IOWA STATE UNIVERSITY

EE 303 – Electric Machines

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Three Phase Induction Motor

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Contents

- Three phase induction motor types
- Construction and principle of operation
- Rotating magnetic field
- Equivalent circuit of three phase induction motor
- Torque speed characteristics

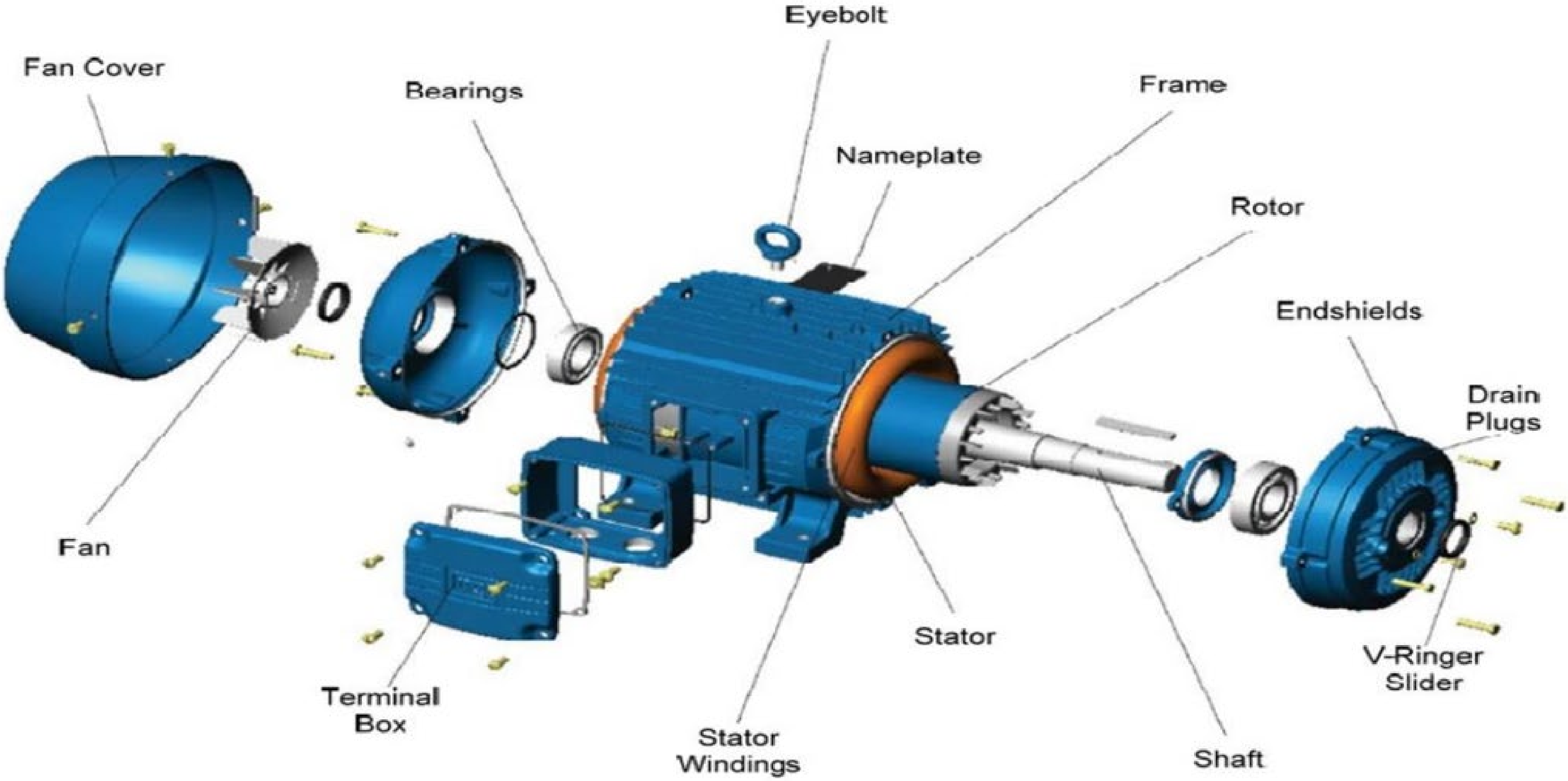
Three phase induction motor

- Invented by Nikola Tesla in 1888
- Induction motor is the commonly used machine for converting electrical to mechanical energy.
- Widely used in industry (e.g., water pumps, chillers, blowers, etc.) and home appliances (e.g., HVAC, Refrigerator, etc.)
- Available size vary from half a kilowatt to thousands of kilowatts.
- Advantages:
  - ❑ Rugged construction
  - ❑ Reliable operation
  - ❑ Simple mechanism for torque and speed control

Types and construction

1. **Squirrel cage induction motor**
2. **Slip ring induction motor**

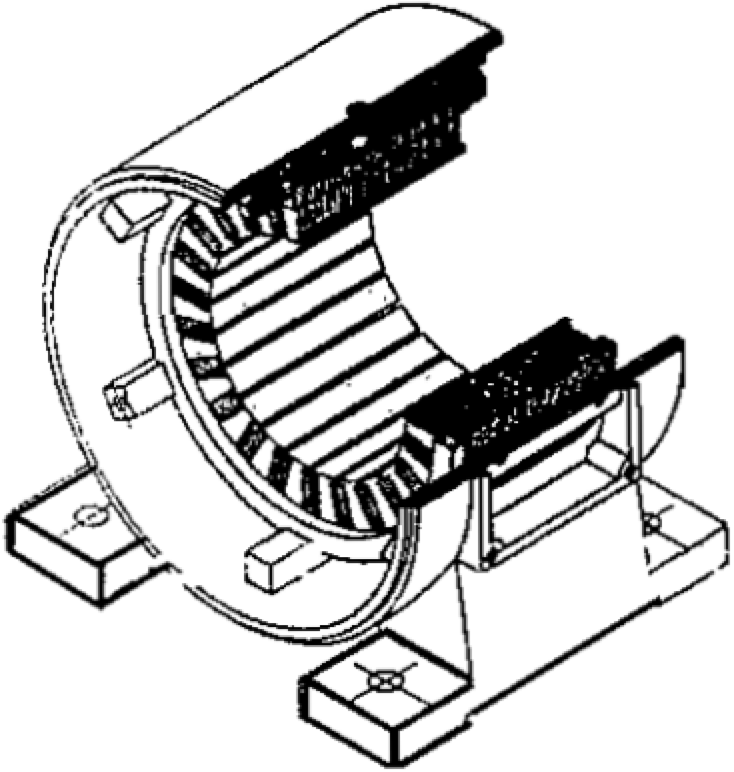
Main difference is the rotor construction

