Induction Motor

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Introduction: AC Machines

- **Induction machines (Asynchronous):** Motors and generators whose magnetic field is supplied by magnetic induction transformer action.

- **Synchronous machines:** Motors and generators whose magnetic field is supplied by a separate dc power supply.

Induction Machines

The induction machine is the most rugged and the most widely used machine in industry. Like dc machine, the induction machine has a stator and a rotor mounted on bearings and separated from the stator by an air gap. However, in the induction machine both stator winding and rotor winding carry alternating currents. The induction machine can operate both as a motor and as generator

As Induction generator, it has many disadvantages and low efficiency. Therefore, induction machines are usually referred to as induction motors.

Induction Machines

As motors, they have many advantages.

1. Three-phase induction motors are the most common and frequently encountered machines in industry
2. They are rugged, relatively inexpensive, simple design and require very little maintenance.
3. They range in size from a few watts to about 10,000 hp.
4. The speed of an induction motor is nearly but not quite constant, dropping only a few percent in going from no load to full load.
5. Speed is power source frequency dependent

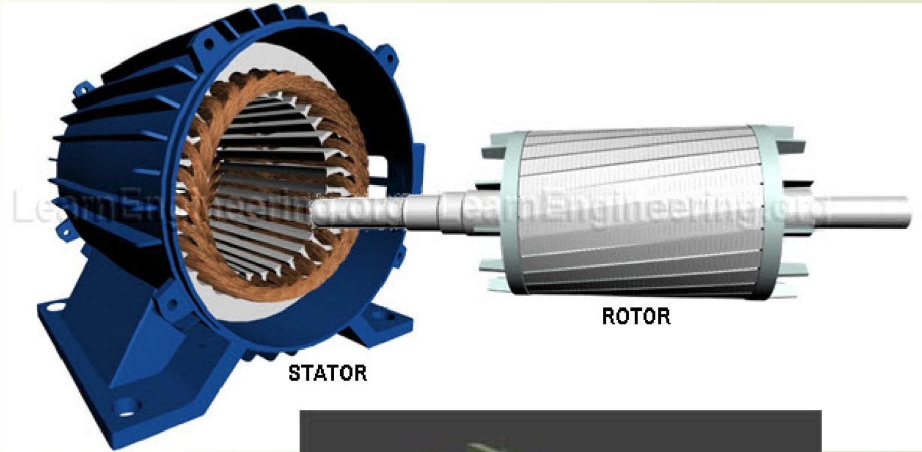
The main disadvantages of induction motors are:

1. The speed is not easily controlled.
2. Requires a variable-frequency power-electronic drive for optimal speed control
3. The starting current may be five to eight times full-load current.
4. The power factor is low and lagging when the machine is lightly loaded.

