Introduction to Electrical Engineering

Course Code: EE 103

Department: Electrical Engineering

Instructor Name: B. G. Fernandes

E-mail id: bgf@ee.iitb.ac.in

Energy efficiency and Electric machines

"The electric motors and systems they drive are the largest single-energy end user and account for more than 40% of global electricity consumption."*

Total installed capacity of power generation in World is about 25,530 TW#
India's installed capacity is 417.6 GW$

Huge scope for energy efficient electric machines

*Report — May 2011, https://www.iea.org/reports/energy-efficiency-policy-opportunities-for-electric-motor-driven-systems

https://www.statista.com/statistics/280704/world-power-consumption/ (checked on ***12.09.2023***)

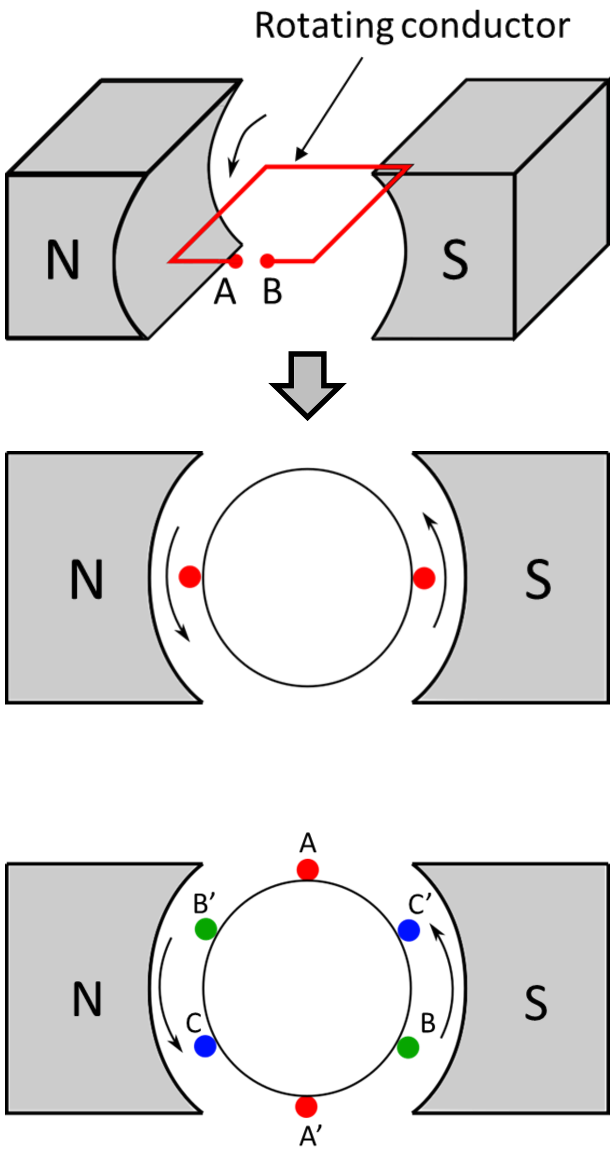
$ https://powermin.gov.in/en/content/power-sector-glance-all-india ***(As on 31.05.2023)***

Elementary concepts

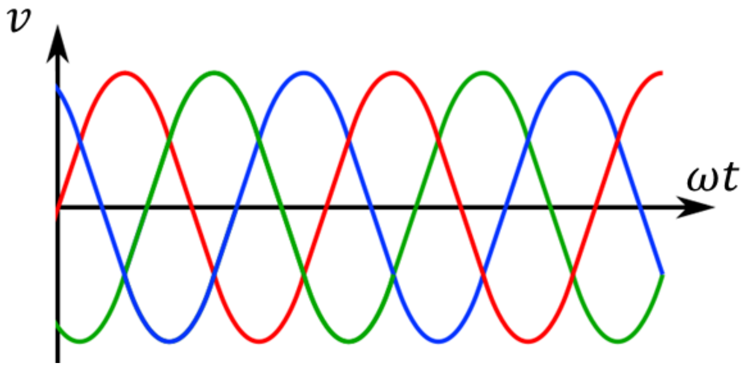
- When a conductor is moved in a magnetic field, voltage is induced in it
- And when, a current carrying conductor is placed in a magnetic field, it experiences a force
- Magnetomotive force (MMF) developed by a coil is defined as NI (unit AT), where N is the number of turns and I is the current through the coil

Elementary concepts

- If a conductor is rotated in a magnetic field, voltage induced in it is ‘AC’ (average value = 0)
- It is possible to generate a sinusoidal voltage
- Instead, if 3 coils which are placed 120˚ apart and rotated in a magnetic field, voltage induced in these coils is ‘AC’ but they are time displaced by 120˚
- It is possible to generate 3 sinusoidal voltages which are 120˚ apart



$$v_{AA'} = V_m \sin(\omega t)$$
$$v_{BB'} = V_m \sin(\omega t - \frac{2\pi}{3})$$
$$v_{CC'} = V_m \sin(\omega t - \frac{4\pi}{3})$$



