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Lecture 1

EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

Topics

1. AC Machines
   i. Induction Motors
2. DC Machines
   i. DC Machinery Fundamentals
   ii. DC Motors
   iii. DC Generators

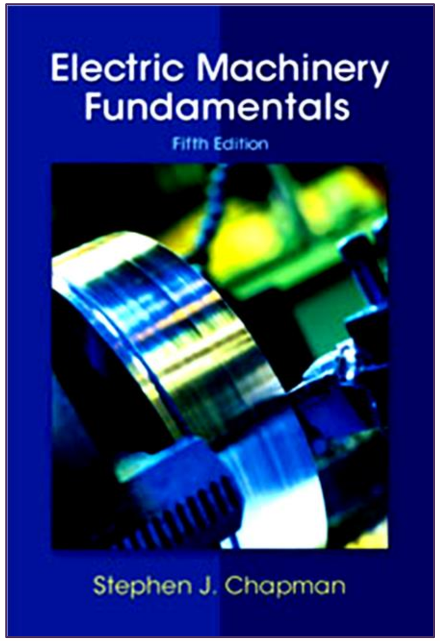
Books

❖ Main textbook

- Stephen J. Chapman, **Electric Machinery Fundamentals**, 5th Edition, McGraw Hill, (TK2000.C466 2012)

❖ Reference textbook

- Theodore Wildi, **Electrical Machines, Drives and Power Systems**, 6th Edition, Pearson, (TK2182.W673 2006)



Learning Objectives

By the end of this lecture, you should be able to:

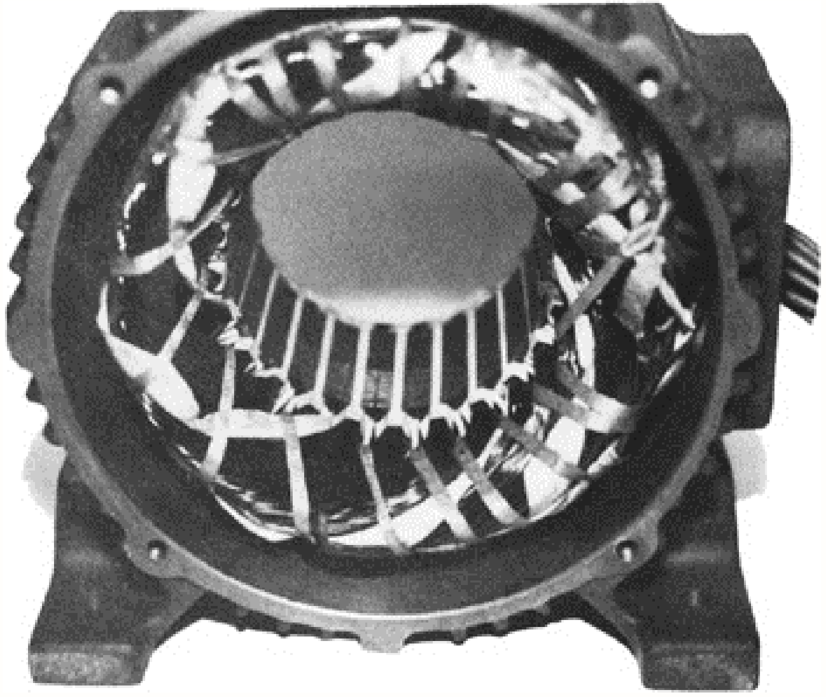
- Describe the basic structure of an induction motor.
- Explain how a rotating magnetic field is created from the three-phase stator.
- Determine and apply the relationships between electrical frequency, the number of poles, and the rotational speed of an induction motor.
- Interpret the concept of slip and its relationship to rotor frequency.

Introduction to Induction Motors

- The induction motor was invented by Nikola Tesla (1856-1943).
- Three-phase induction motors are the motors most frequently encountered in the industry.
- They are simple, rugged, easy to maintain and are less expensive than DC motors of equal power and speed ratings.

