Lecture: Energy Systems - 2

Instructor

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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 →

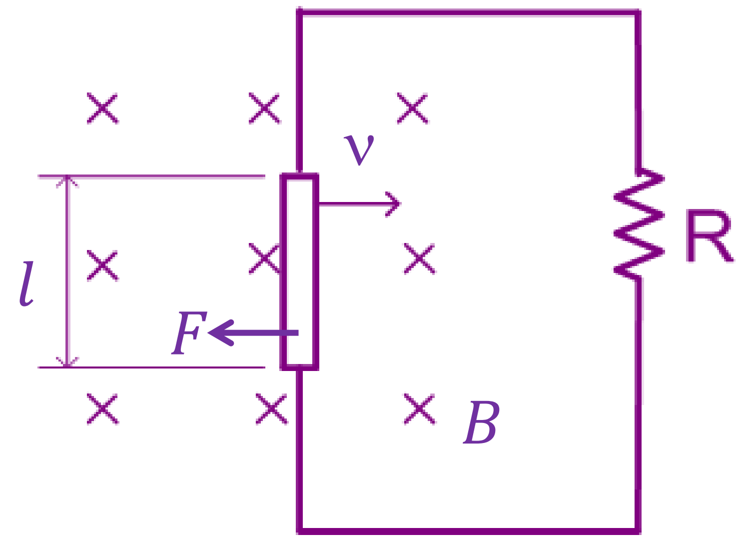
Generator

Mechanical Energy → Electrical Energy →

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

Elementary Concepts

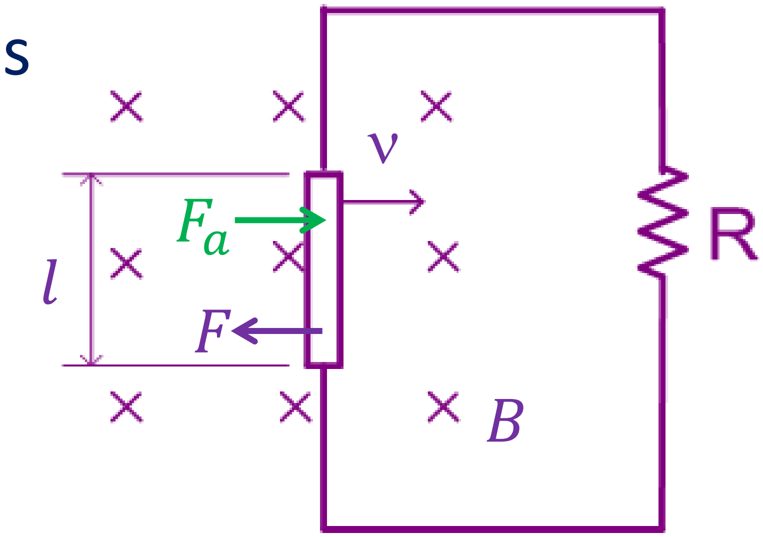
- A conductor of length 'l' is moving with a uniform velocity of 'v'
- If 'B' is the magnetic field, voltage induced, $e = Blv$
- If external 'R' is connected, current 'i' will flow



- Current carrying conductor placed in a magnetic field experiences a force, $F = Bil$
- This 'F' opposes the movement of conductor

- In order to sustain the movement, external force F_a is applied such that $F_a > F$
- 'i'will continue to flow
- i^2R = power is available at the o/p
- This power is generated from mechanical input