Elementary concepts

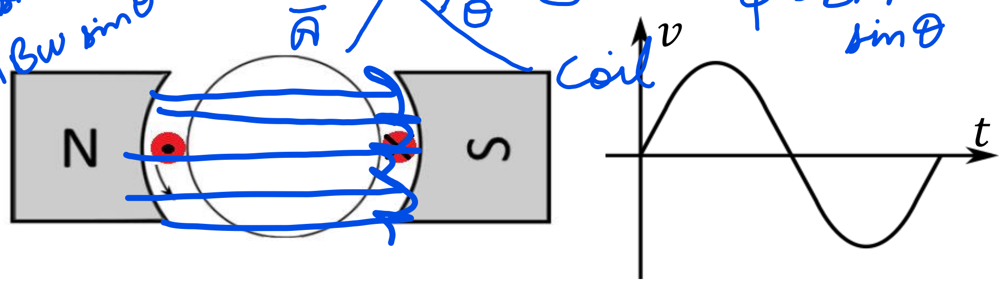
$\phi = B \cdot A$
$= AB\cos\theta$
$\varepsilon = \frac{d\phi}{dt} = AB\sin\theta \frac{d\theta}{dt}$
$= AB\omega \sin\theta$

$\phi = BA \sin\theta$

Consider a coil rotating in a magnetic field

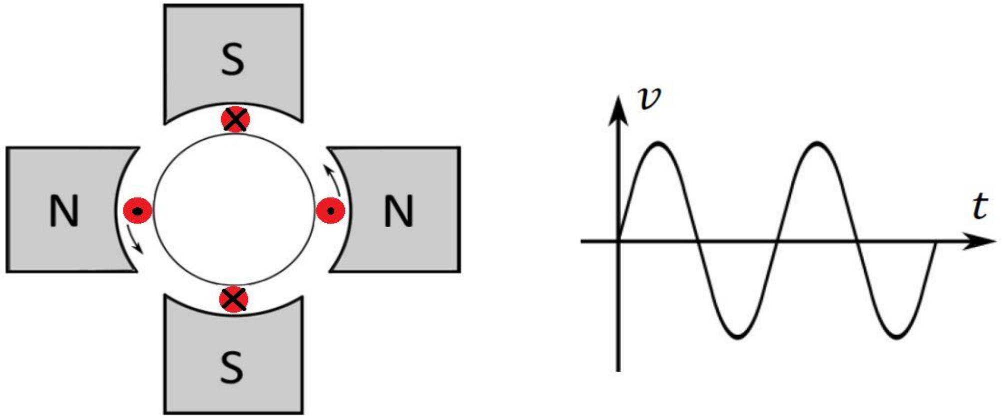
Case 1: 2-poles

- In one rotation (360°), voltage induced in the conductor has completed 1 cycle (360°)



Case 2: 4-poles

- In one rotation (360°), voltage induced in the conductor has completed 2 cycles (720°)



- No. of cycles induced voltage completes in one rotation depends on no. of poles

- Thus, to determine the angular frequency of the induced voltage, we need to know the rotational speed of the coil and the number of poles

$$\omega = \frac{P}{2} \cdot 2\pi \cdot (\text{rotations per second})$$

$\omega_{voltage} = (\text{magnets})(2\pi)(\text{rps})$

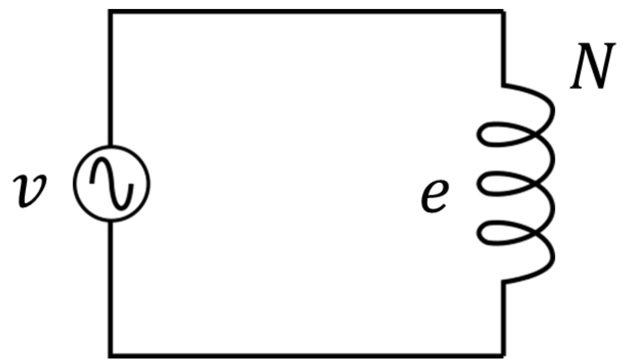
$\omega_{coil} = (\text{rps})(2\pi)$

$\omega_{voltage} = (\text{magnets})(\omega_{coil})$

Elementary concepts

Let a sinusoidal voltage is applied to a coil having 'N' turns
Assuming ideal condition

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



Let $\phi = \phi_m \sin(\omega t)$

$$\therefore e = \omega N\phi_m \cos(\omega t)$$
$$= E_m \cos(\omega t) = v$$

RMS value of e $= \frac{2\pi f}{\sqrt{2}} N\phi_m$

$= \boxed{4.44 f N\phi_m = 'V'}$ (RMS value of the supply voltage)

$\therefore$ Flux in the coil is determined by the supply voltage alone, provided that the frequency is constant