Stationary Stator

- It essentially consists of a steel frame housing, and the 3-phase stator windings which are displaced from each other by 120 degrees.
- The windings are placed in slots cut on the inner surface of the stator frame.
- The windings are connected in either wye or delta configurations.
- Electrical power is supplied to the stator windings.



The stator of a typical induction motor, showing the stator windings. (*Used with courtesy of MagneTek, Inc.*)

Revolving Rotor

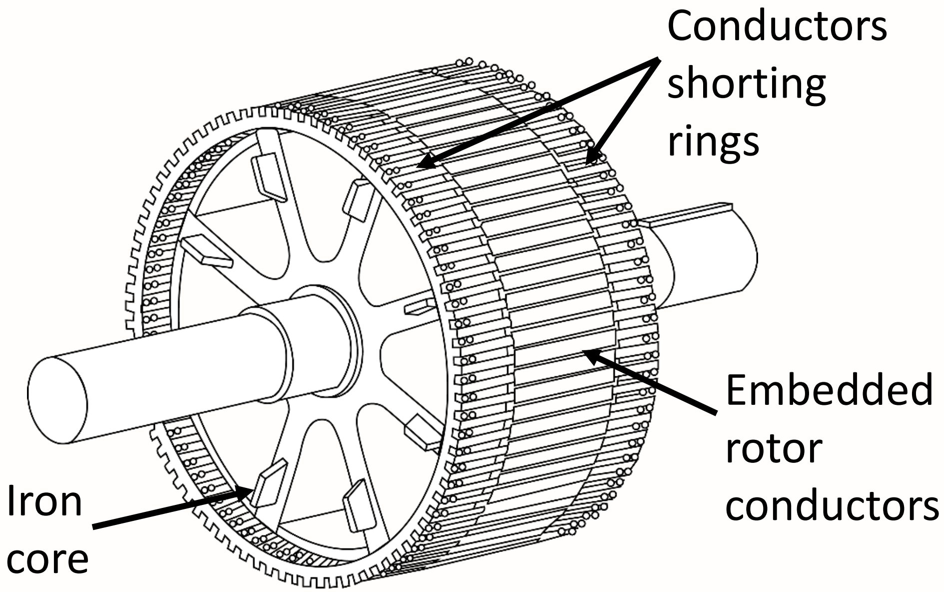
- It composes of punched laminations which are carefully stacked to create a series of rotor slots to provide space for the rotor windings.

- The type of rotor windings gives rise to two main types of motors:

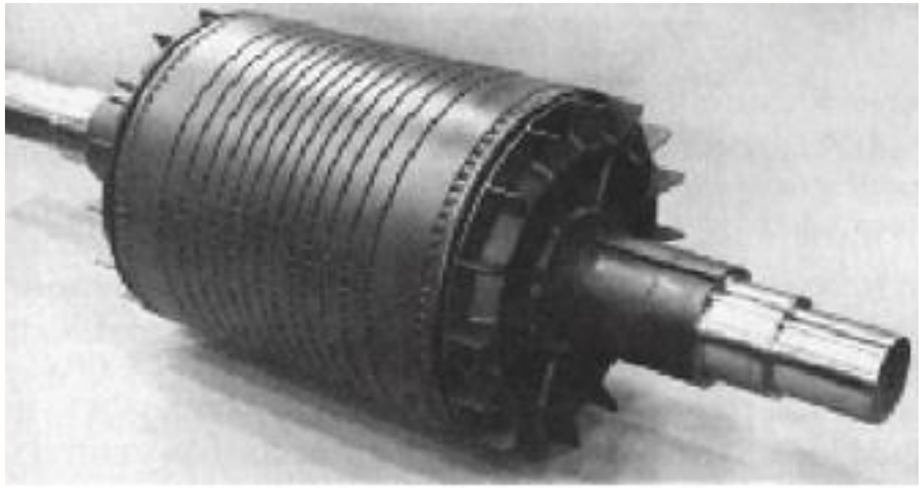
  - Squirrel-cage induction motors

  - Wound-rotor induction motors

Squirrel-cage Rotor



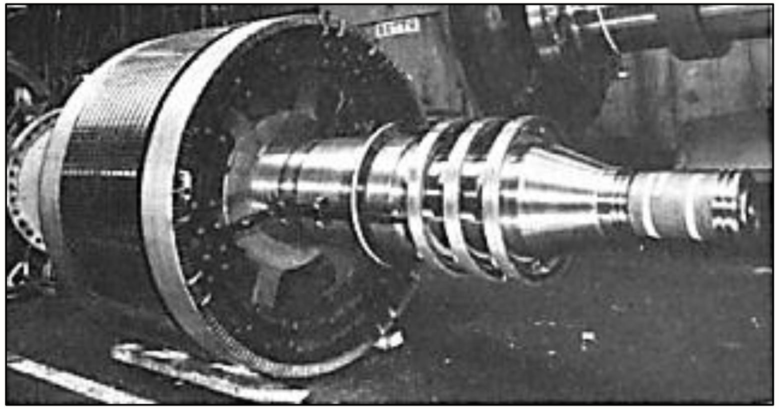
Sketch of squirrel-cage rotor. (*Used with courtesy of General Electric Company*)

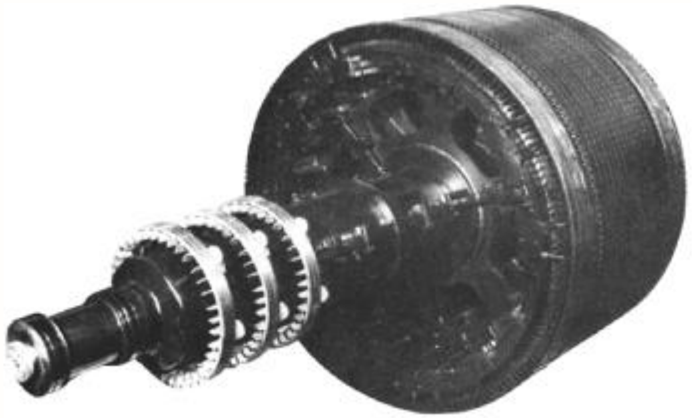


A typical squirrel-cage rotor. (*Used with courtesy of General Electric Company*)

- Series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings.

Wound-Rotor



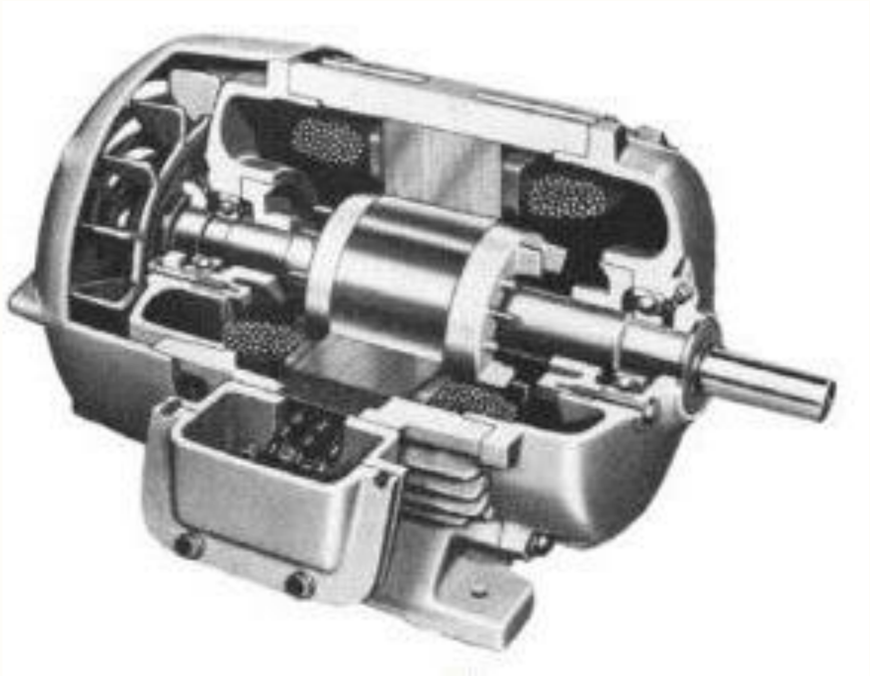


Typical wound-rotors for induction motors. Notice the slip rings.
(*Used with courtesy of General Electric Company*)