→ Generator action



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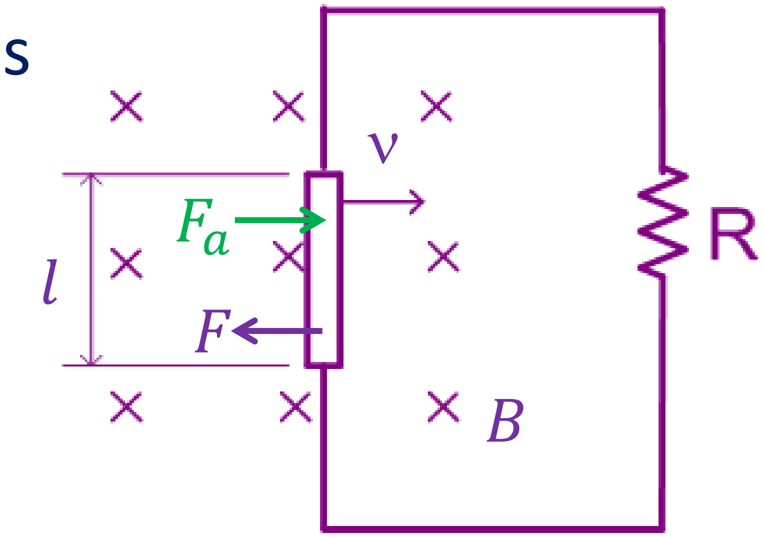
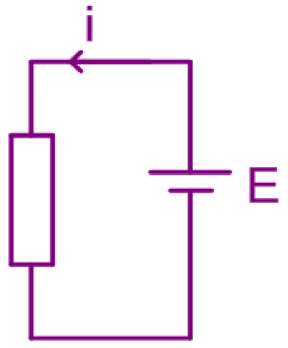


- Instead if $V > E$ is applied to the conductor, no external force is required to maintain the motion of the conductor
- Input is electrical energy and output is mechanical energy

→ Motor action



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 conductor carrying 'I' to experience a force ?

- In rotating machine 'V' induced in the conductor is sinusoidal, irrespective of nature of field flux
- If dc is required, some arrangement must be made to convert ac to dc

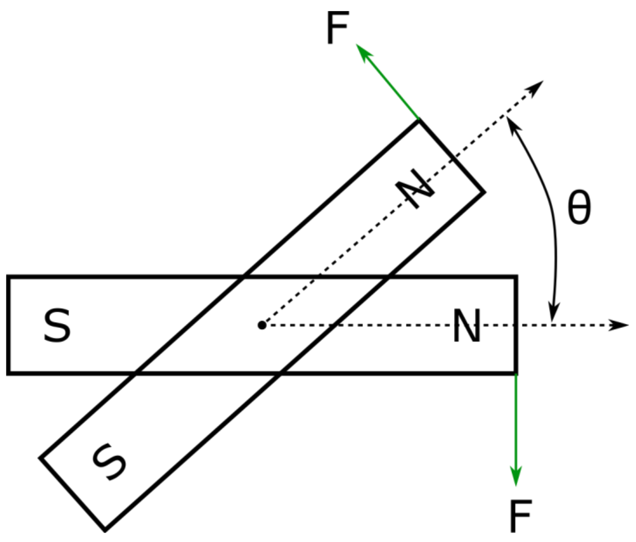
Basic structure

Stator $\rightarrow$ stationary, does not move
$\rightarrow$ normally outer frame

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 AT required to establish ϕ in the air gap is small
- Air gap is uniform $\therefore$ uniform reluctance
- Some machines have non uniform air gap $\rightarrow$ salient pole structure

Torque Production in Rotating Machines



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

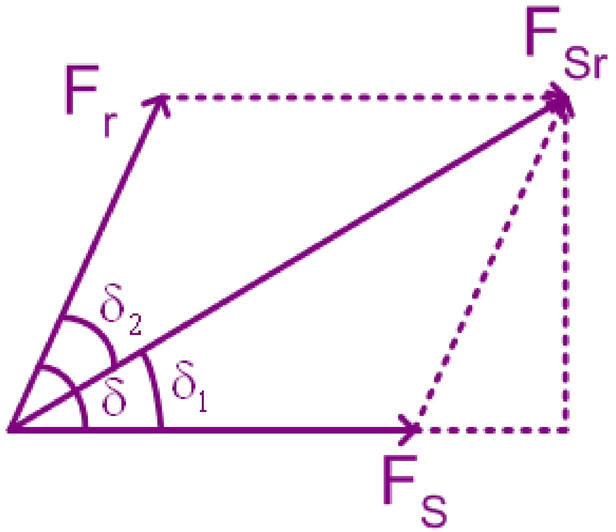
Stator $\rightarrow$ coil
Rotor $\rightarrow$ coil

both of them are carrying 'I'