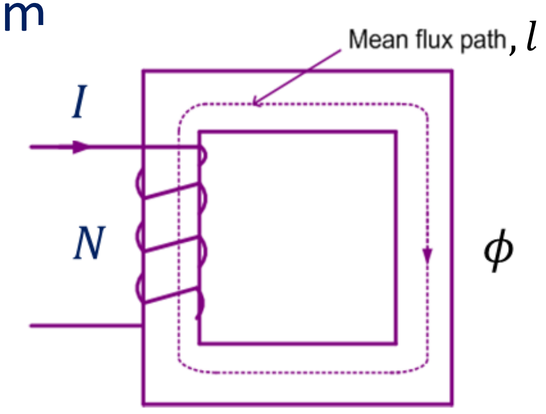
Elementary concepts

Magnetic circuits:

- Electric circuit provides a path for the flow of 'I'
- 'Magnetic circuit' provides a path for the flow of magnetic flux
- These are integral part of Electromechanical systems like electric machine
- In machines, these circuits may be formed by magnetic materials only OR magnetic materials + air as medium

Magnetic field intensity, $H = \frac{B}{\mu}$ AT/m

Where, B is the flux density in Wb/m^2 and μ is the permeability of the medium



Magnetic equivalent circuit:

Let the coil has N turns and current 'I' flows through it, and assume that all the flux is confined to core

Using Ampere's circuit law: $\oint \boxed{\underbrace{\vec{H} \cdot d\vec{l} = NI}_{\text{Magneto motive force (MMF)}}} \longrightarrow$ ampere turns

Elementary concepts

$\frac{1}{Z}$ = Admittance Z = impedence

$X_c \mid X_L$ = reactance

$$\therefore H = \frac{MMF}{l}$$

$$B = \mu H \; \& \; \phi = B \cdot A \qquad \therefore \phi = \frac{\mu \cdot MMF \cdot A}{l} = \frac{MMF}{\left(\frac{l}{\mu A}\right)} = \frac{NI}{\mathcal{R}}$$

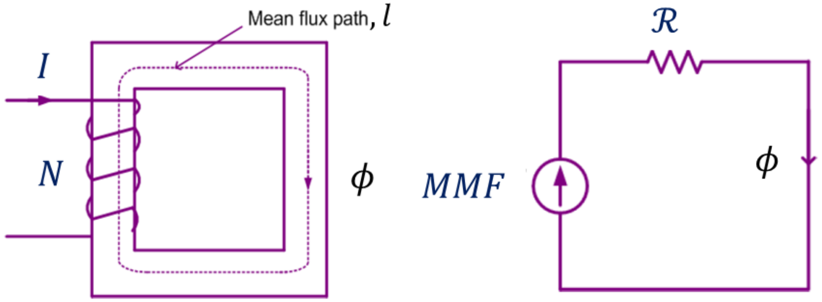
$\mathcal{R} \rightarrow$ reluctance of magnetic path

$\mathcal{P} = \frac{1}{\mathcal{R}} \rightarrow$ permeance

Observations:

$\phi = \frac{NI}{\mathcal{R}}$ is similar to $I = \frac{V}{R}$

$\mathcal{R} = \frac{l}{\mu A}$ is similar to $R = \frac{\rho l}{a}$

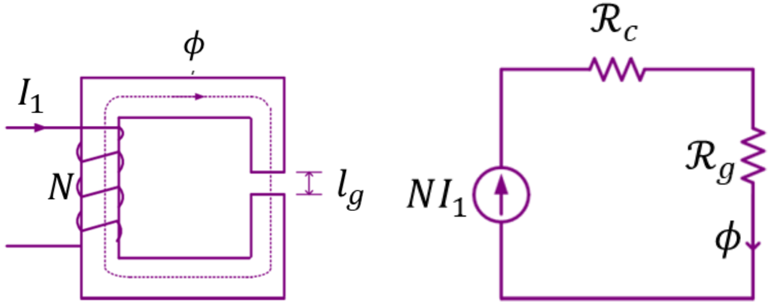


Consider an air gap s.t. $l_g \ll l$

- Flux has to cross the air gap → it will encounter two reluctances

$\mathcal{R}_g \rightarrow$ reluctance of air gap = $\frac{l_g}{\mu_0 A_g}$ ⟵ cross-section area of air gap

