

$$\text{Maximum value of flux, } \phi_m = 0.6 \text{ mWb} = 6 \times 10^{-4} \text{ Wb}$$

$$\text{Area of } x\text{-section, } a = 3 \times 3 = 9 \text{ cm}^2 = 9 \times 10^{-4} \text{ m}^2$$

$$\text{Flux density, } B_m = \frac{\phi_m}{a} = \frac{6 \times 10^{-4}}{9 \times 10^{-4}} = 0.667 \text{ T}$$



Solution:

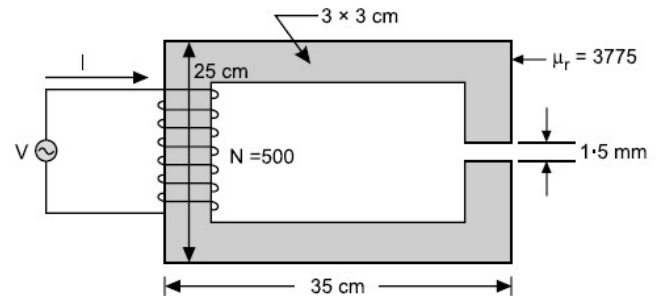
Length of air gap, $l_g = 1.5 \text{ mm} = 1.5 \times 10^{-3} \text{ m}$

Length of iron path, $l_i = \left(25 - 2 \times \frac{3}{2} + 35 - 2 \times \frac{3}{2}\right) \times 2 - 0.15 = 107.85 \text{ cm}$
 $= 1.0785 \text{ m}$

$$\begin{aligned}\text{Total ampere-turns required, } AT_m &= \frac{B_m}{\mu_0} l_g + \frac{B_m}{\mu_0 \mu_r} l_i \\ &= \frac{0.667 \times 1.5 \times 10^{-3}}{4\pi \times 10^{-7}} + \frac{0.667 \times 1.0785}{4\pi \times 10^{-7} \times 3775} \\ &= 796.3 + 151.7 = 948\end{aligned}$$

Maximum value of excitation current required,

$$I_m = \frac{AT_m}{N} = \frac{948}{500} = 1.896 \text{ A}$$



Solution:



RMS value of excitation current,

$$I_{\text{rms}} = \frac{I_m}{\sqrt{2}} = \frac{1 \cdot 896}{1 \cdot 414} = 1 \cdot 34 \text{ A (Ans.)}$$

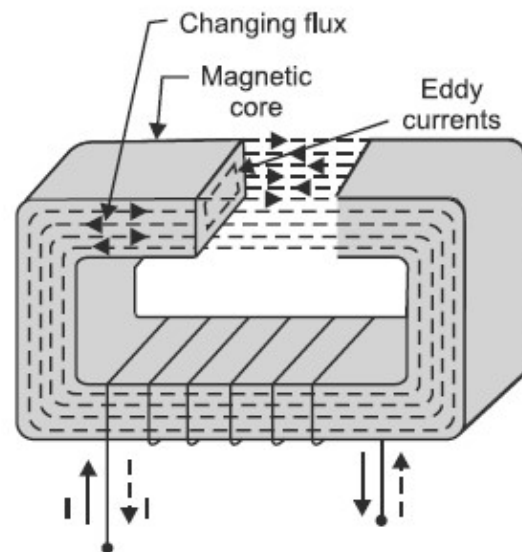
RMS value of induced emf in the coil, $E_{\text{rms}} = 4 \cdot 44 f N \phi_m$

$$= 4 \cdot 44 \times \frac{314}{2\pi} \times 500 \times 0 \cdot 6 \times 10^{-3} = 66 \cdot 57 \text{ V (Ans.)}$$

Eddy Current



eddy currents are the circulate currents within the body of the magnetic material. These circulating currents are of no use. They produce a loss ($i^2 R$ loss) in the magnetic material called *eddy current loss*.

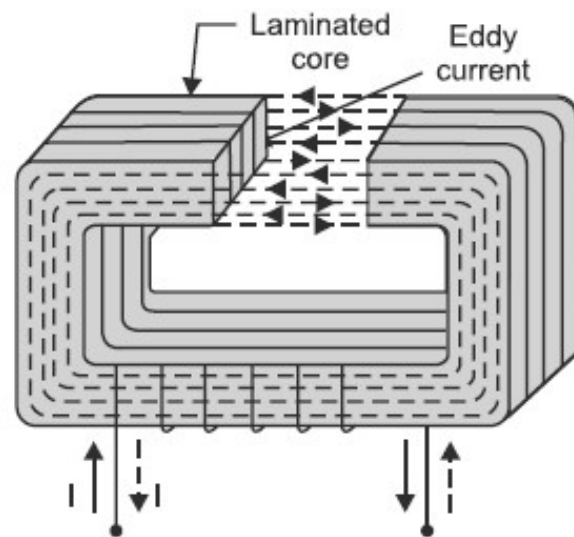


Solid core

Eddy Current



Like hysteresis loss, this loss also increases the temperature of the magnetic material. The hysteresis and eddy current losses in a magnetic material are called *iron losses* or *core losses* or *magnetic losses*.



Laminated core

Eddy Current



eddy currents can be found mathematically using the following equation:

$$P_e = K_e B_m^2 t^2 f^2 V \text{ watt}$$

Where,

K_e = co-efficient of eddy current, depends on the nature of magnetic material

B_m = maximum value of flux density in Wb/m^2

t = thickness of lamination in m

f = frequency of reversal of magnetic field in Hz

V = volume of magnetic material in m^3