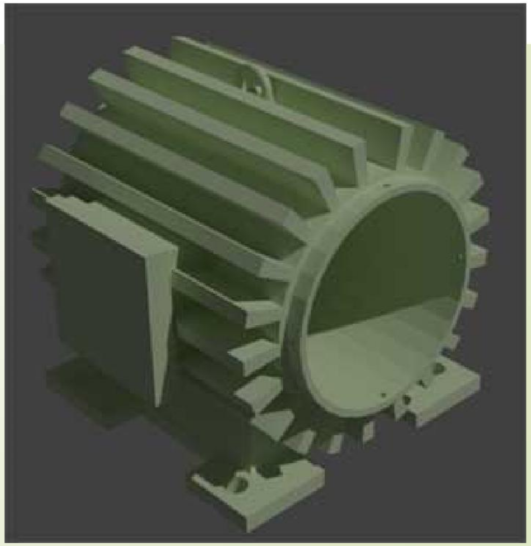
Induction Motor: Construction

An induction motor has two main parts

1. A stationary stator
2. A revolving Rotor

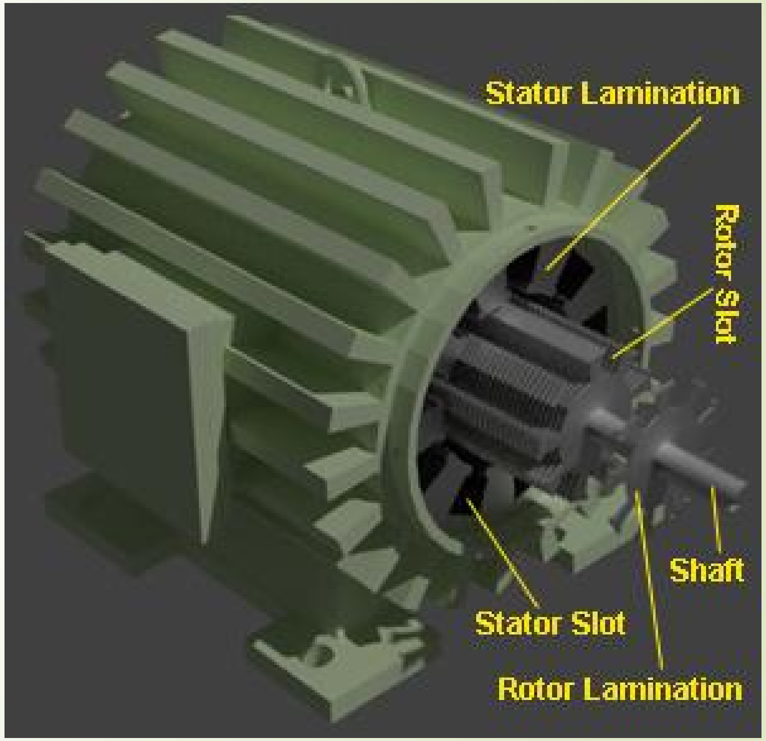


- Stator
  - Stator frame
    - Support the stator core and the field winding
    - Provide protection to IM parts
    - Die cast or fabricated steel.



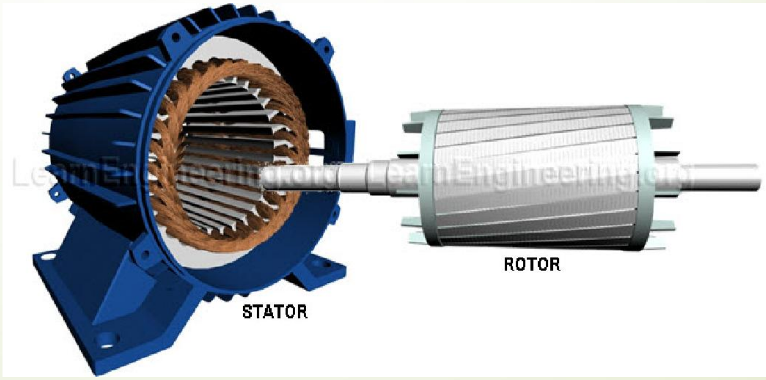
Induction Motor: Construction

- Stator core
  - carry the alternating flux
  - is laminated (reduce eddy current loss)
- Stator winding (field winding)
  - carries three phase windings
  - winding are connected either in star or delta
  - when this winding is excited by three phase ac supply it produces a rotating magnetic field