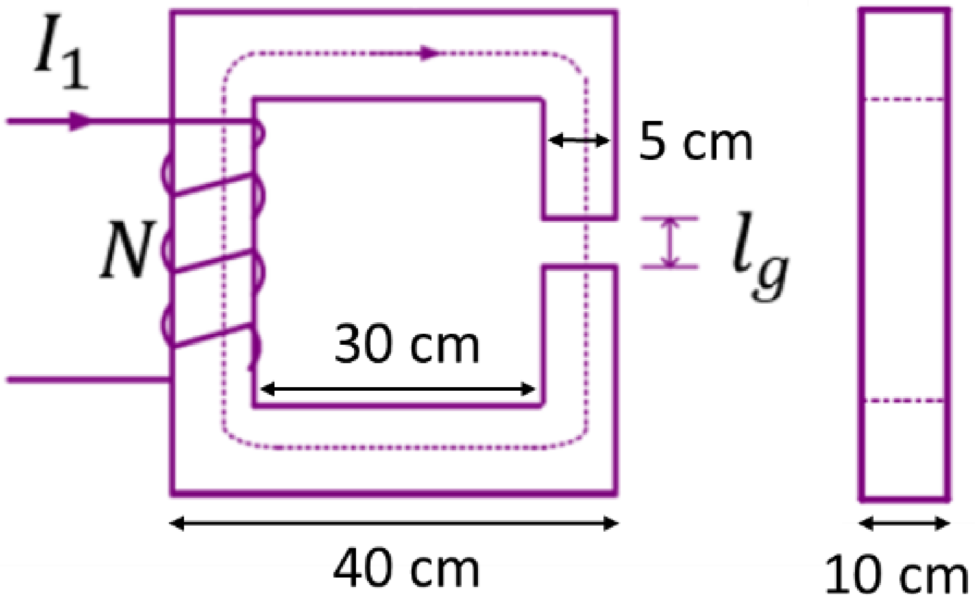
$\mathcal{R}_c \rightarrow$ reluctance of core = $\frac{l}{\mu A}$



As the core permeability is very high, $\mu \rightarrow \infty \Rightarrow R_c \rightarrow 0$

Thus, the entire MMF (NI_1) is applied across the $\mathcal{R}_g$, that is, the air gap

A magnetic flux of 2.5×10^{-3} Wb is required in the airgap shown below. The airgap length is 0.2 cm. First determine the reluctance of the core and the airgap, and then determine the MMF required to set up the required flux. Also comment on the MMF drop across the core and the airgap. Assume that the cross-section area of the core and the airgap region is same and the relative permeability of the core material is 6000.



$A_c = 5 \times 10 \text{ cm}^2 = 50 \times 10^{-4} \text{ m}^2 = A_g$

length of mean path (flux) $= 4 \times 35 \text{ cm} = 140 \text{ cm} = 1.4 \text{m}$

Now, $R_c = \dfrac{l - l_g}{\mu_0 \mu_r \cdot A_c} = \dfrac{1.4 - 0.002}{\mu_0 \cdot 6000 \cdot 50 \times 10^{-4}} = 3.71 \times 10^4 \; {}^1/_H$

$$R_g = \frac{l_g}{\mu_0 \cdot A_g} = \frac{0.002}{\mu_0 \cdot 50 \times 10^{-4}} = 3.18 \times 10^5 \; {}^1/_H$$

$$R_c = \frac{l - l_g}{\mu_0 \mu_r \cdot A_c} = \frac{1.4 - 0.002}{\mu_0 \cdot 6000 \cdot 50 \times 10^{-4}} = 3.71 \times 10^4 \; {}^1/_H$$

Now, MMF Required by the airgap 'OR' the mmf drop across the airgap.

$$MMF_g = R_g \cdot \phi = 3.18 \times 10^5 \times 2.5 \times 10^{-3}$$
$$= 795 \text{ AT}$$

