# 29-Principles of Induction Machines

ECEGR 450
Electromechanical Energy Conversion

## Overview

- Introduction
- Applications
- Three-Phase Induction Motor Rotation
- Slip Speed



## Introduction

- Practical three-phase induction motor invented by Nikola Tesla in 1883
- Induction machines do not require brushes or slip rings
- Induction motors are very common
  - 1/3 of electrical energy consumption
  - Induction generators often used in wind turbine
- "singly-fed" machine (only stator is connected to power)
  - Induction generators may be "doubly fed"



## Applications

- Large range of power ratings
  - Several watts to 40,000 hp
- Can be single phase, two phase, three phase…
  - >5 hp usually three phase
- Typical applications:
  - Washers, dryers, blenders, electric vehicles, fans, pumps



## Applications

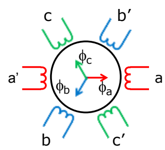
- Advantages:
  - Low cost
  - Simple and rugged construction
  - Low maintenance
  - Appealing torque-speed characteristics
- Disadvantages:
  - consumes reactive power (lagging)
  - speed cannot be easily controlled if connected to fixed-frequency AC source



## Applications

## Induction Motor

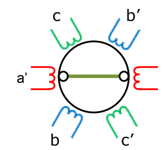
Recall: revolving magnetic field established by connecting armature (stator) windings to three-phase AC source






## Induction Motor

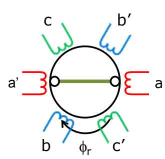
Consider a single rotor coil with shorted terminals






## Induction Motor

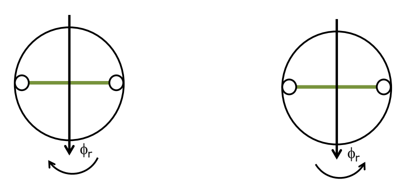
- Assume rotor is locked in place (cannot rotate)
- Net flux through the coil varies with time
  - Voltage induced in rotor, current flows






## Induction Motor

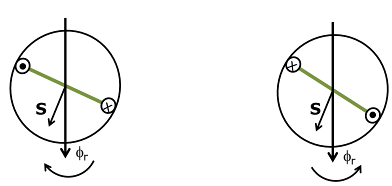
Determine the direction of the induced current for the shown rotational directions of flux.






## Induction Motor

Determine the direction of the torque on the conductors.

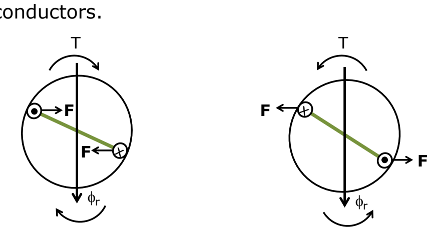



**S • B** increasing   **S • B** decreasing



## Induction Motor

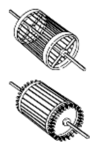
Determine the direction of the torque on the conductors.




Torque is in the same direction as rotating field

## Squirrel Cage Induction Motors

- Most common induction motor type
- Rotor made of solid conductors shorted through end rings
  - Low resistance
  - Promotes high current flow
  - No external connection





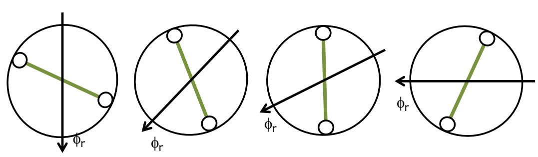
## Wound Rotor Induction Motors

- Rotor wound with phases
- Slip rings used to connect rotor to external stationary circuit
- Greater control of motor
  - often used in induction generators




## Induction Motor

- Now assume rotor rotates at synchronous speed $N_s$ (same speed as rotating field)
- Does any current flow?