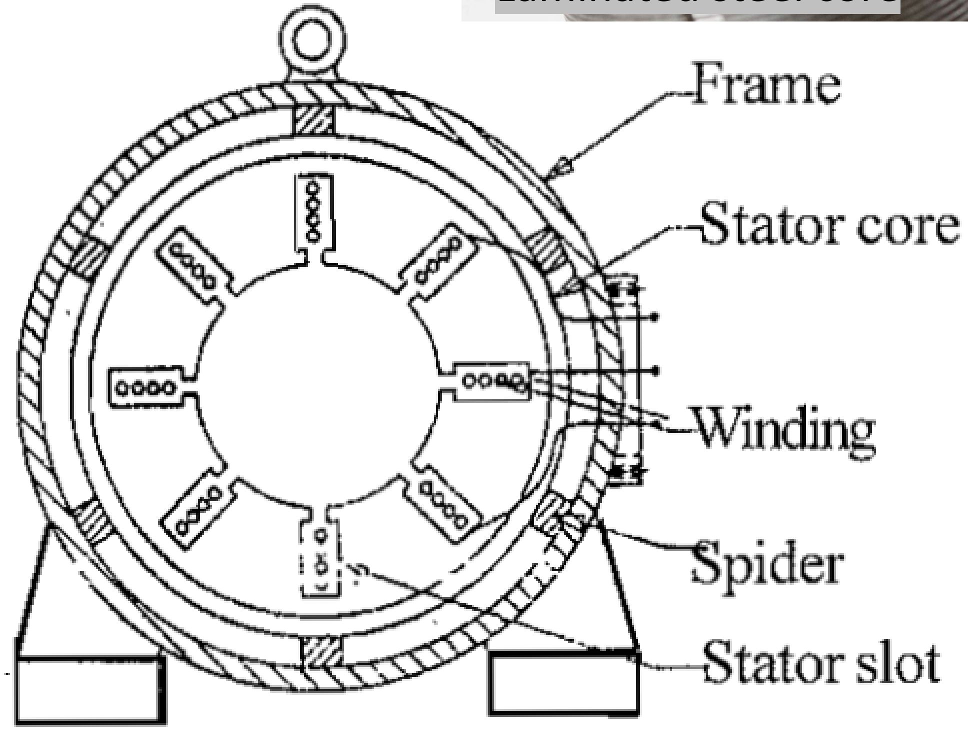


Squirrel cage induction motor

Stator

- Constructed with laminated steel core
- Holds the stator windings

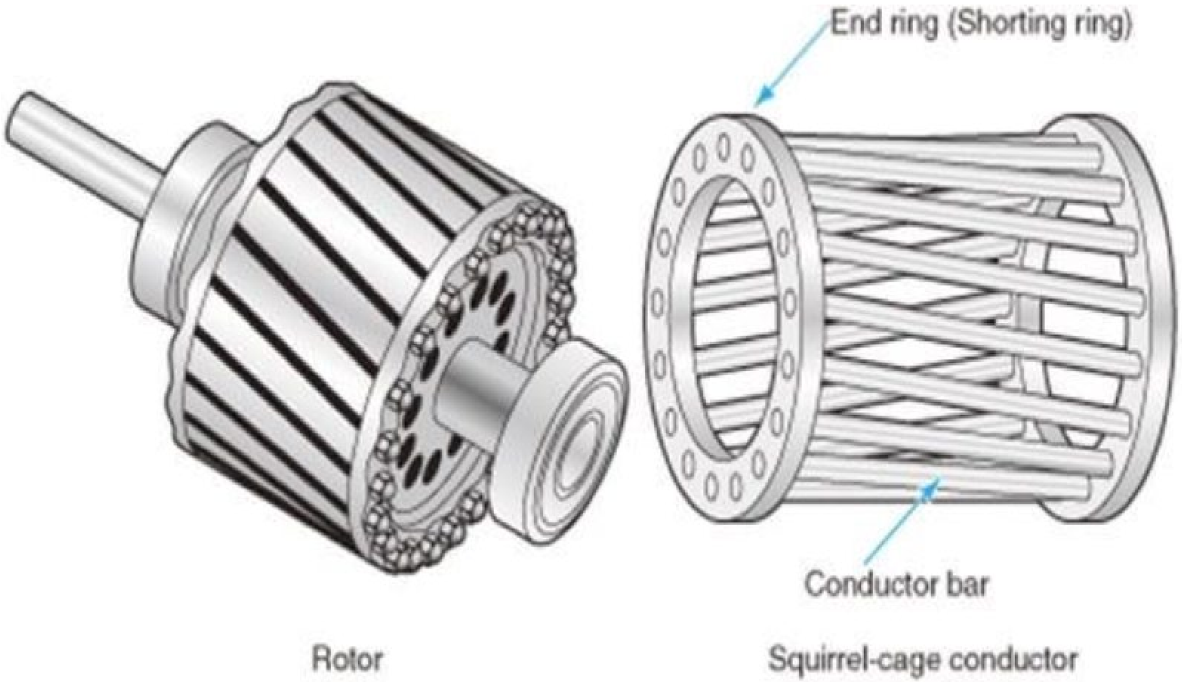




Squirrel cage induction motor

Rotor

- Constructed with laminated steel core
- Contains no windings but conductor bars that are short circuited by an end ring.

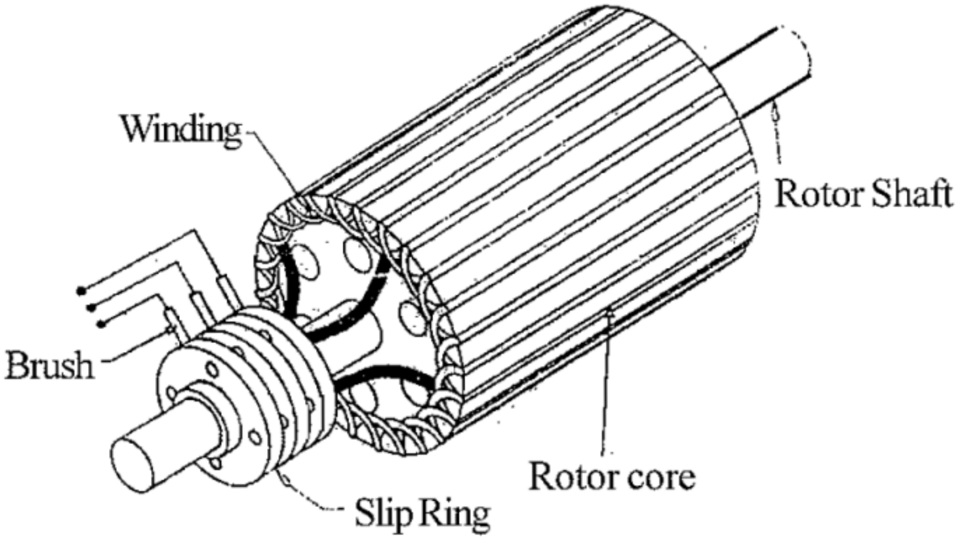


Slip ring induction motor

Stator: Same as squirrel cage induction motor

Rotor

- Constructed with laminated steel core
- Holds the rotor windings.
- The terminals of rotor windings are connected to slip rings.
- The terminals of slip rings are brough out through stationary carbon brushes.



Comparison of Squirrel cage and slip ring motor

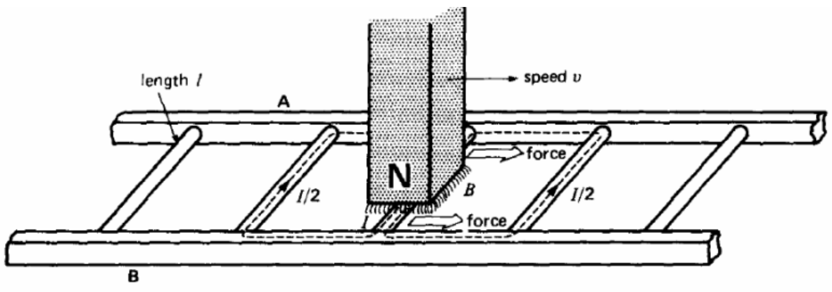
	Features	Squirrel cage motor	Slip ring motor
1	Rotor construction	• Metallic bar are used in rotor • No slip ring and brush rather the terminals of metallic bars are shorted by end rings.	• Rotor windings are made of copper • Slip ring and brush mechanism outlets the rotor windings' terminals.
2	Starting torque	• Low	• High
3	Starting Current	• High	• Low
4	Speed variation	• Not easy, but could be varied by changing supply frequency	• Easy to vary speed • Speed can be changed by changing rotor resistance or supply frequency
5	Maintenance	• Almost ZERO maintenance	• Requires frequent maintenance

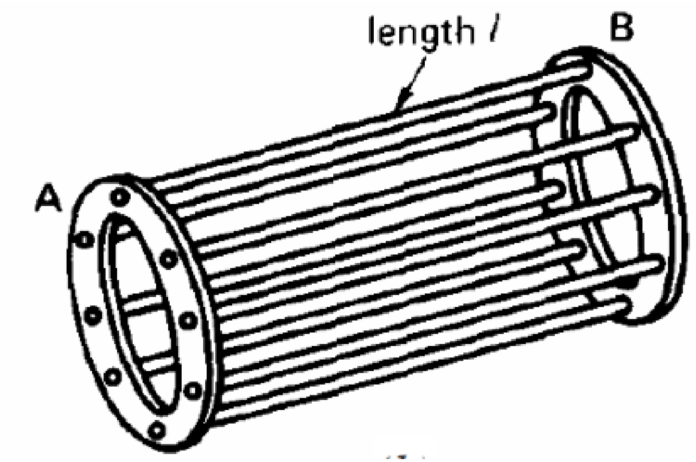
Principle of Operation

Sequence of events

1. A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).
2. The induced voltage immediately produces a current I, which flows down the conductor
3. Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force)
4. The force always acts in a direction to drag the conductor along with the magnetic field.