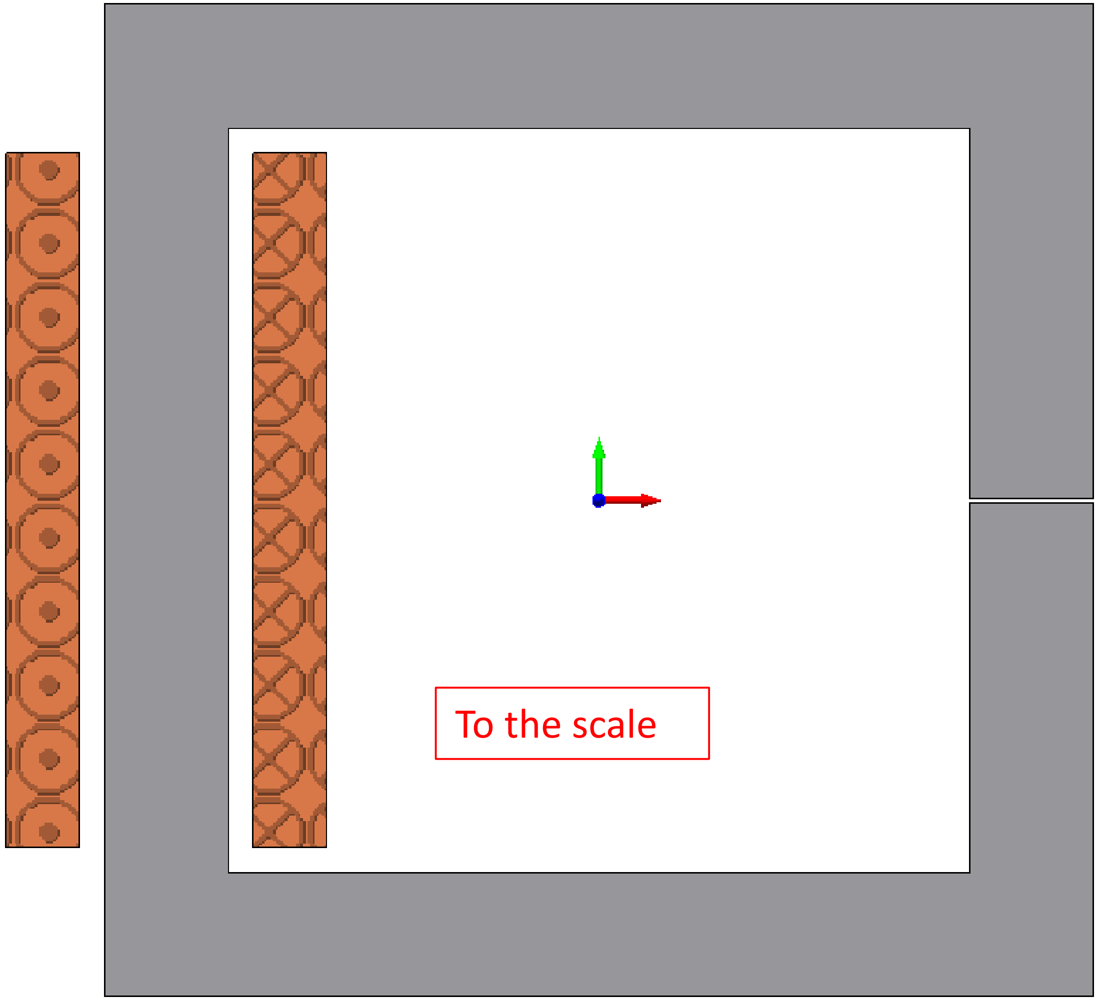
Similarly,

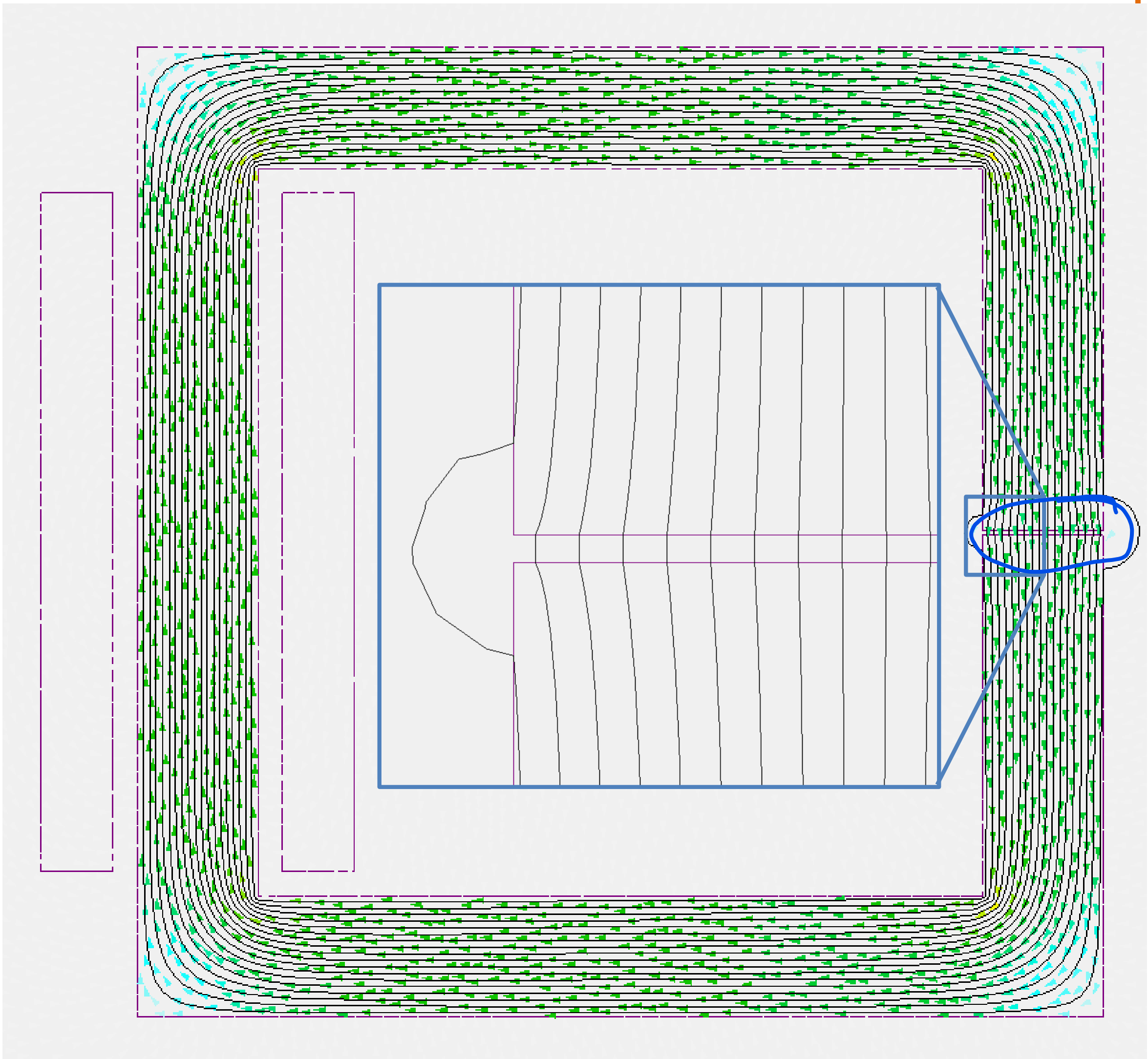
$$MMF_c = R_c \cdot \phi = 3.71 \times 10^4 \times 2.5 \times 10^{-3}$$
$$= 93 \text{ AT}$$