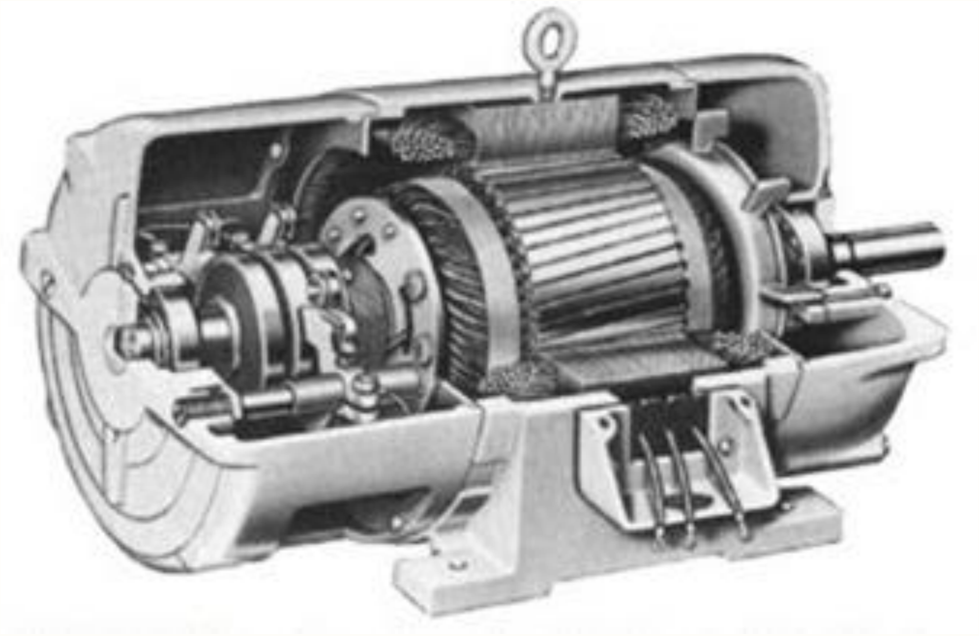
- It consists of a set of 3-phase windings similar to the stator windings and usually wye connected. The ends are tied to slip rings on the rotor's shaft.

- The rotor windings are shorted through brushes riding on the slip rings. This allows external resistors to be connected in series with the rotor windings, to modify the torque-speed characteristics.

Wound-Rotor



Cutaway diagram of a typical squirrel-cage induction motor. (*Used with courtesy of MagneTek, Inc.*)



Cutaway diagram of a typical wound-rotor induction motor. (*Used with courtesy of MagneTek, Inc.*)

Operating Principle of an Induction Motor

- The operating principle of the 3-phase induction motor is very straightforward but unfortunately, the simplicity is obscured by the complicated construction of practical induction motors.
- There is no electrical connections to the rotor. The 3-phase supply is connected to the stator windings.
- The transfer of energy from the stationary member to the rotating member is by means of electromagnetic induction.

Operating Principle of an Induction Motor

- A rotating magnetic field, produced by the stator, induces an alternating emf and current in the rotor. The resultant interaction of the induced rotor current with the rotating magnetic field produces motor torque.

- The torque-speed characteristics is directly related to the resistance and reactance of the rotor.

- Hence, different torque-speed characteristics may be obtained by designing rotor circuits with different ratios of rotor resistance to rotor reactance.

The Rotating Magnetic Field

❖ In a nutshell, the basic principle of all AC motor operation is as follows:

- If two magnetic fields are present in a machine, a torque will be created which will tend to line up the two magnetic fields.

- If one magnetic field is produced by the stator of an AC machine and the other one is produced by the rotor of the machine, a torque will be induced in the rotor, which will cause the rotor to turn and align itself with the stator magnetic field.