Thought Experiment



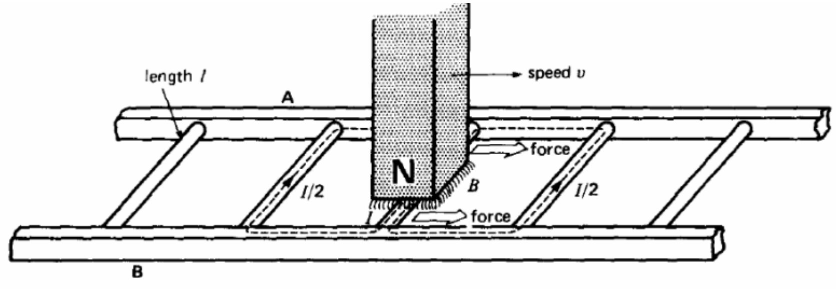


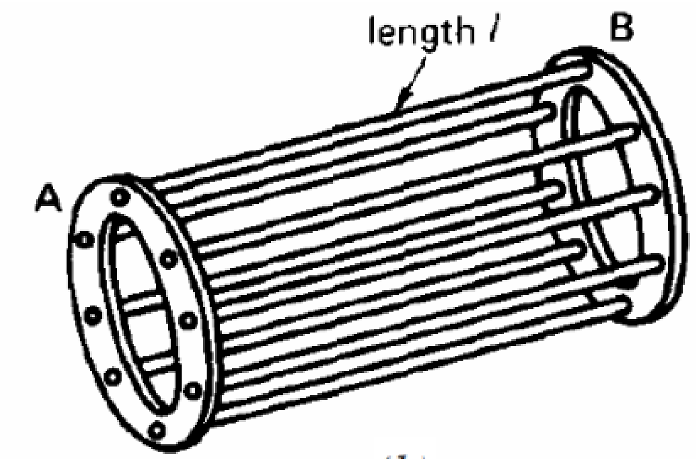
Principle of Operation

Sequence of events

5. If the conducting ladder is free to move, it will accelerate toward the right.
6. As it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish
7. Consequently, the force acting on the conductors wilt also decreases.
8. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.

Thought Experiment



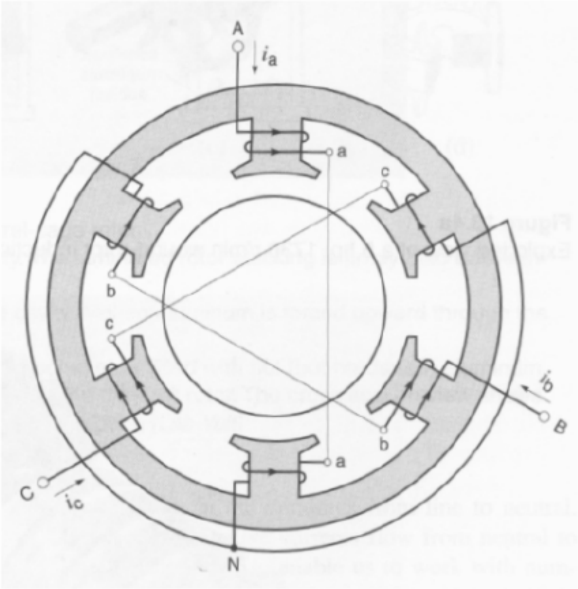


Rotating Magnetic Field

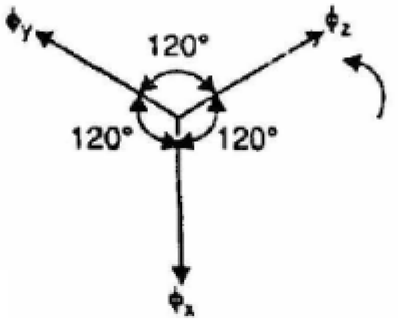
The three-phase winding produces magnetic flux along their axes.

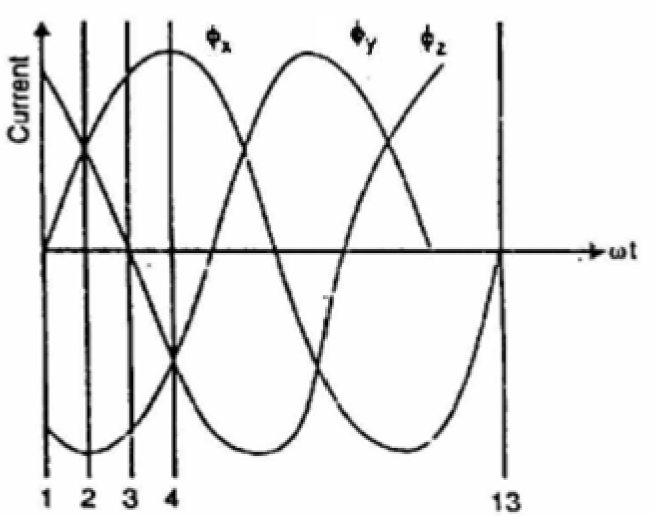
$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin(\omega t - 120°)$$
$$\phi_z = \phi_m \sin(\omega t - 240°)$$

The resultant flux is given by vector sum of ϕ_x, ϕ_y, and ϕ_z.



Stator windings





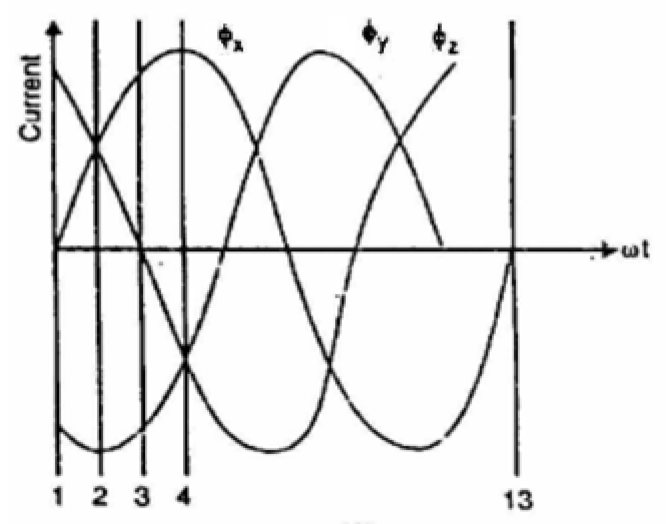
Rotating Magnetic Field

At instant 1, $\omega t = 0°$, the three fluxes are given by;

$$\phi_x = 0$$

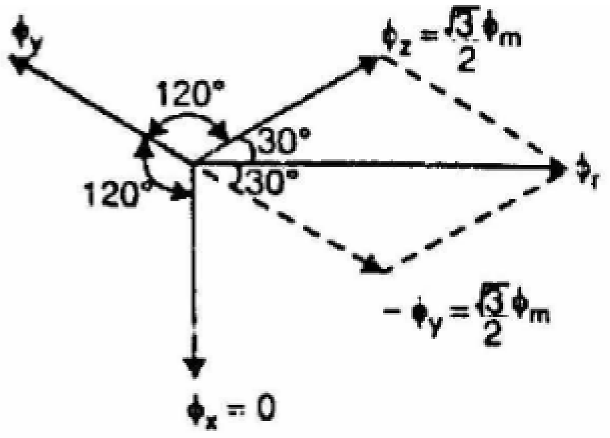
$$\phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

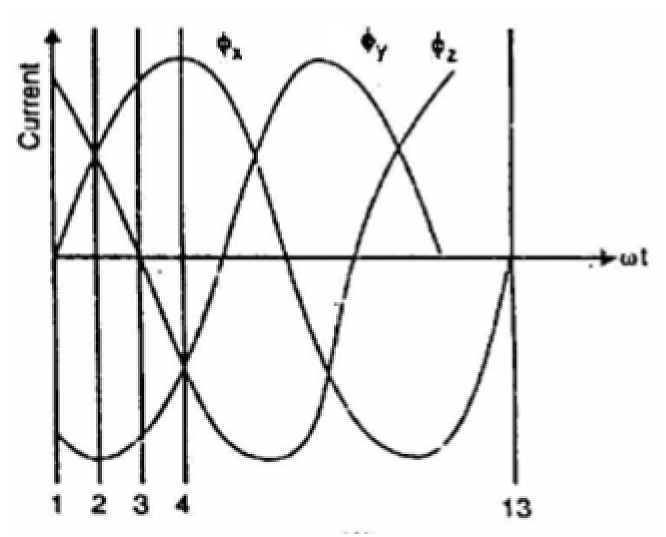


Resultant flux, $\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2}$

$$= 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\phi_m$$



Rotating Magnetic Field

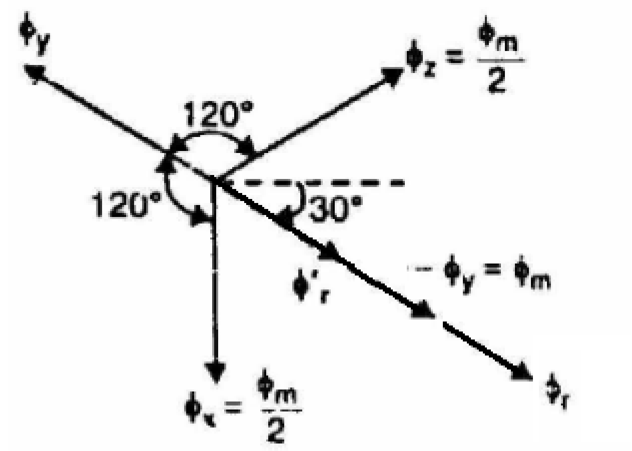


At instant 2, $\omega t = 30°$, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-180°) = 0$$