- Two MMF sources, F_s & F_r
- Create magnetic flux in the air gap between stator and rotor
- Similar to magnetic poles on both stator and rotor centered on their respective magnetic axis

Torque Production in Rotating Machines

- Torque is produced by the tendency of two magnetic fields to align



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

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

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

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

Classification of Machines

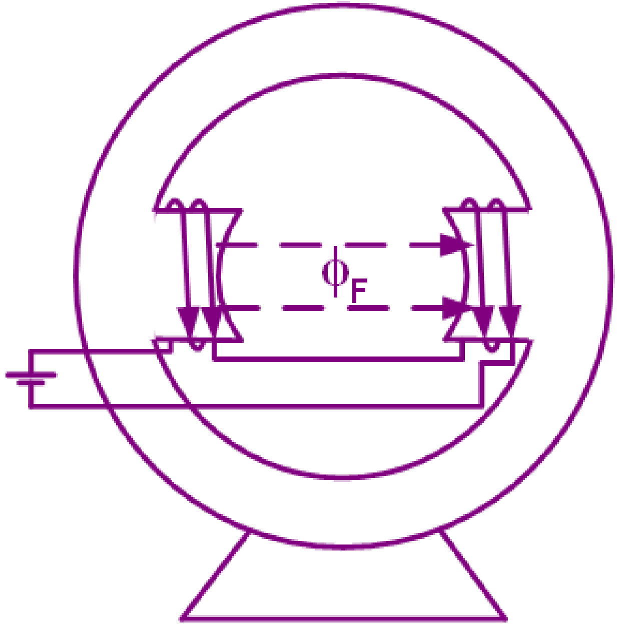
DC machine
- stator $\rightarrow$ DC
- rotor $\rightarrow$ 'I' flowing in the load OR in from external source is DC

AC machine
- synchronous machine
  - stator $\rightarrow$ AC/DC
  - rotor $\rightarrow$ DC/AC
- asynchronous machine
  - stator, rotor $\rightarrow$ AC

DC Machine

Stator:

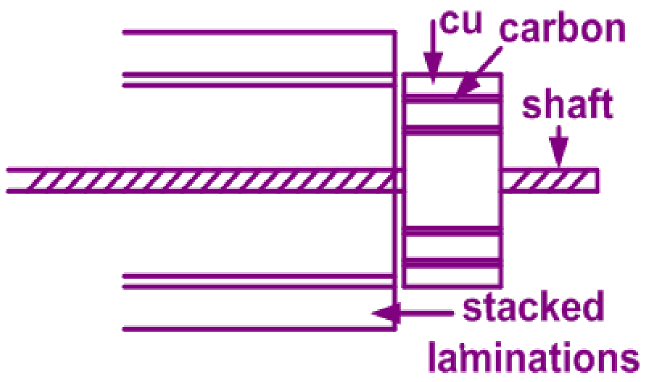
- Field coils are mounted on the projected part & connected to dc source
- Coil is stationary and 'I' is dc (can be replaced by PM)
- Time invariant field → angular speed of $F_s = 0$

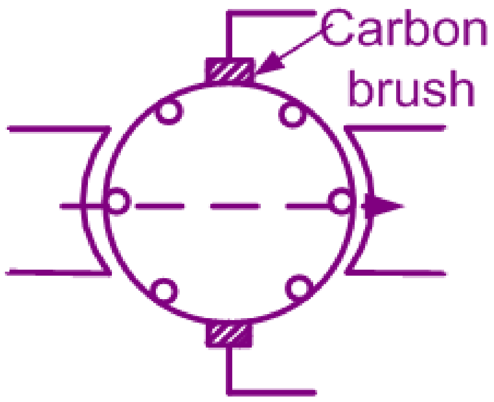


- In the airgap, either the conductor is rotated or external 'I' should be supplied