- If there are some ways to make the stator magnetic field rotate, the induced torque in the rotor would cause it to constantly "chase" the stator magnetic field around in a circle.

The Rotating Magnetic Field

- How can the stator magnetic field be made to rotate?
- The fundamental principle of AC machine operations:

  If a 3-phase set of currents, each of equal magnitude and differing in phase by 120 degrees, flows in a three-phase windings, then it will produce a rotating magnetic field of constant magnitude.

The Rotating Magnetic Field

- The following demonstrates the above:
  - Three coils spaced 120 electrical degrees apart.
  - A balanced 3-phase currents are applied to them.

$$i_a(t) = I_{\max} \sin(\omega t)\text{A}$$

$$i_b(t) = I_{\max} \sin(\omega t - 120^\circ)\text{A}$$

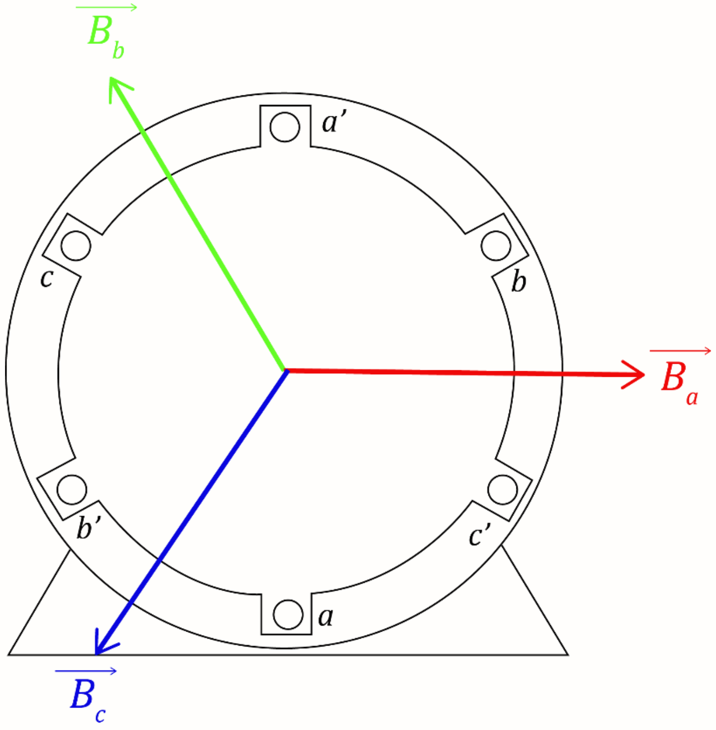
$$i_c(t) = I_{\max} \sin(\omega t - 240^\circ)\text{A}$$

$$\omega = 2\pi f_s \ ,$$

f_s is the frequency of the supply at the stator

The Rotating Magnetic Field

- The currents will establish three time-varying magnetic field intensity and hence magnetic flux density vectors given by



$$\mathbf{B}_a = \hat{B}_a \angle 0^\circ \text{ T}$$

$$\mathbf{B}_b = \hat{B}_b \angle 120^\circ \text{ T}$$

$$\mathbf{B}_c = \hat{B}_c \angle 240^\circ \text{ T}$$

$$\hat{B}_a = B_{\max} \sin(\omega t)$$

$$\hat{B}_b = B_{\max} \sin(\omega t - 120^\circ)$$

$$\hat{B}_c = B_{\max} \sin(\omega t - 240^\circ)$$

The current flows into the *a* end and out of the *a'* end of the coil.

The Rotating Magnetic Field

- The resultant net magnetic flux density in the stator is the sum of the individual flux density.

$$\mathbf{B}_{net} = \mathbf{B}_a + \mathbf{B}_b + \mathbf{B}_c$$

$$= 1.5 B_{\max} \angle (\omega t - 90^\circ)\,\mathrm{T}$$

- We can examine its value at specific instant of time.

$$\text{At } \omega t = 0^\circ, \mathbf{B}_{net} = 1.5 B_{\max} \angle (-90^\circ)\,\mathrm{T}$$

$$\text{At } \omega t = 90^\circ, \mathbf{B}_{net} = 1.5 B_{\max} \angle 0^\circ\,\mathrm{T}$$

- The magnitude of the field is *constant*.
- It rotates counter-clockwise at an angular velocity.
- The speed of the rotating flux is called *synchronous speed,* ω_{sync} rad/s.