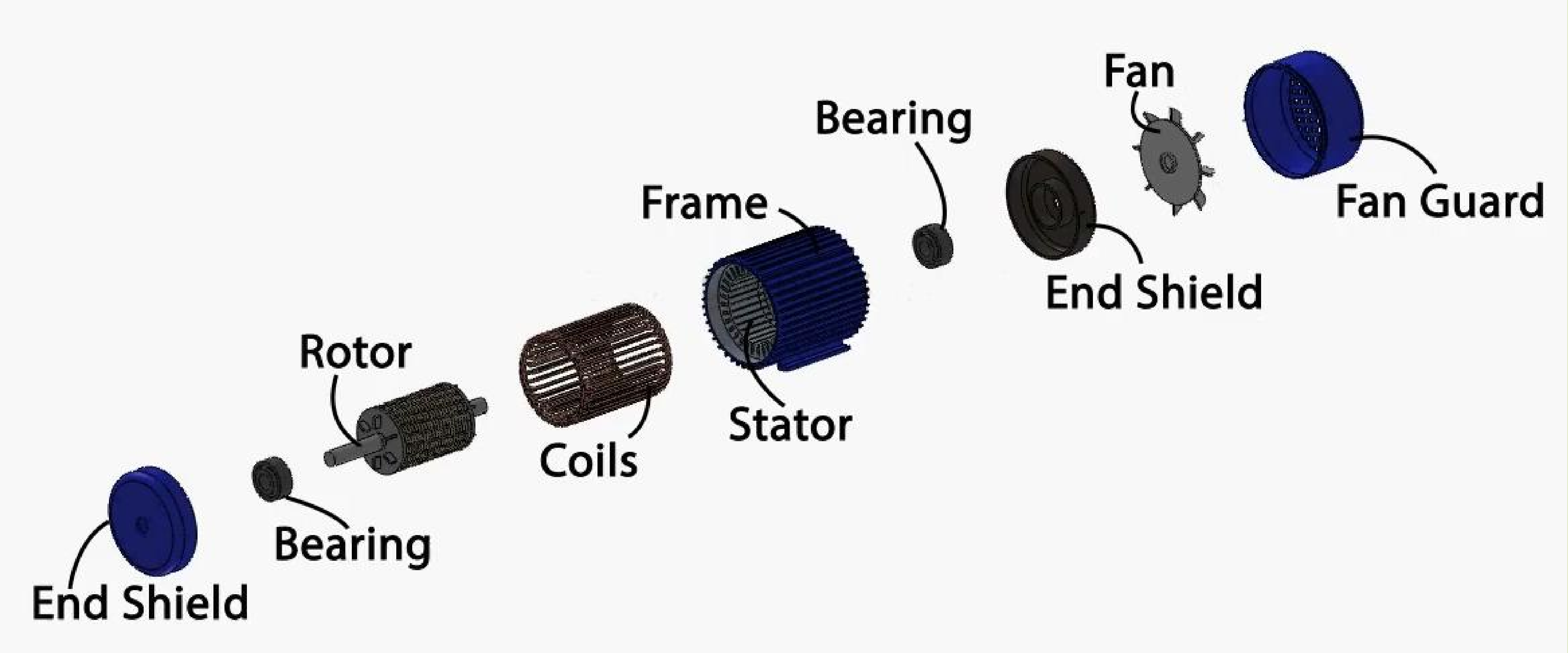


Induction Motor: Construction

- a revolving rotor
  - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
  - one of two types of rotor windings
  - conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
  - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)