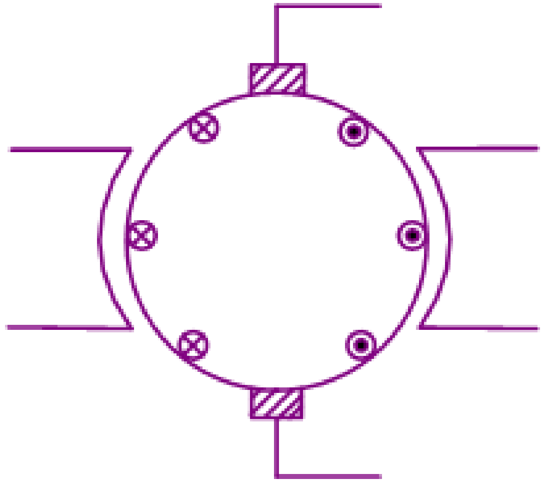
Rotor:

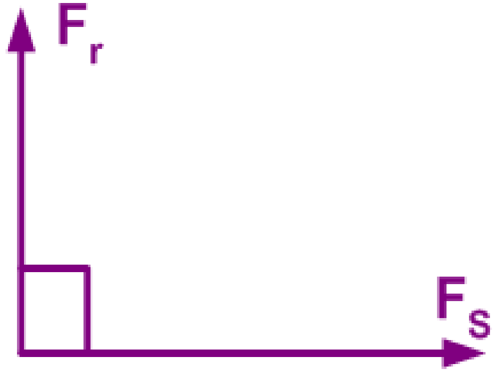
- Rotor having slots at the outer periphery
- In addition there is a commutator $\rightarrow$ it has large number of copper segments & these segments are insulated by mica
- Coils having desired number of turns are placed in these slots and two ends of the coil are connected to the copper strips
- Two carbon brushes are placed as shown on the copper commutator
- These carbon brushes are mounted on the commutator but fixed to the stator





- Carbon brushes are stationary
- Direction of ‘I’ reverses when the coil crosses the brush
- Conductors under one pole carry ‘I’ in one direction
- Armature mmf axis is fixed and it is along brush (q) axis
- Angle between F_s and F_r is 90° and is fixed, this angle is independent of load
- If F_s is held constant, F_r will change with load
- ‘I’ flowing into/out of the carbon brush is dc
- mmf w.r.t. carbon brush is stationary





Equivalent circuit of dc machine

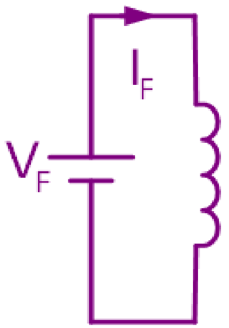
- dc current (If) is flowing in the field coil
  $R_F \rightarrow$ field winding resistance
  $L_F \rightarrow$ field winding inductance
- At steady state $V_F = RFI_F$
- Armature is rotating in the magnetic field Voltage induced is $E \propto \phi\omega$, where ϕ flux setup by field, and ω is angular speed
- E can be represented by $E = K\phi\omega$

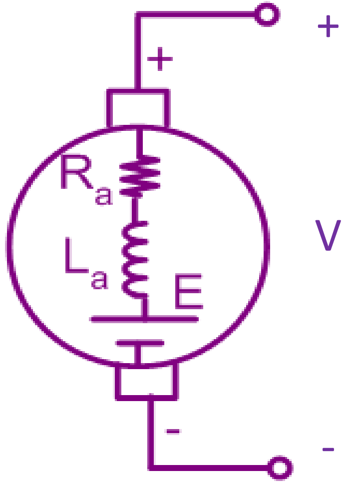
  In motoring mode, terminal voltage, V is given as