Thus, Total MMF required from the source is

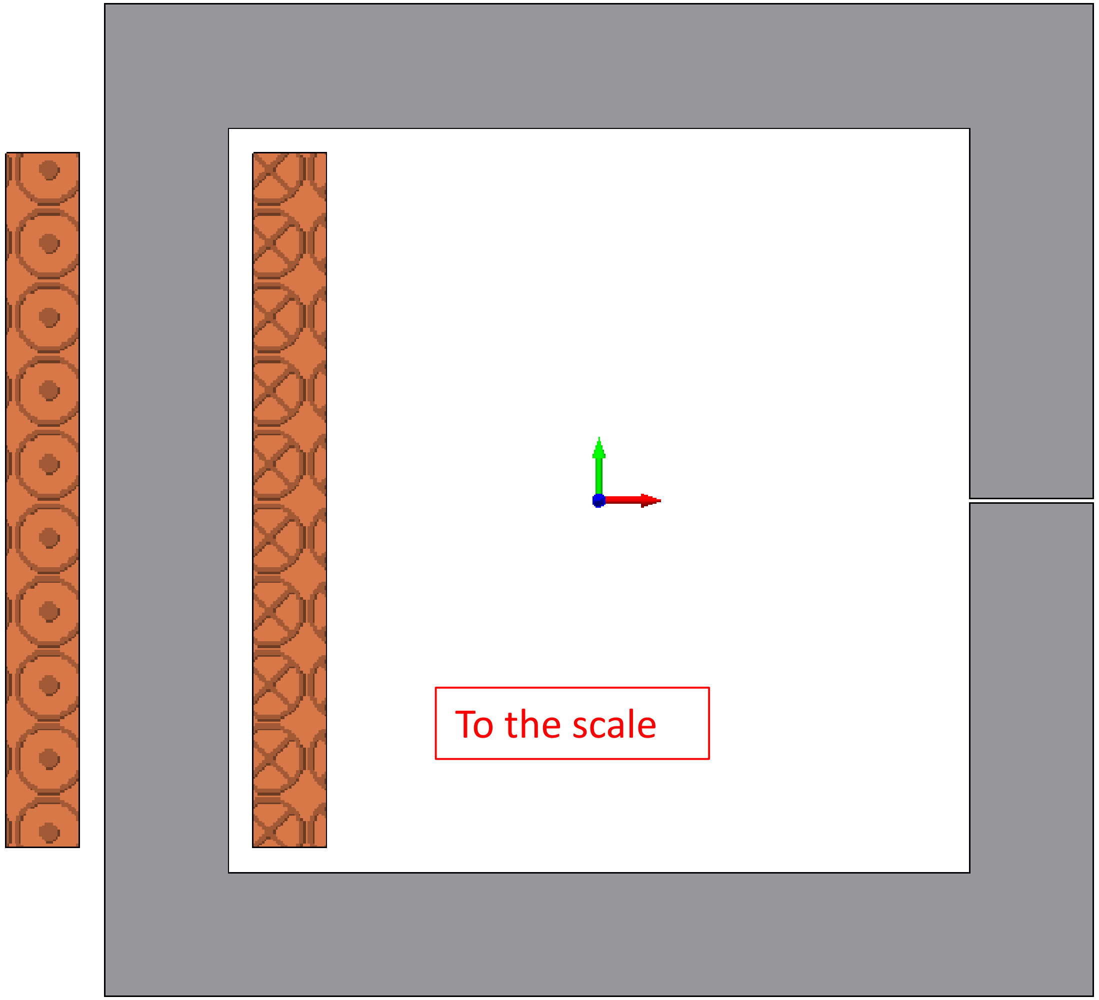
$$MMF = MMF_g + MMF_c$$
$$\approx 888 \text{ AT}$$