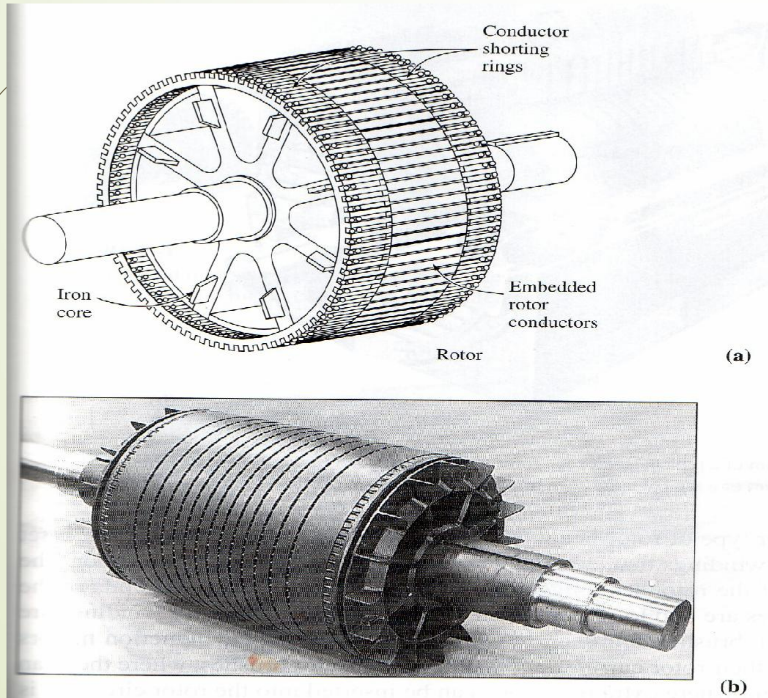
Induction Motor: Construction



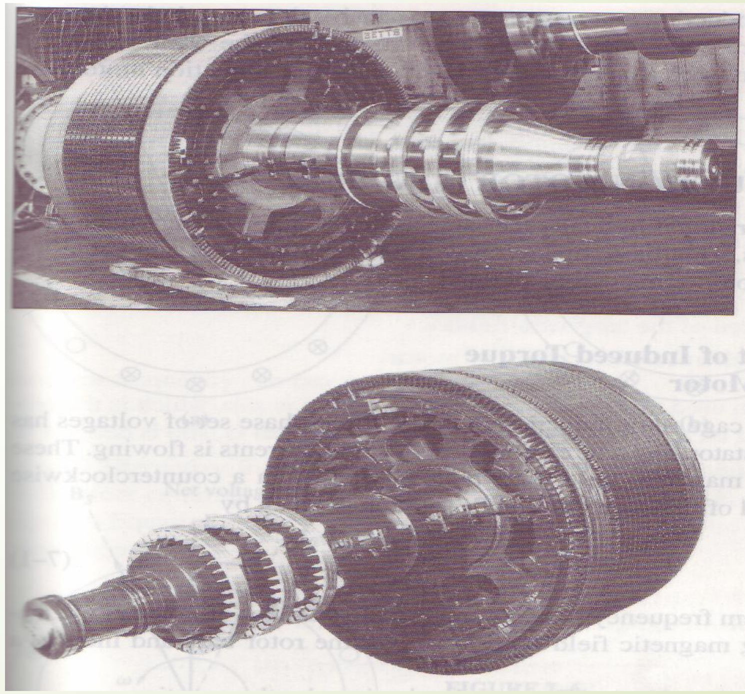
Induction Motor: Construction

Two different types of induction motor which can be placed in stator:

a) **squirrel cage rotor**
b) **wound rotor**



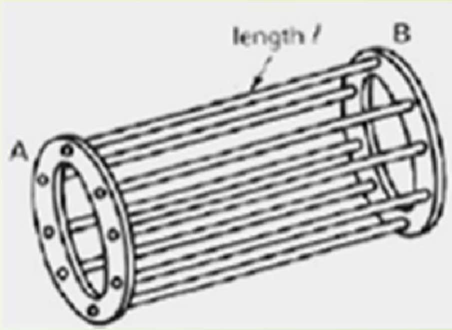
Squirrel Cage rotor

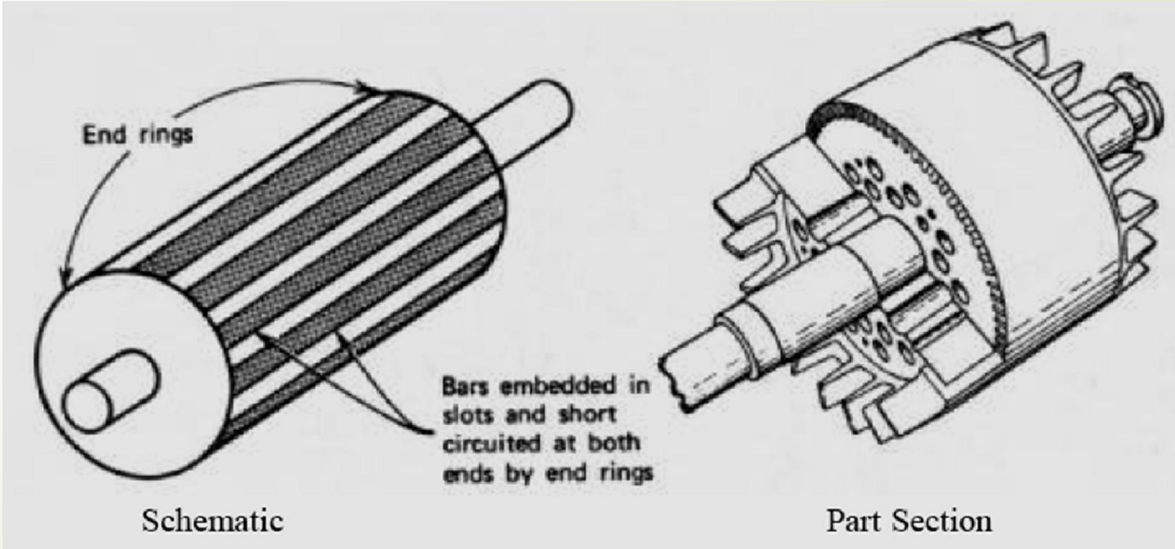


Wound rotor

Induction Motor: Construction

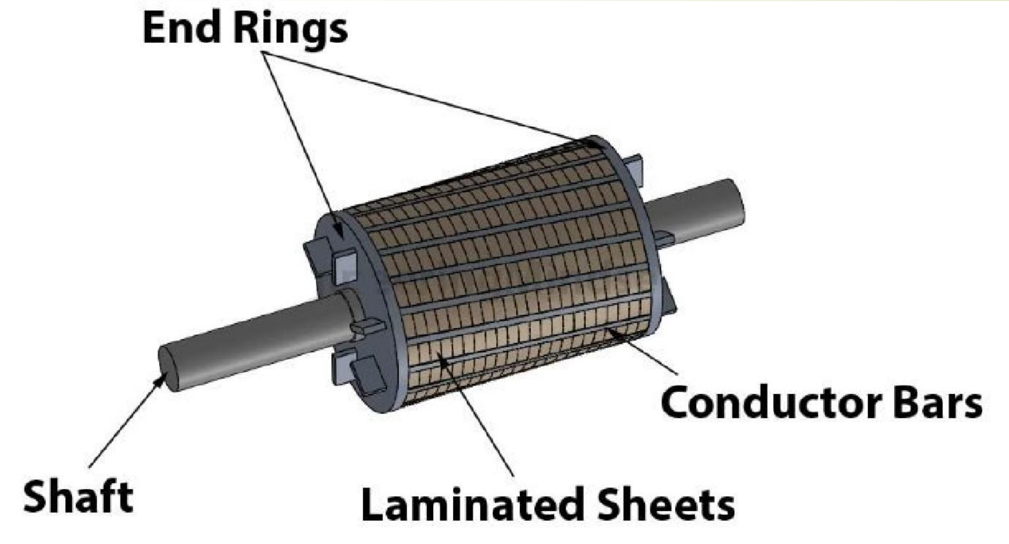
1. **Squirrel cage**
   - cylindrical in shape
   - have slots on its periphery
   - are not made parallel to each other but are bit skewed
     - prevents magnetic locking of stator and rotor teeth
     - makes the working of motor more smooth and quieter
   - consists of aluminum, brass or copper bars (rotor conductor)





Induction Motor: Construction

1. **Squirrel cage**
   - the rotor conductors are permanently shorted by the copper or aluminum rings called the end rings.
   - rotor conductor are braced to the end ring
     - to provide mechanical strength
     - form a complete closed circuit (resembling cage)- that's why it is call squirrel cage
   - Because bars are permanently shorted by end rings
     - rotor resistance is very small
     - Can't add external resistance



Induction Motor: Construction

- Slip ring rotor (wound rotor)
  - Most motors use the **squirrel-cage rotor** because of the robust and maintenance-free construction.
  - However, large, older motors use a wound rotor with three phase windings placed in the rotor slots.
  - The three end terminals are connected together to form star connection.
  - consists of slip rings connected on same shaft as that of rotor.

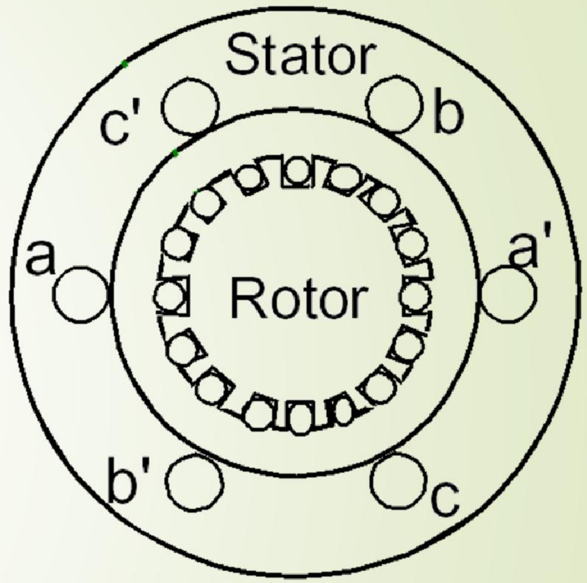
  - three ends of three phase windings are permanently connected to these slip rings
  - Resistors or power supplies are connected to the slip rings through brushes for reduction of starting current and speed control