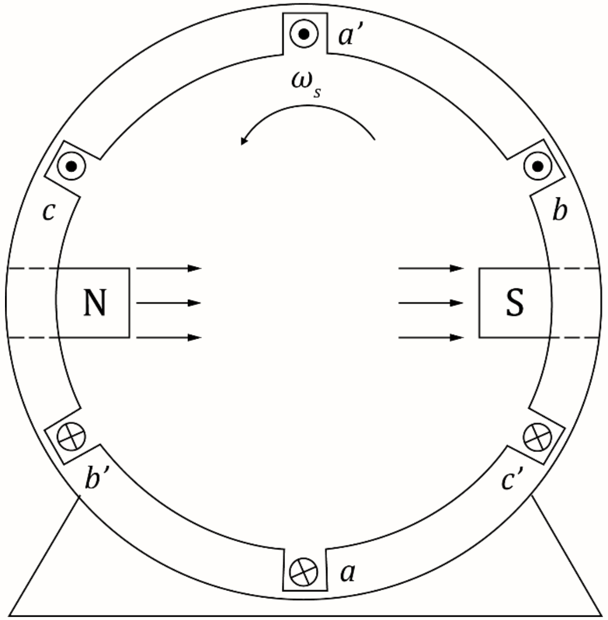
The Rotating Magnetic Field – Two-pole

- The rotating magnetic field in a stator represented as moving north and south stator poles – **two-pole**.
- The poles complete one complete mechanical rotation around the stator surface for each electrical cycle of the applied current.
- Therefore, the mechanical speed of rotation of the magnetic field in revs per sec is equal to the electric frequency in hertz.

$$\omega_{sync} = \omega \text{ rad/s}$$

$$\Rightarrow n_{sync}\left(\frac{2\pi}{60}\right) = 2\pi f_s$$

$$\Rightarrow n_{sync} = \frac{120 f_s}{2} \text{ rpm}$$



Two-pole rotating magnetic field.

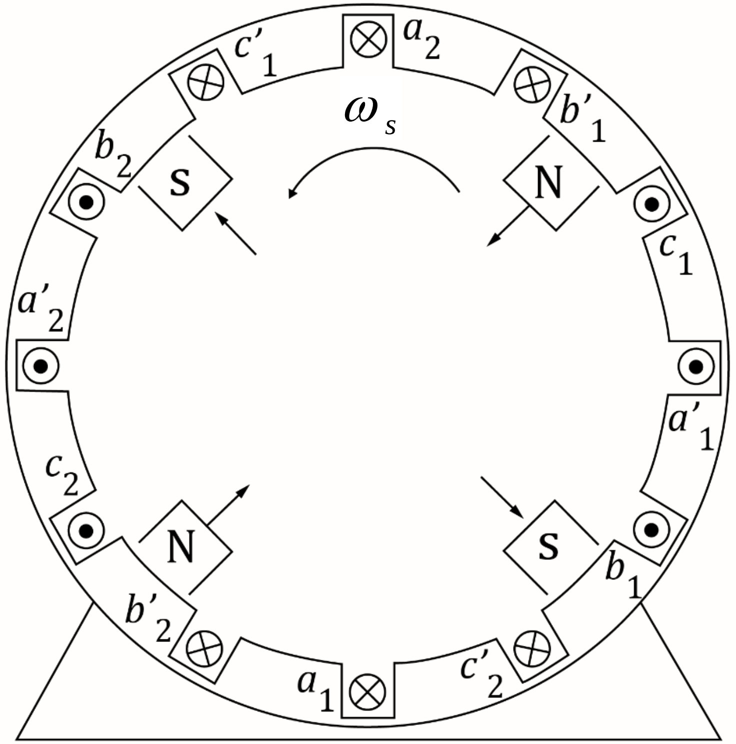
The Rotating Magnetic Field – Four-pole

- In the **four-pole** stator rotating magnetic field, the stator windings are doubled. In this case, each pole moves halfway around the stator surface in one electrical cycle.