$$V = E + I_a R_a$$

  and in generating mode

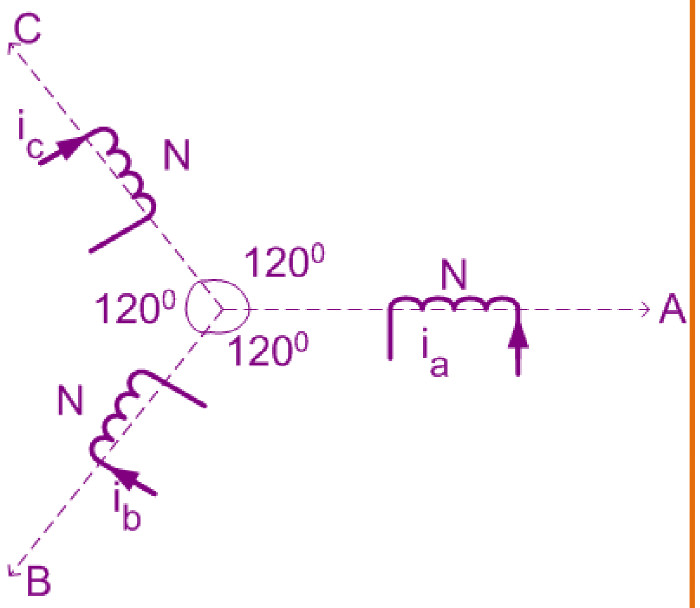
$$V = E - I_a R_a$$





Induction machine

- Consider 3 coils of ‘N’ turns, displaced in space by 120°
- Let i_a, i_b & i_c are given as



$$i_a = I_m \sin(\omega_s t)$$
$$i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3}\right),$$
$$i_c = I_m \sin\left(\omega_s t - \frac{4\pi}{3}\right), \text{ where } \omega_s = 2\pi f$$

- Current in each coil produces a pulsating magnetic field
- Amplitude & direction depend on the instantaneous value of ‘I’ flowing through it
- Each phase winding produces a similar magnetic field displaced by 120° in space from each other

Induction machine

Magnitude and position of the resultant field can be determined as follows

- Resolve the field produced by individual coil along x & y axes
- Determine $\sum x$ & $\sum y$ components
- Resultant, $R = \sqrt{(\sum x)^2 + (\sum y)^2}$

$\theta = \tan^{-1}\frac{\sum y}{\sum x}$, w.r.t axis of coil ‘A’

$$\sum x = Ni_a + Ni_b\cos(-120) + Ni_c\cos(-240)$$
$$= Ni_a - \frac{1}{2}Ni_b - \frac{1}{2}Ni_c$$
$$\because i_a + i_b + i_c = 0, \Rightarrow \sum x = \frac{3}{2}Ni_a$$

$$\sum y = 0 + Ni_b\sin(-120) + Ni_c\sin(-240)$$
$$= -\frac{\sqrt{3}}{2}Ni_b + \frac{\sqrt{3}}{2}Ni_c$$
$$\Rightarrow \sum y = \frac{\sqrt{3}}{2}N(i_c - i_b)$$

i_a, i_b & i_c are sinusoidal varying quantities

$\omega_s t$	i_a	i_b	i_c	Σx	Σy	R	θ
0^0	0	$\frac{-\sqrt{3}}{2} I_m$	$\frac{\sqrt{3}}{2} I_m$	0	$\frac{3}{2} NI_m$	$\frac{3}{2} NI_m$	$\frac{\pi}{2}$
30^0	$\frac{I_m}{2}$	$-I_m$	$\frac{I_m}{2}$	$\frac{3}{4} NI_m$	$\frac{3\sqrt{3}}{4} NI_m$	$\frac{3}{2} NI_m$	$\frac{\pi}{3}$
90^0	I_m	$\frac{-I_m}{2}$	$\frac{-I_m}{2}$	$\frac{3}{2} NI_m$	0	$\frac{3}{2} NI_m$	0
180^0	0	$\frac{\sqrt{3}}{2} I_m$	$\frac{-\sqrt{3}}{2} I_m$	0	$\frac{3}{2} NI_m$	$\frac{3}{2} NI_m$	$\frac{-\pi}{2}$

Observations:

- Magnitude of 'R' is constant and equal to $\frac{3}{2}NI_m$ where I_m is the peak
- Input 'I' completes 1/4 cycle, 'R' rotates by 90°
- Input 'I' completes 1/2 cycle, 'R' rotates by 180°

Conclusion:

- The result of displacing 3 windings by 120° in space and displacing the winding 'I' by 120° in time phase is a single revolving field of constant magnitude
- For a given winding arrangements speed of rotation is determined by 'f' of input alone

Rotor construction

squirrel cage $\rightarrow$ aluminum/ copper bars are embedded in the rotor slots and permanently shorted at both ends by Al/Cu end rings

$\Rightarrow$ electrically closed circuit

$\Rightarrow$ no additional ‘R’ can be connected