resultant flux

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 1.5\phi_m$$

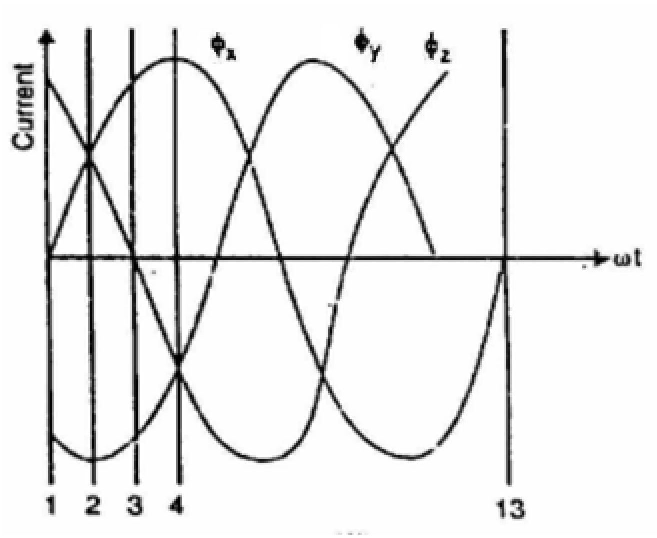
Rotating Magnetic Field

At instant 3, $\omega t = 60°$, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

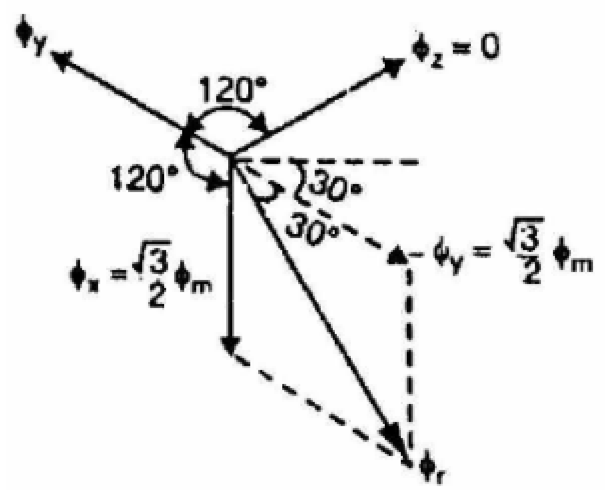
$$\phi_z = \phi_m \sin(-180°) = 0$$



Phasor sum of ϕ_x and ϕ_z, $\phi_r' = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$

Phasor sum of ϕ_r' and $-\phi_y$, gives the resultant flux

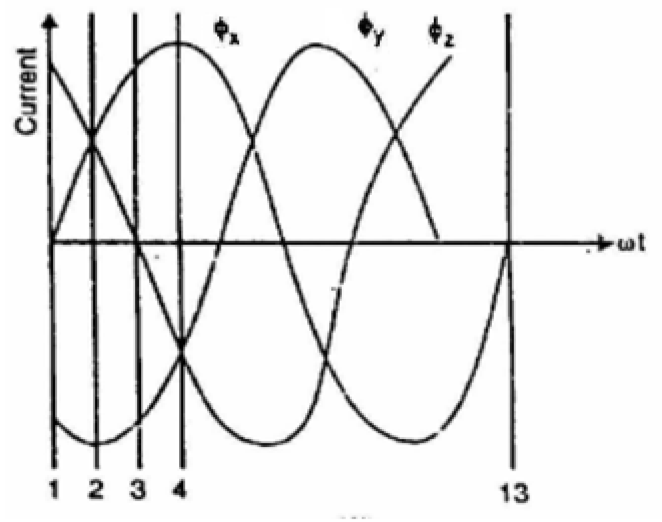
$$\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\phi_m$$



Rotating Magnetic Field

At instant 4, $\omega t = 90°$, the three fluxes are given by;

$$\phi_x = \phi_m \sin 90° = \phi_m$$
$$\phi_y = \phi_m \sin(-30°) = -\frac{\phi_m}{2}$$
$$\phi_z = \phi_m \sin(-150°) = -\frac{\phi_m}{2}$$

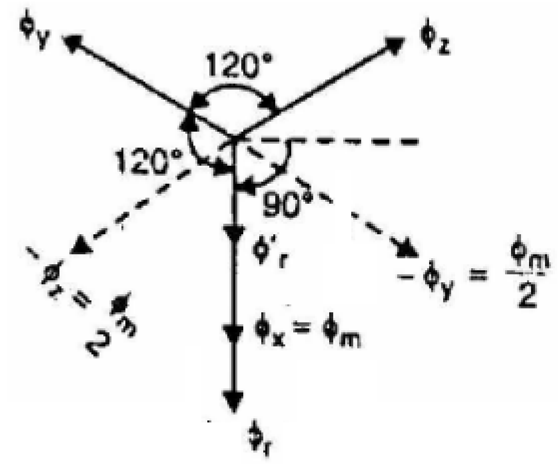


Phasor sum of $-\phi_z$ and $-\phi_y$, $\phi_r' = 2 \times \frac{\phi_m}{2} \cos \frac{120°}{2} = \frac{\phi_m}{2}$

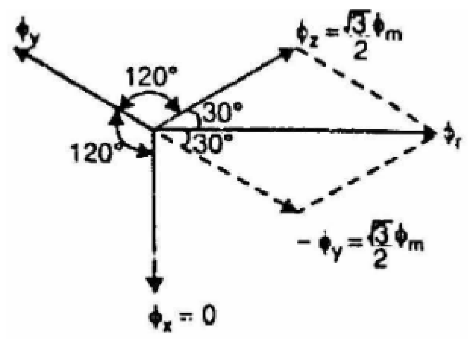
Phasor sum of ϕ_r' and ϕ_x, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\phi_m$

resultant flux

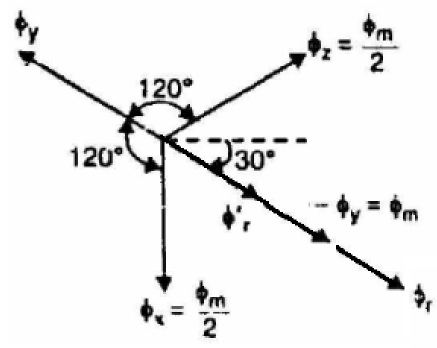
$$\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\phi_m$$



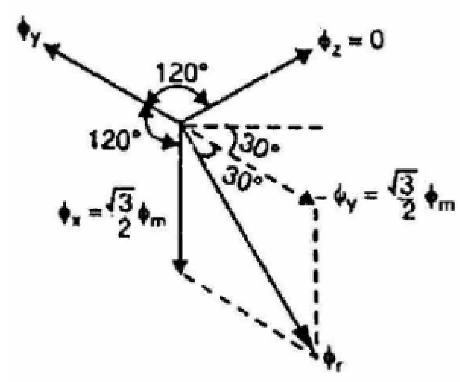
Resulting magnetic field



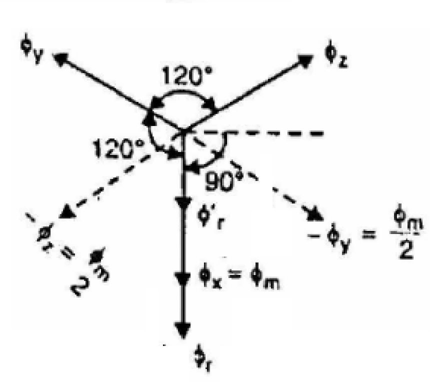
(i)



(ii)



(iii)



(iv)

- The 3-phase supply in the stator winding produces a rotating field of constant value (= 1.5 ϕ_m, where ϕ_m is the maximum flux due to any phase).
- The field is rotating in clockwise direction.