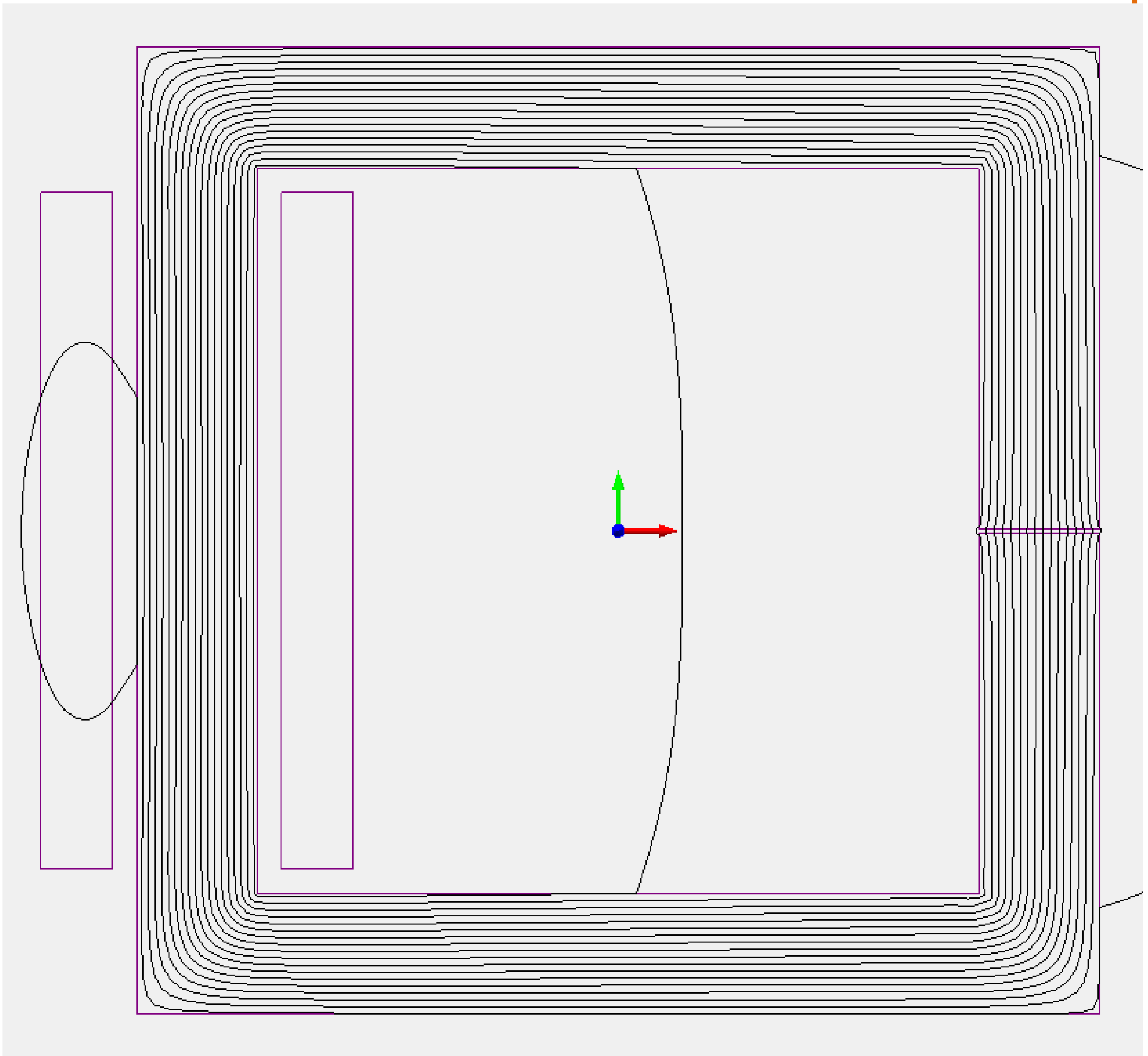
Flux-fringing



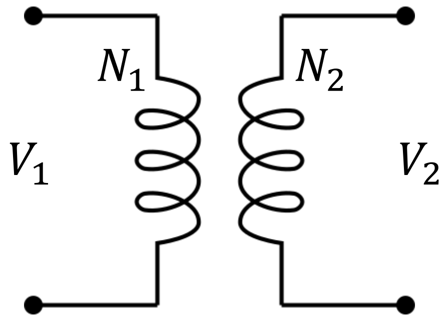


Flux-linkage and flux-leakage





Rotating Machines



Electro Mechanical Energy Conversion (EMEC)

- Transformer converts electrical power from one 'V' level to another
- EMEC equipment convert electrical energy into mechanical energy & vice versa

Motor

Electrical Energy → Mechanical Energy →

Generator

Mechanical Energy → Electrical Energy →

- In both the systems, there is an electrical system & a mechanical system
- Coupled by a magnetic field