- The electrical frequency of the current is twice the mechanical frequency of rotation.

$$2\omega_{sync} = \omega$$

$$\Rightarrow n_{sync} = \frac{120 f_s}{4}$$



Four-pole rotating magnetic field.

The Rotating Magnetic Field

Therefore,

$$n_{sync} = \frac{120\, f_s}{p}$$

where

$f_s =$ frequency of the 3-phase supply in Hz

$n_{sync} =$ synchronous speed, i.e., the speed of the rotating flux in r/min

$p =$ number of poles formed by the stator winding

Example 1

Determine the synchronous speed of a six-pole, 460 V, 60 Hz induction motor if the frequency is reduced to 85 percent of its rated value.

$$n_{sync} = \frac{120 f_s}{p}$$

$$= \frac{120(60)(0.85)}{6}$$

$$= 1020 \text{ r/min}$$

Remarks

- The rotor consists of either conductor bars or windings.
- As the stator magnetic field rotates, by Faraday's law, a voltage is induced in the rotor conductors and a current flows in its closed circuit. Thus, an electromagnetic torque will be produced.
- As a result, the rotor starts rotating in the direction of the revolving magnetic field, and ultimately reaches a steady-state speed which is close to the synchronous speed.

Remarks

- The rotor speed can never be equal to the synchronous speed.
- If the rotor did turn at the same speed as the field (synchronous speed), the flux would no longer cut the rotor bars and the induced voltage and current would fall to zero. Under these conditions, the force acting on the rotor bars would also become zero, and the friction and windage would immediately cause the rotor to slow down.
- An induction motor can, thus, speed up to near-synchronous speed, but it can never exactly reach synchronous speed.

Concept of Rotor Slip

- The voltage induced in the rotor bar depends on the speed of the rotor relative to the magnetic fields. Two terms are used to define the relative motion of the rotor and magnetic fields.

a) Slip speed: $n_{slip} = n_{sync} - n_m$

$$\text{where } n_{slip} = \text{slip speed of the machine, r/min}$$
$$n_{sync} = \text{speed of the magnetic field, sync speed, r/min}$$
$$n_m = \text{mechanical shaft speed of motor, r/min}$$

Concept of Rotor Slip

b) Slip:

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

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

$$\boxed{\begin{aligned} n_m &= (1-s)n_{sync} \\ \omega_m &= (1-s)\omega_{sync} \end{aligned}}$$

$s = 0 \Rightarrow$ rotor turns at synchronous speed

$s = 1 \Rightarrow$ rotor is stationary

Electrical Frequency on the Rotor

- An induction motor works by inducing voltages and currents in the rotor of the machine – sometimes called a rotating transformer.

- Unlike a transformer, the rotor (secondary) frequency is not the same as the stator (primary) frequency.

$$s = 0 \Rightarrow n_m = n_{sync},\ f_r = 0$$

$$s = 1 \Rightarrow n_m = 0,\ \text{rotor is stationary},\ f_r = f_s.$$

<u>The rotor frequency</u>

$$f_r = s f_s$$

$$f_r = \frac{p}{120}(n_{sync} - n_m)$$

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Example 2

A 208 V, 10 horse-power (hp), four-pole, 60 Hz, wye-connected induction motor has a full-load slip of 5 percent.

a) What is the synchronous speed of the motor?

b) What is the rotor speed of this motor at the rated load?

c) What is the rotor frequency of this motor at the rated load?

d) What is the shaft torque of this motor at the rated load?