Speed of rotating magnetic field

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns), which is given by

$$N_s = \frac{120f}{P}$$

Note P refers to number of poles and f refers to frequency

Slip

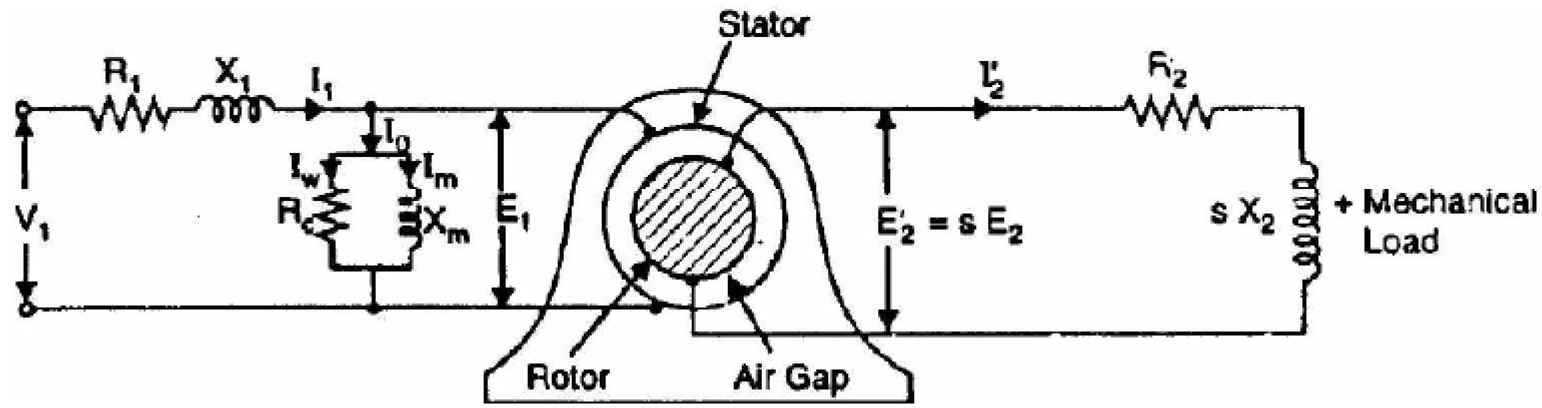
- In practice, the rotor can never reach the speed of stator flux
- If the relative speed between the stator field and rotor conductors is 0, then the rotor current are not induced and, hence, no torque to drive the rotor
- The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip and is given by

$$s = \frac{N_s - N}{N_s}$$

The slip is typically less than 15% in induction motors.

- The induced rotor current frequency is sf , where f is frequency of stator current.

Equivalent circuit of Three phase induction motor



- An induction motor may be considered a transformer with a rotating secondary (short-circuited).
- The stator winding corresponds to a transformer primary and the rotor winding as secondary.

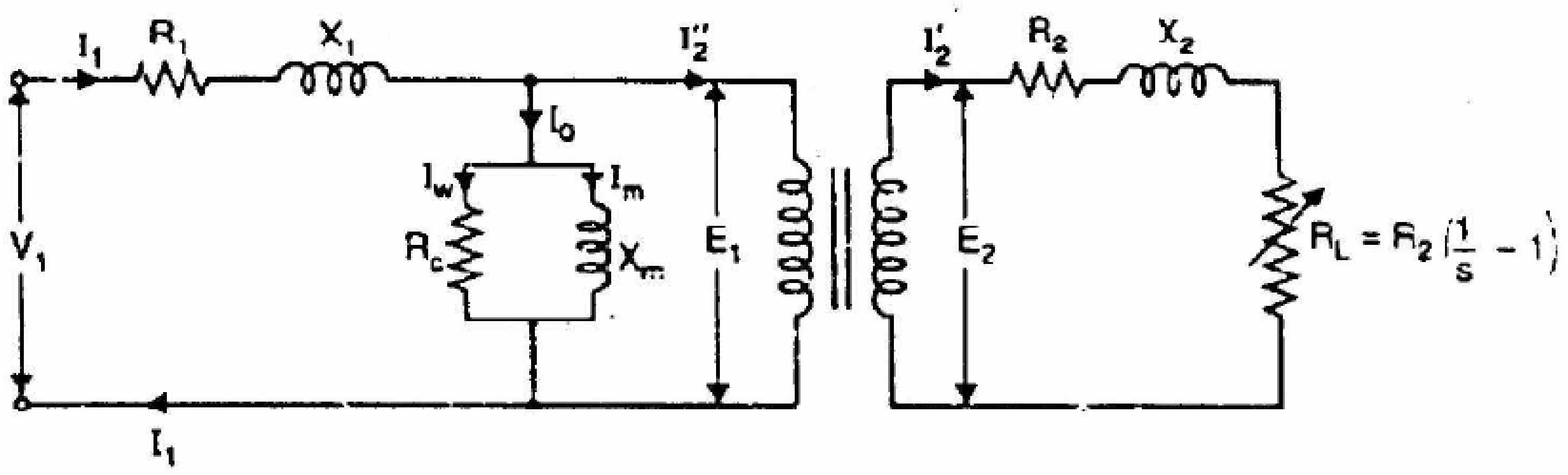
$$I_2' = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Equivalent circuit of Three phase induction motor

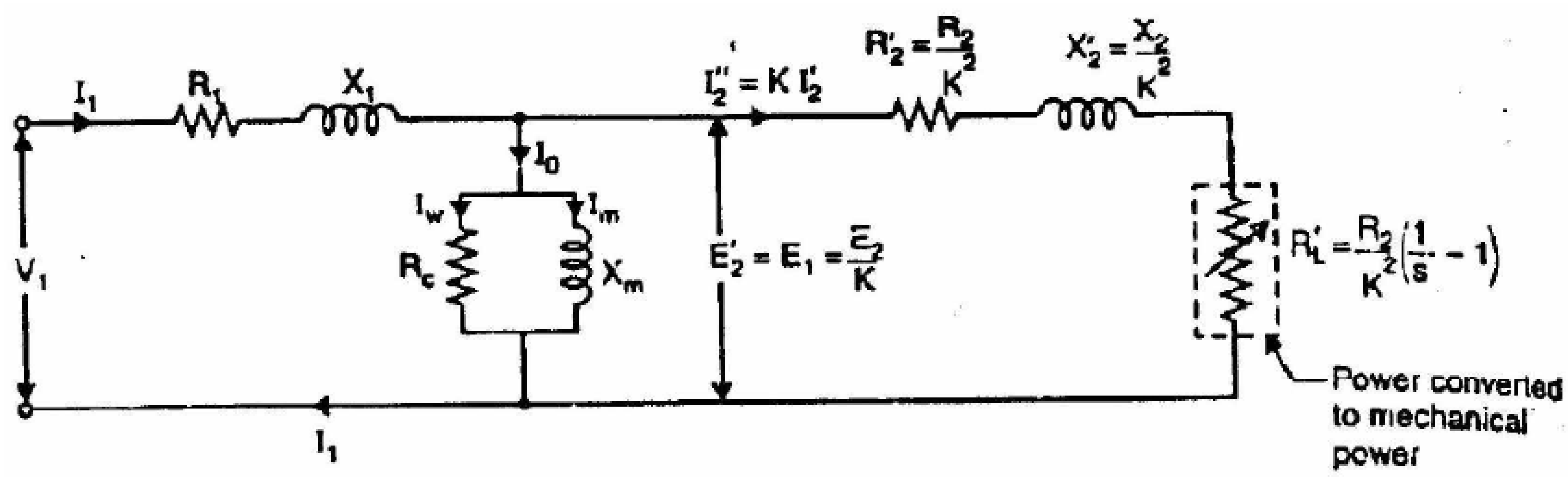
Alternatively, I_2' can be written as:

$$I_2' = \frac{E_2}{\sqrt{(R_2/s)^2 + (X_2)^2}}$$

Hence the equivalent circuit can be written as:

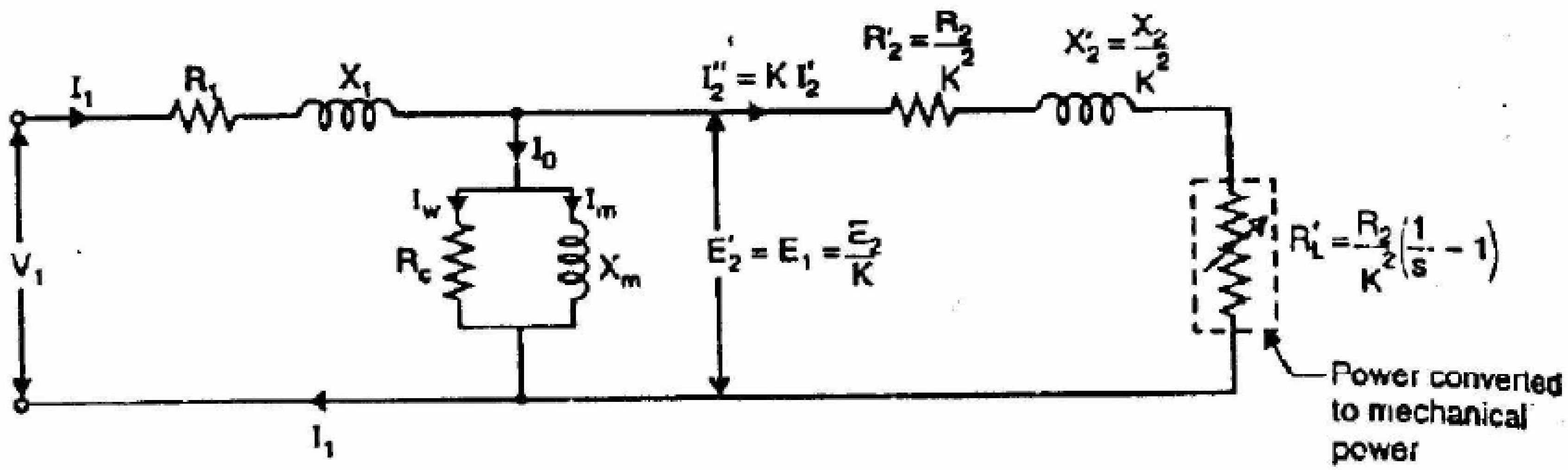


Equivalent circuit of Three phase induction motor



K is the transformation ratio at standstill position of the rotor

Torque equation



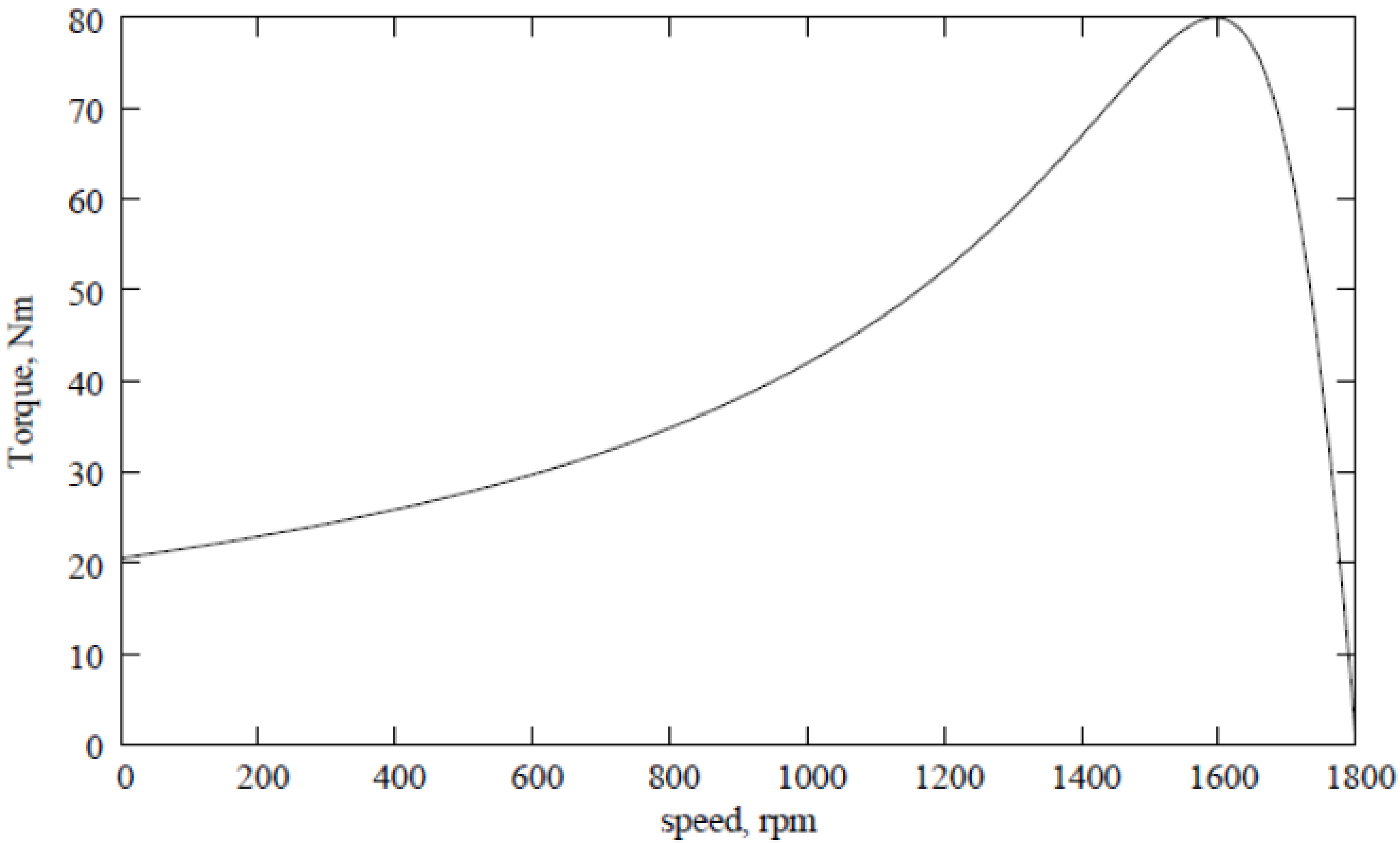
$$I_2' = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} = \frac{sKE_1}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor Power} = 3 \times \frac{s^2 E_1^2 R_2}{R_2^2+(sX_2)^2} \times \left(\frac{1}{s} - 1\right) = \frac{3s\ E_1^2 R_2(1-s)}{R_2^2+(sX_2)^2}$$

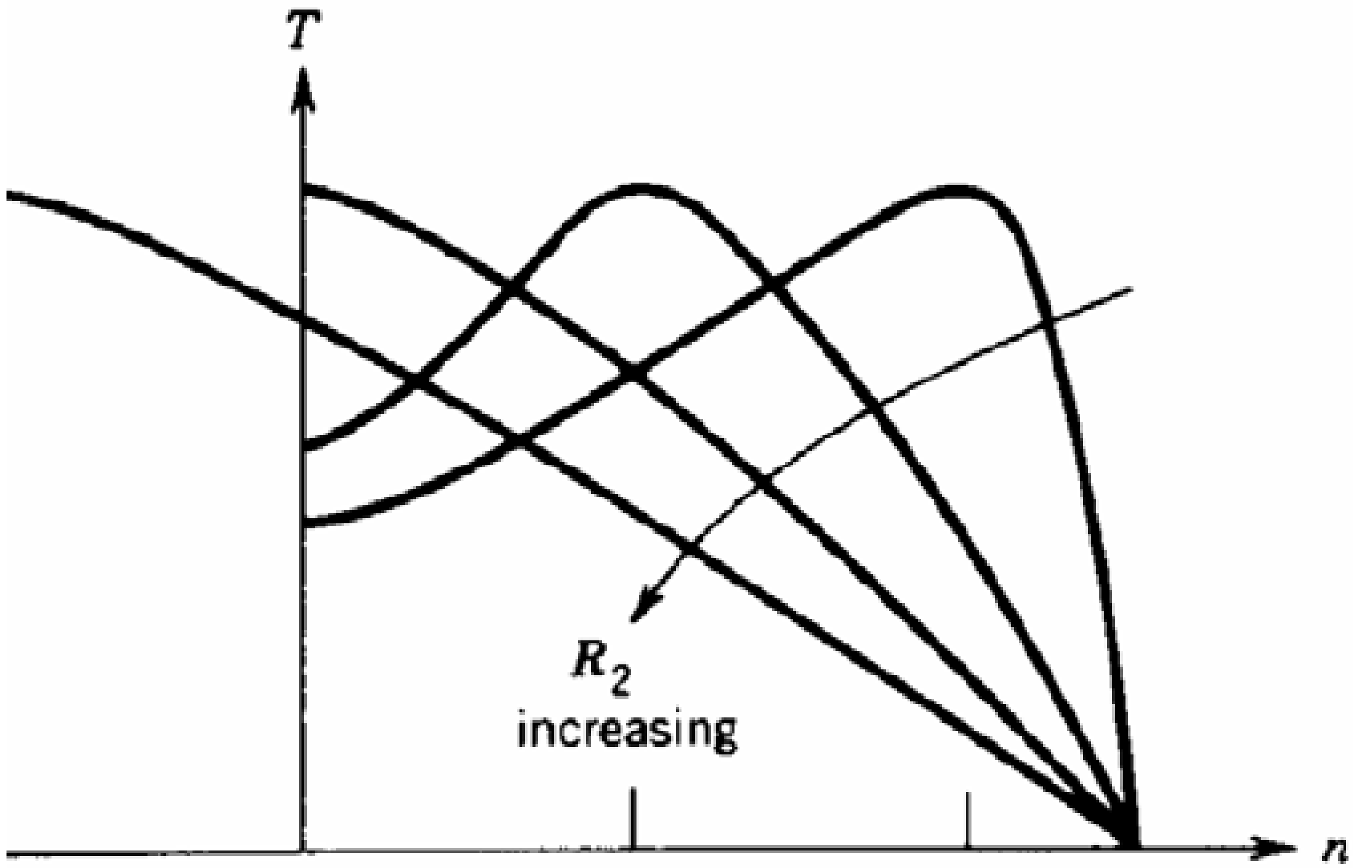
$$\text{Rotor Power} = T\,\omega = 2\pi TN$$