Induction Motor: Basic Concept

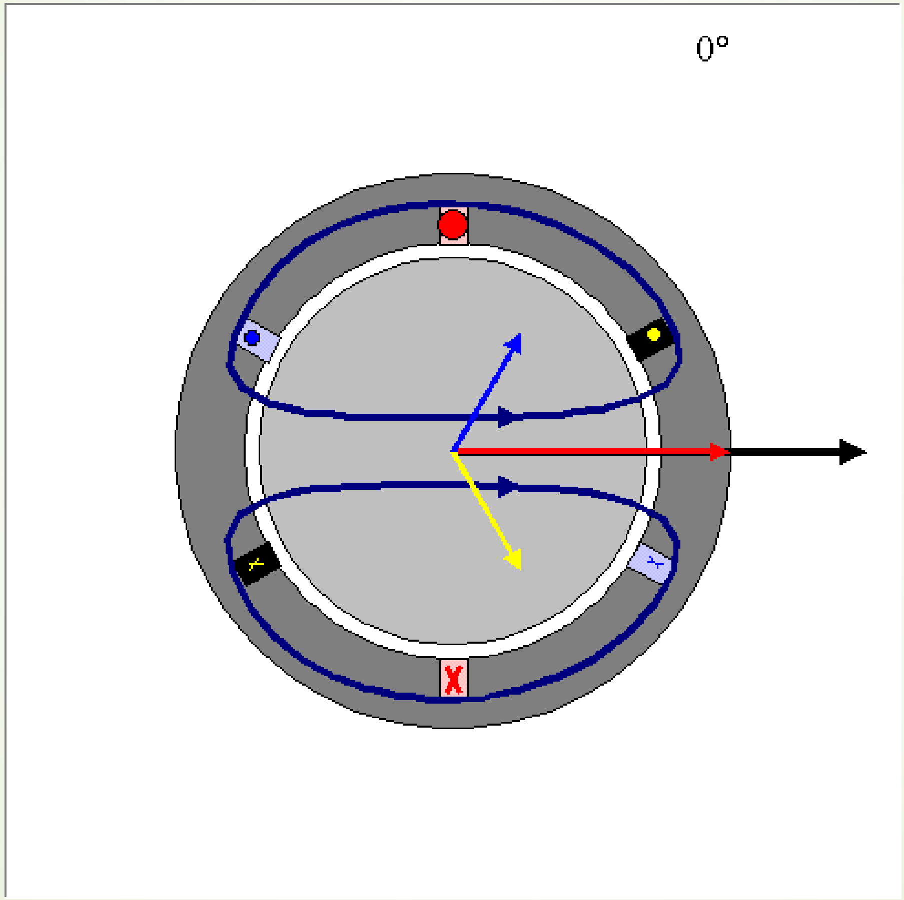
- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$n_{sync} = \frac{120 f_e}{P} \quad rpm$$

- Where f_e is the supply frequency and P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)



Induction Motor: Rotating Magnetic Field



Induction Machine - Operation

Speed of rotation (synchronous speed)

$$n_S = \frac{120 \cdot f_e}{P} \qquad (rpm)$$

$$\omega_S = \frac{4\pi \cdot f_e}{P} \qquad (rad / S)$$

P is the number of magnetic poles designed into the machine,
f_e is the power line frequency.