(Solutions →)

Example 2 - Solutions

a) $n_{sync} = \dfrac{120 f_s}{p} = \dfrac{120(60)}{4} = 1800 \text{ r/min}$

b) $\text{slip, } s = \dfrac{n_{sync} - n_m}{n_{sync}} \Rightarrow 0.05 = \dfrac{1800 - n_m}{1800}$

$\Rightarrow n_m = 1710 \text{ r/min}$

c) $f_r = s f_s = 0.05(60) = 3\,\text{Hz}$

d) $T_{load}\omega_m = P_{out} \Rightarrow T_{load}(1710(2\pi)/60) = 10(746 \text{ W/hp})$

$\Rightarrow T_{load} = 41.7 \text{ N.m}$

Summary

In this lecture, you have learnt:

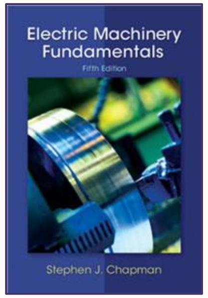
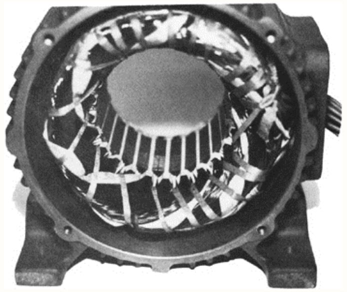
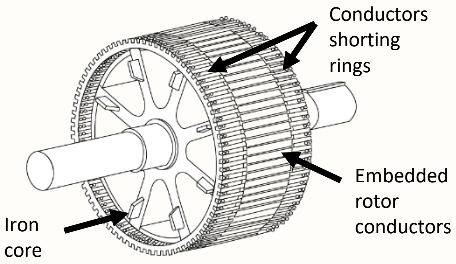
- A rotating magnetic field is produced when the stator is connected to a three-phase supply. Due to transformer action, voltages and currents are induced in the rotor circuit.

- There are two types of induction motors: squirrel-cage and wound-rotor.

- An induction motor operates at near synchronous speed, but never exactly at the synchronous speed.

- The relationships between electrical frequency, number of poles, synchronous speed, rotor speed and slip.

References

No.	Slide No.	Image	Reference
1	4		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (Cover), by S.J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
2	7		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 308), by S.J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
3	9		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 308), by S.J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission

References

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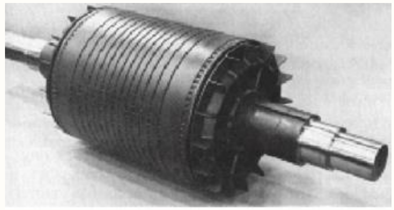
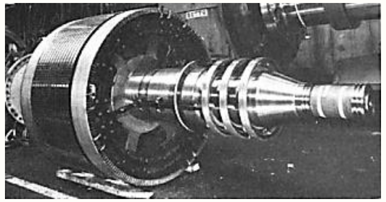
4	9		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 308), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
5	10		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 310), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
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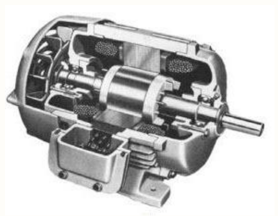
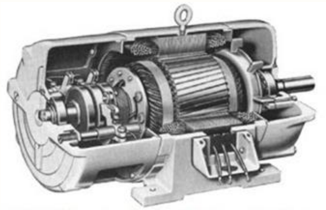
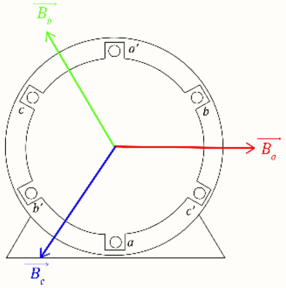
7	11		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 309), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
8	11		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 311), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
9	17		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 161), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.

References

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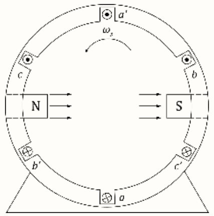
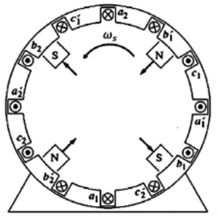
10	19		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 165), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Adapted with permission.
11	20		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 166), by S. J. Chapman, 2012, New York, NY: McGraw Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Adapted with permission.