$$T = \frac{Rotor\ Power}{2\pi N} = \frac{3s\ E_1^2 R_2}{(R_2^2+(sX_2)^2)2\pi N_s} = \frac{3}{2\pi N_s} \times \frac{s\ E_1^2 R_2}{(R_2^2+(sX_2)^2)}$$

Torque speed characteristics



Torque speed characteristics on varying R_2



Q&A

THANKS

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Synchronous Generator

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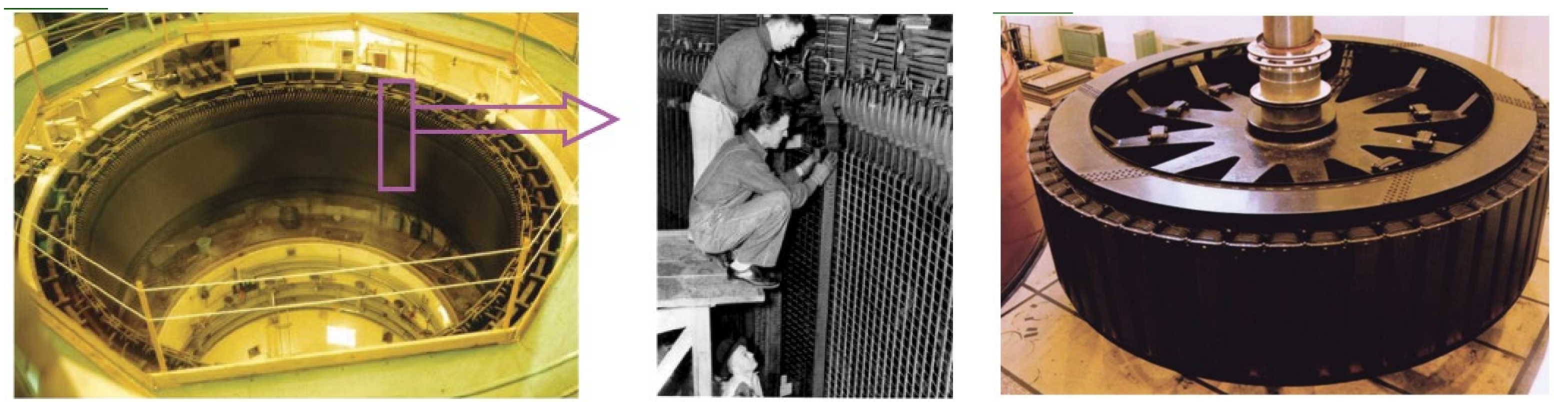
Synchronous Generator

- Synchronous generators convert the mechanical power of the turbine into electrical power
- The source mechanical power could be a diesel engine, steam turbine, hydro turbines, etc.
- Widely used in large scale power production in the range of several Mega Watts to Giga Watts.

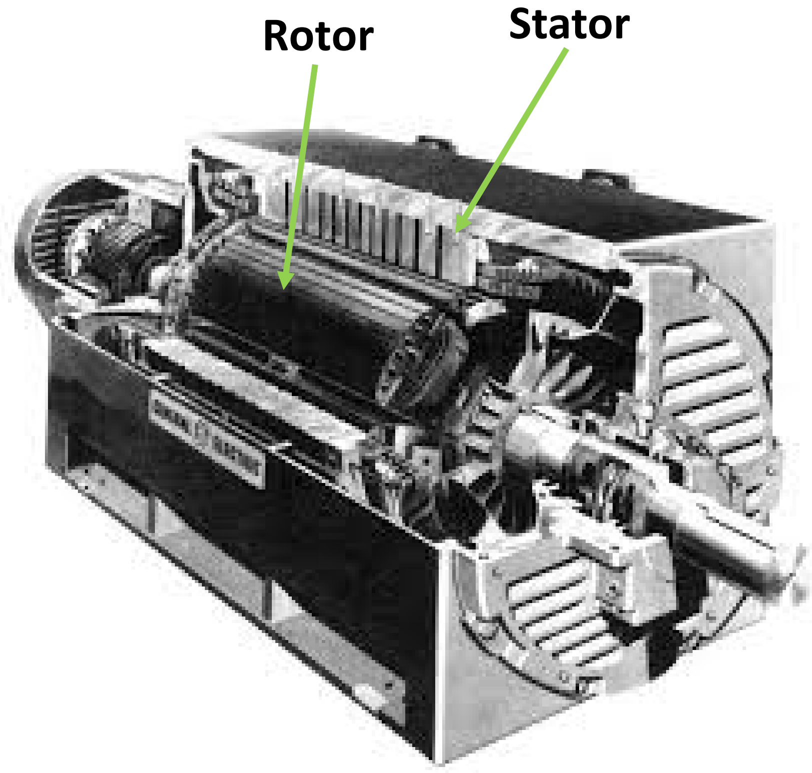


Stator and Rotor of Synchronous generator of Grand Coulee hydroelectric power plant on the Columbia River in Washington State.

Basic Topology

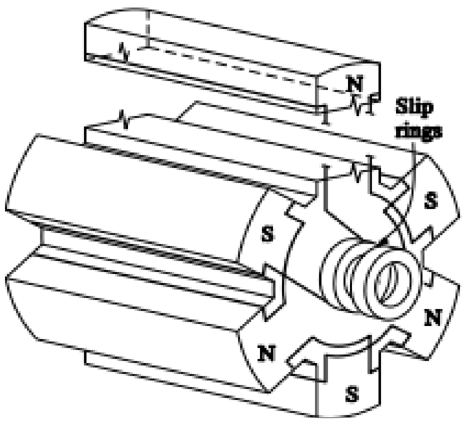
- **Stator**: support the placement of three phase winding as in Induction motor.
- Stator winding are also referred to as armature winding.

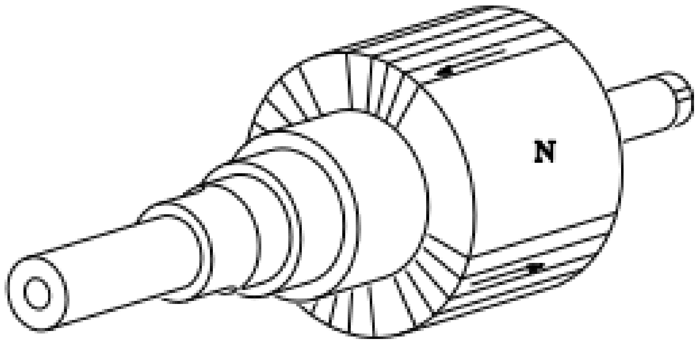
- **Rotor**: Unlike induction generator, the magnetic field is generated either by a permanent magnet or by applying dc current to rotor windings.
- Rotor winding are referred to as field windings.