## Three-Phase Induction Motor

- The rotor must rotate at a <u>different speed than the synchronous speed</u>
  - rotor speed < synchronous (motor)
  - rotor speed > synchronous (generator)
- If it rotated at the same speed, the flux through the closed would be constant and no emf would be induced
- Rate of change of flux through coil is difference between field speed and mechanical speed
- For this reason, induction motors are known as <u>asynchronous motors</u>



## Three-Phase Induction Motor

- The rotor speed is dependent on the load (torque)
- As load increases the rotor will start to slow down
- As it slows down, the rate of change of the flux through the closed loop increases, resulting in greater current and hence greater applied torque
- The rotor will speed up until the load torque equals the applied torque



## Slip Speed

- Slip speed: difference in synchronous speed and rotor speed
  - Relative speed of the revolving flux ahead of the rotor

$$N_r = N_s - N_m$$
$$\omega_r = \omega_s - \omega_m$$

- $N_r$: slip speed (rpm)
- $N_m$: rotor speed (rpm)
- $\omega_r$: slip speed (rpm)
- $\omega_m$: rotor speed (rpm)

## Slip

Slip of a motor is:

$$s = \frac{\omega_r}{\omega_s} = \frac{\omega_s - \omega_m}{\omega_s} = \frac{N_s - N_m}{N_s}$$

Note: slip is often expressed as a percent

0.5 slip = 50% slip



## Three-Phase Induction Motor

Compute the synchronous speed of a 4-pole, 50 Hz three phase induction motor. What is the percent slip if the rotor rotates at 1200 RPM?



## Three-Phase Induction Motor

Compute the synchronous speed of a 4-pole, 50 Hz three phase induction motor. What is the percent slip if the rotor rotates at 1200 RPM?

$$N_s = \frac{120f}{P} = \frac{120(50)}{4} = 1500 \text{ rpm}$$

$$s = 100 \times \frac{N_s - N_m}{N_s} = 20\%$$



## Induced Voltage

- Voltage induced in rotor depends on rate of change of flux
- The closer to synchronous speed the rotor rotates, the smaller the change in flux
- Induced voltage in the rotor: $\mathbf{E}_r = s\mathbf{E}_b$
  - $\mathbf{E}_r$: induced voltage in the rotor (V)
  - $\mathbf{E}_b$: induced voltage in the rotor at standstill (V)
  - s: slip



## Example

- A 2-pole induction motor is connected to a 60 Hz three phase AC supply. The maximum flux through the rotor is 0.1 Wb. Assume the rotor has a single, full-pitch coil with 10 turns.
- Compute the magnitude of the induced voltage if:
  - The rotor is locked in place
  - The rotor rotates at 3500 rpm
  - The rotor rotates at 3000 rpm



## Example

- A 2-pole induction motor is connected to a 60 Hz three phase AC supply. The maximum flux through the rotor is 0.1 Wb. Assume the rotor has a single, full-pitch coil with 10 turns.

$$|\mathbf{e}| = \frac{\omega_e \times \phi_p \times N_c \times s}{\sqrt{2}} = \frac{2\pi \times 60 \times 0.1 \times 10 \times 1}{\sqrt{2}} = 266.6\text{V}$$

$$|\mathbf{e}| = \frac{\omega_e \times \phi_p \times N_c \times s}{\sqrt{2}} = \frac{2\pi \times 60 \times 0.1 \times 10 \times 0.028}{\sqrt{2}} = 7.4\text{V}$$

$$|\mathbf{e}| = \frac{(\omega_e - \omega_m) \times \phi_p \times N_c \times s}{\sqrt{2}} = \frac{2\pi \times 60 \times 0.1 \times 10 \times 0.17}{\sqrt{2}} = 44.4\text{V}$$

## Summary

- Induction motors are the “workhorse” of the industry
- Synchronous revolving field induces current in rotor circuit
- Rotor rotates in direction of revolving field
- Rotor rotates at different speed than field
- Percent difference in speed is called “slip”
  - Higher the slip, the slower the rotation of the rotor