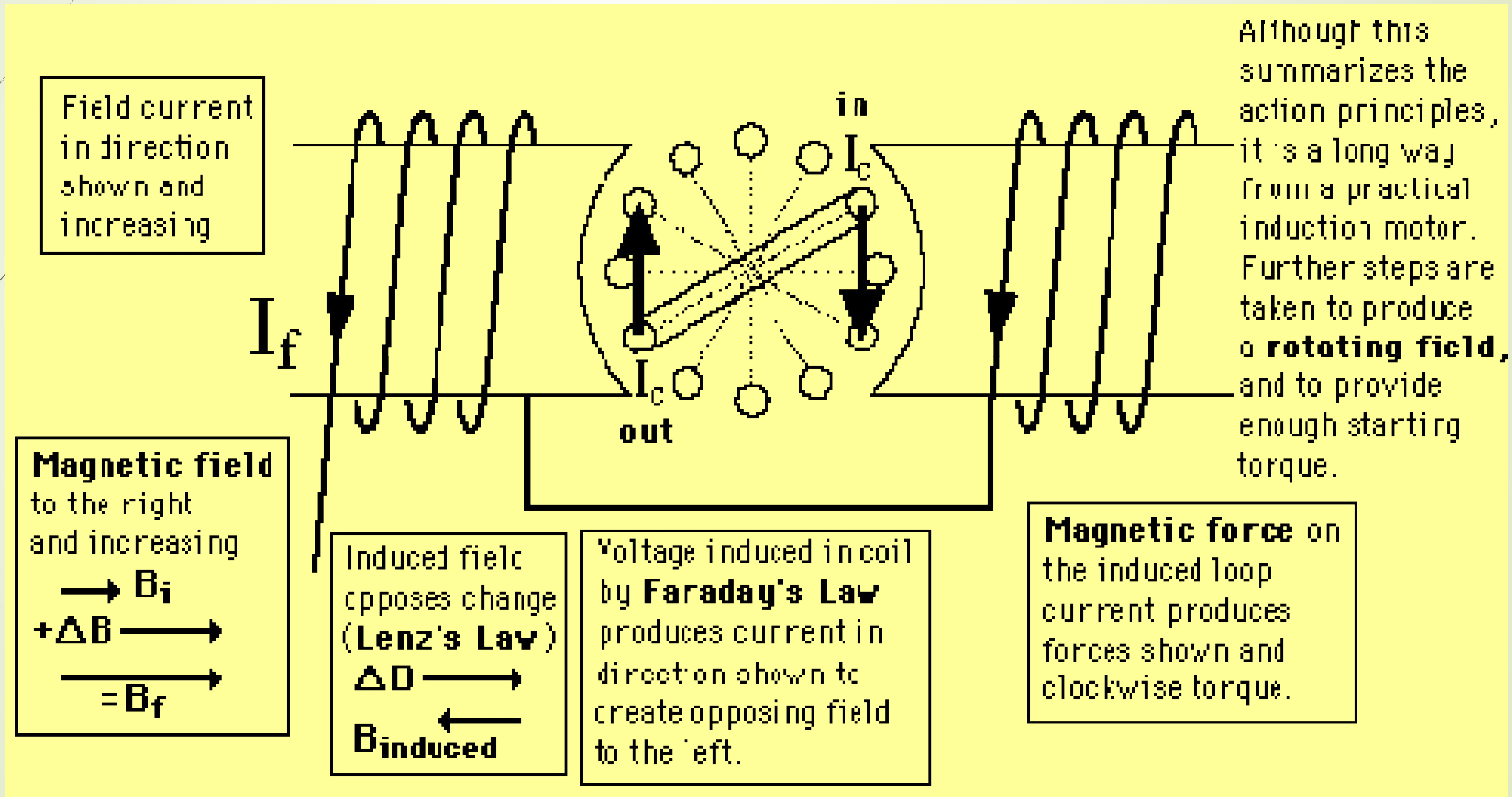
Induction Motor: Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = kB_R \times B_s$$

- Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction in Armature Coils



Induction motor: Slip Speed

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

The Concept of Rotor Slip

- The voltage induced in a rotor bar of an induction motor depends on the speed of the rotor relative to the magnetic fields

1. **Slip speed** – defined as the difference between synchronous speed (magnetic field's speed) and rotor speed.

$$\boxed{n_{slip} = n_{sync} - n_m}$$

Where

n_{slip} = slip speed of the machine

n_{sync} = speed of the magnetic fields

n_m = mechanical shaft speed of motor

The Concept of Rotor Slip

- 2. Slip – defined as the relative speed expressed on a per-unit (or sometimes as percentage) basis

$$s = \frac{n_{slip}}{n_{sync}}$$

$$s = \frac{n_{sync} - n_m}{n_{sync}} \quad or \quad s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}}$$