Types

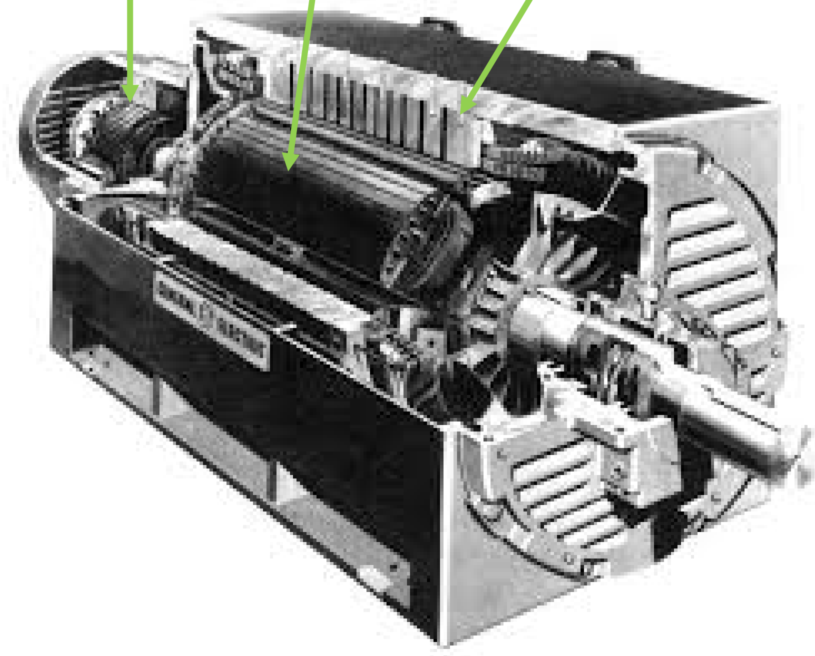
- **Salient-pole rotor**
  - **Has protruding poles**
  - **Air gap between stator and rotor is not uniform**
  - **Designed for low-speed generator, e.g., Hydro**
- **Cylindrical rotor**
  - **Uniform airgap**
  - **Designed for high-speed generator, e.g., steam generators**





Exciter system

1. DC generator-based excitation system
2. Brushless excitation system/AC generator-based excitation system



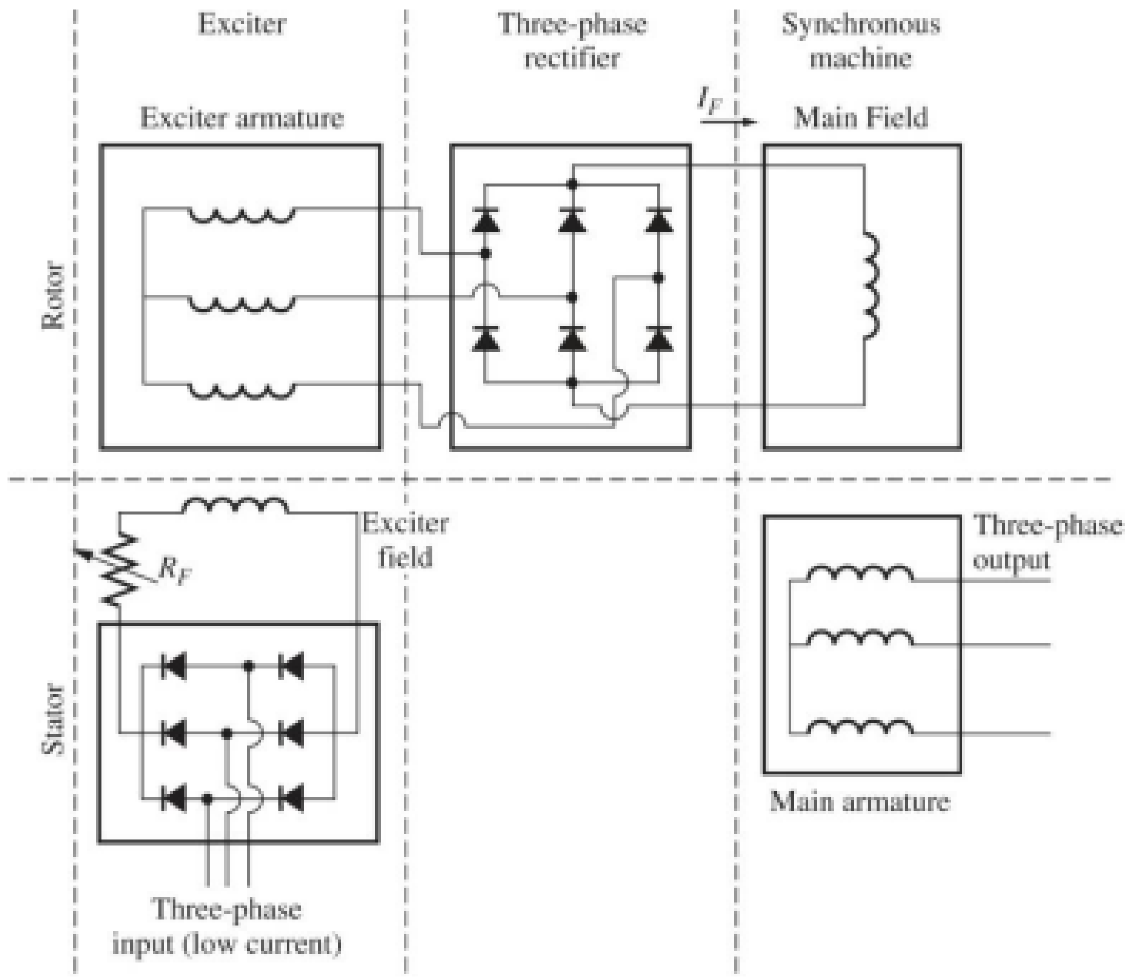
DC generator-based excitation system

- Supply DC power to field winding from a special DC generator mounted directly on the shaft of the synchronous generator.
- DC generators have carbon brush, which require higher maintenance.

AC generator-based excitation system

- Commonly referred as brushless excitation system
- A small AC generator whose field circuits are mounted on the stator and armature circuits are mounted on the rotor shaft.
- AC exciter output is rectified to DC by a 3-phase rectifier (mounted on the shaft) and fed into the main DC field circuit.
- It is possible to adjust the field current on the main machine by controlling the small DC field current of the exciter generator (located on the stator).

AC generator-based excitation system



Rotation speed of synchronous generator

$$f_e = \frac{N_m P}{120}$$

Where,

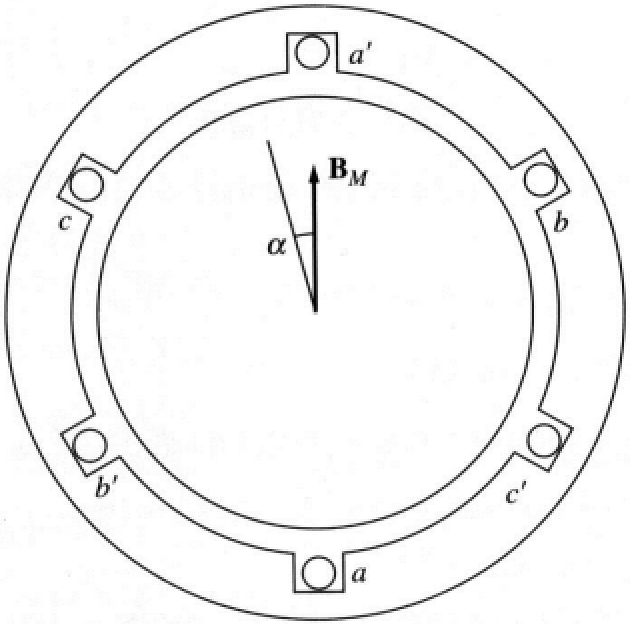
f_{e} = electrical frequency, in Hz
N_m = mechanical speed of magnetic field, in rpm = rotor speed, in rpm
P = number of poles

- For two pole generator to produce AC power at 60 Hz, it should be rotated at 3600 rpm

Generation Voltage

- A uniform rotating magnetic flux (ϕ_r) produced by rotating rotor at ω_m angular speed is $\phi_r = \phi \sin\omega_m t$
- If N_c is the number of coil in each stator windings, the emf induced in each phase would be

$$e_{aa'}(t) = N_C \phi \omega_m \cos \omega_m t$$
$$e_{bb'}(t) = N_C \phi \omega_m \cos(\omega_m t - 120°)$$
$$e_{cc'}(t) = N_C \phi \omega_m \cos(\omega_m t - 240°)$$



Peak voltage:

$$E_{\max} = N_C \phi \omega_m$$
$$E_{\max} = 2\pi N_C \phi f_e$$

RMS voltage:

$$E_A = \frac{2\pi}{\sqrt{2}} N_C \phi f = \sqrt{2}\pi N_C \phi f_e$$

Q&A

THANKS