Basic requirements of EMEC devices

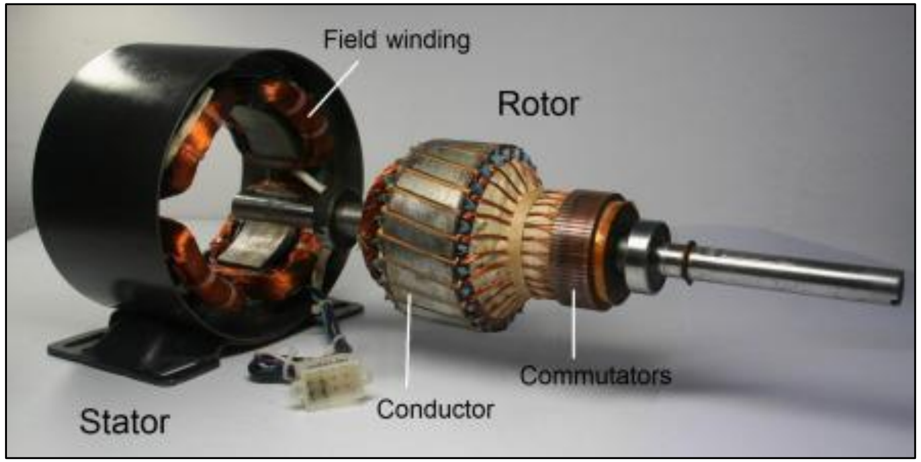
- For motoring /generating action, there has to be magnetic flux field produced by a set of coils → field coil
- This flux induces 'V' or 'I' in another coil which is rotating in the magnetic field → armature coil

- Do we need to have a conductor carrying 'I' to experience a force ?

- In rotating machine, voltage induced in the armature coil is AC

- If dc is required, some arrangement must be made to convert AC to DC

Basic structure



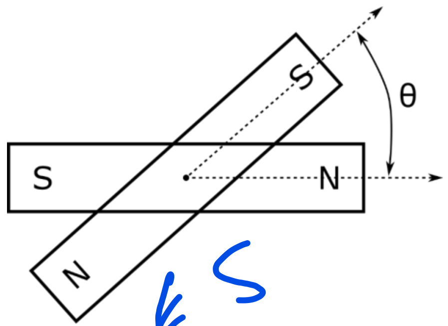
Stator $\rightarrow$ stationary, does not move
$\rightarrow$ normally outer frame
$\rightarrow$ It is possible that stator is inside the rotor

Rotor $\rightarrow$ which rotates inside the stator
$\rightarrow$ separated by small air gap (0.5 – 1 mm)

- Generally, stator and rotor are made up of high permeability ferromagnetic material
- Length of the air gap is kept as small as possible so that MMF required to establish ϕ in the air gap is small

Image: https://www.sciencedirect.com/topics/engineering/direct-current-motor

Torque Production in Rotating Machines



- Consider two bar magnets pivoted at their center on the same axis
- Torque $\propto$ sine(angular displacement)

Stator $\rightarrow$ coil
Rotor $\rightarrow$ coil

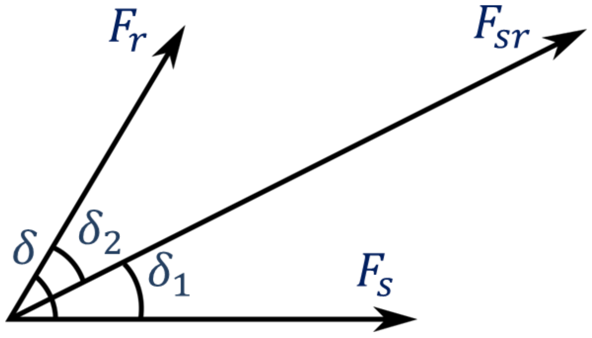
both of them are carrying 'I' A

S
N

- They will produce their own MMF, F_s & F_r
- Torque is produced by the tendency of two magnetic fields to align

on Rotor

$$T \propto F_s F_r \sin\left(\angle_{F_s}^{F_r}\right) \quad A$$
$$\propto F_s F_r \sin(\delta)$$

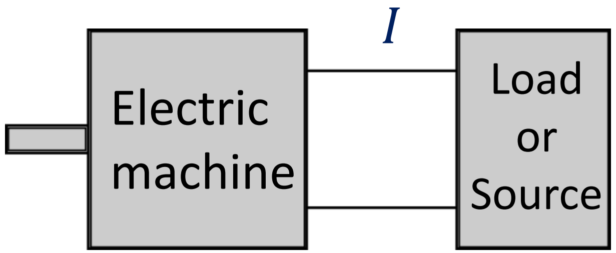


$$F_{sr} \sin\delta_1 = F_r \sin\delta \qquad \therefore T \propto F_s F_{sr} \sin\delta_1$$
$$F_{sr} \sin\delta_2 = F_s \sin\delta \qquad \therefore T \propto F_r F_{sr} \sin\delta_2$$

- For steady torque, F_s & F_r should be stationary with respect to each other A

Classification of Machines

IM



DC machine
- stator → DC
- rotor → 'I' flowing in the load OR from an external source is DC → input current

AC machine

synchronous machine
- stator → AC/DC
- rotor → DC/AC

$\bar{B}_s$

$\bar{B}_r$ $\bar{B}_r$

Not Fixed → External excitation

asynchronous machine
- stator, rotor → AC

$\bar{B}_s$

$\bar{B}_r$

Fixed → Self Excitation