- If the rotor turns at synchronous speed,

  s = 0

- while if the rotor is stationary (standstill),

  s = 1

- Slip may be expressed as a percentage by multiplying the above equation by 100.
- Notice that the slip is a ratio and doesn't have units

The Concept of Rotor Slip

- % Slip is defined as;

$$s = \frac{n_{\text{slip}}}{n_{\text{sync}}}(\times\ 100\%)$$

$$s = \frac{n_{\text{sync}} - n_m}{n_{\text{sync}}}(\times\ 100\%)$$

- This equation can also be expressed in terms of angular velocity ω (radians per second) as

$$s = \frac{\omega_{\text{sync}} - \omega_m}{\omega_{\text{sync}}}(\times\ 100\%)$$

- Mechanical speed (rotor's speed) can be expressed in term of synchronous speed and slip as below:

$$\mathbf{n_m = (1\text{-}s)n_{sync}\ (in\ rpm)}$$

or

$$\mathbf{\omega_m = (1\text{-}s)\ \omega_{sync}\ (in\ rad/s)}$$

Converting X rpm into radian per second :

$$\text{Y radian per second (rps)} = X\,\frac{\text{rev}}{\text{min}} \times \frac{2\pi\,\text{rad}}{1\,\text{rev}} \times \frac{1\ \text{min}}{60\ s}$$

The Electrical Frequency on the Rotor

- The rotor frequency can be expressed as

$$f_{re} = sf_{se}$$

where

fr = rotor frequency

s = slip

fe = electrical frequency

$$f_{re} = \frac{n_{sync} - n_m}{n_{sync}} f_{se}$$

But $n_{sync} = 120 f_{se} / P$ [from Equation (6–1)], so

$$f_{re} = (n_{sync} - n_m) \frac{P}{120 f_{se}} f_{se}$$

Therefore,

$$\boxed{f_{re} = \frac{P}{120} (n_{sync} - n_m)}$$

- Alternative to find fr is defined as below:

$$f_{re} = \frac{P}{120} (n_{sync} - n_m)$$

Example 1

- A 208V, 10hp, 4 pole, 60Hz, Y connected induction motor has full load slip of 5%.

Calculate,

i) n_{sync} (Ans:1800rpm)

ii) n_m (Ans: 1710rpm)

iii) f_r at the rated load (Ans: 3 Hz)

iv) Shaft torque at the rated load (Ans: 41.7Nm)

Solution

1. $$n_{sync} = \frac{120 f_e}{P} = \frac{120(60)}{4} = 1800\ rpm$$

2. $$\begin{aligned} n_m &= (1-s)n_s \\ &= (1-0.05)\times 1800 = 1710\ rpm \end{aligned}$$

3. $$f_r = sf_e = 0.05\times 60 = 3Hz$$

4. $$\begin{aligned} \tau_{load} &= \frac{P_{out}}{\omega_m} = \frac{P_{out}}{2\pi \frac{n_m}{60}} \\ &= \frac{10\,hp\times 746\,watt/hp}{1710\times 2\pi\times(1/60)} = 41.7\ N.m \end{aligned}$$

Example 2

A 220-V, three-phase, two-pole, 50-Hz induction motor is running at a slip of 5 percent. Find:

(a) The speed of the magnetic fields in revolutions per minute

(b) The speed of the rotor in revolutions per minute

(c) The slip speed of the rotor

(d) The rotor frequency in hertz

Solution

(a) The speed of the magnetic fields is

$$n_{sync} = \frac{120 f_e}{P} = \frac{120(50\text{ Hz})}{2} = 3000\text{ r/min}$$

(b) The speed of the rotor is

$$n_m = (1 - s)\, n_{sync} = (1 - 0.05)(3000\text{ r/min}) = 2850\text{ r/min}$$

(c) The slip speed of the rotor is

$$n_{slip} = s n_{sync} = (0.05)(3000\text{ r/min}) = 150\text{ r/min}$$

(d) The rotor frequency is

$$f_r = \frac{n_{slip} P}{120} = \frac{(150\text{ r/min})(2)}{120} = 2.5\text{ Hz}$$