Chapter 13: Three-Phase Induction Motors
Introduction

• Three-phase induction motors are the most common and frequently encountered machines in industry
  – simple design, rugged, low-price, easy maintenance
  – wide range of power ratings: fractional horsepower to 10 MW
  – run essentially as constant speed from zero to full load
  – speed is power source frequency dependent
    • not easy to have variable speed control
    • requires a variable-frequency power-electronic drive for optimal speed control
  – two basic design types
    • squirrel-cage
    • wound-rotor
Principal Machine Components

• An induction motor has two main parts
  – a stationary stator
    • consisting of a steel frame that supports a hollow, cylindrical core
    • core, constructed from stacked laminations, having a number of evenly spaced slots, providing the space for the stator winding
  – 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)
Operating Principles

- As with all machines, the induction motor operation is based on Faraday’s law and the Lorentz force on a conductor
  - consider a series of conductors of length $l$, whose extremities are short-circuited by two continuous bars, A and B
  - a permanent magnet is placed just above this conducting ladder structure
  - the magnet moves rapidly to the right at a speed $v$ such that the magnetic flux cuts across the conductors
Operating Principles

- consequently
  - a voltage $E = B l v$ is induced in each conductor as the flux cuts across
  - the induced voltage immediately drive a current $I$ down the conductor underneath the magnet pole, through the end-bars and back through the other conductors
  - the current-carrying conductors that lie in the magnetic field of the permanent magnet experience a mechanical force, $\mathbf{F} = \mathbf{I} \times \mathbf{B}$
  - the mechanical force always acts in a direction to drag the conductor along with the magnetic field movement
- with freedom to move, the conducting ladder accelerates to the right
  - as the ladder structure picks up speed, the conductors will be cut less rapidly by the moving magnet
  - the magnitudes of the inducted voltage $E$ and the driven current $I$ will diminish
  - as a result, the mechanical force will also decrease
Operating Principles

• In an induction motor
  – the ladder is closed upon itself to form a squirrel-case
  – the moving permanent magnet is replace by a rotating magnetic field
  – the rotating field is produced by the three-phase ac current that flows in the stator windings
The Rotating Field

- Consider a simple stator with 6 salient poles, each with a coil
  - coils on diametrically opposite sides are connected in series (see previous page)
    - the two coils are connected to produce mmf’s that act in the same direction
    - creates three identical sets of windings, labeled AN, BN, CN
    - mechanically spaced at 120 degrees to each other
  - the three windings are wye-connected, with a common neutral
    - line-to-neutral impedances are equal, constituting a balanced load
    - the line currents are displaced in time by 120 degrees
    - assume a positive sequence rotation: phases sequence = ABC
  - the magneto-motive force is in-phase with the line currents
    - the mmf’s are displaced in time by 120 degrees
    - the mmf’s are displaced around the stator by 120 mechanical degrees
The Rotating Field

- the total mmf within the stator hollow space is the sum of the three phase mmf’s
  - the resulting mmf is a magnetic field that varies in time and space
  - the magnitude of the total mmf is constant
  - the direction of the mmf revolves around the center axis of the stator
Direction of Rotation

- The positive crests of the currents in a positive ABC phase sequence follow each other in the order $A \rightarrow B \rightarrow C \rightarrow A$
  - this phase sequence produces a magnetic field that rotates clockwise for windings arranged ABC in a clockwise layout around the stator
  - changing either the phase sequence or the winding layout will cause the magnetic field to rotate in the opposite direction

- Salient pole are never used; instead, the stator surface is smooth with slots cut into the stator to hold the windings
  - in practice the use of a single coil per pole is subdivided into 2, 3, or more coils lodged in adjacent slots, constituting a phase group
Synchronous Speed

- The number of poles controls the synchronous speed
  - each 3-phase pole grouping covers a given mechanical angle
  - as the number of poles increase, the angular movement of the revolving flux decreases for one cycle of ac current
  - the number of cycles for the revolving flux to make one complete mechanical rotation is proportional to the pole count

- The speed of rotation for the flux field depends upon both the frequency of the source and the number of poles on the stator

\[ n_s = \frac{120f}{p} \]

where
- \( n_s \) = synchronous speed
- \( f \) = power source frequency
- \( p \) = number of poles

- the synchronous speed increases with frequency and decreases with the number of poles
Synchronous Speed

- Example
  - a three-phase induction motor has 20 poles
  - the motor is connected to a 50 Hz power source
  - calculate the synchronous speed
Starting Characteristics

• Consider the stator of an induction motor connected to a 3-phase source

• let the rotor be locked in a stationary position
  – the revolving magnetic field produced by the stator cuts across the rotor bars and induces a voltage in all the conducting bars
  – the induced voltage is ac because of the rapid succession of time varying flux from N to S to N, etc. (transformer action)
  – the frequency of the induced voltage depends on the number of N and S poles that sweep across a conductor per second
    • at rest (zero speed), it is always equal to the source frequency
  – the end-rings form a three-phase short circuit and the induced voltage drives a large current through all the bars (typically 100’s of amps)
  – the large currents react with the stator magnetic field creating strong forces
  – the sum of all mechanical forces produce a torque on the rotor
Rotor Acceleration

• As soon as the rotor is released
  – the torque causes rapid acceleration in the direction of the rotating flux field
  – the rotor speed increases and the relative velocity of the magnetic field with respect to the rotor progressively diminishes
    • the frequency and the magnitude of the induced voltage decreases because the rotor bars are being cut more slowly
    • as a result, the very large rotor current decreases rapidly with increased rotor speed
    • the mechanical forces and torque weaken
  – the speed continues to increase asymptotically to the speed of the rotating flux (synchronous speed)
    • at synchronous speed, the rotor would no longer cut any flux
    • zero induced voltages, zero current, zero force, zero torque
Applying Loads

- Consider a motor initially running at no-load
  - the produced torque is assumed equal to zero
- A mechanical load is connected to the rotor shaft
  - a counter-torque causes a decrease in rotor kinetic energy and a slow down of the rotor speed
  - the relative speed between the rotor and the rotating flux (at synchronous speed) increases
    - the flux cuts the conducting bars at a higher and higher rate
    - frequency and magnitude of the induced voltage increases
    - the larger induced voltage drive more current in the rotor circuit
    - the current and flux react to produce greater drive torque
- The rotor speed and the mechanical load will reach a state of equilibrium
  - the motor torque will equal the load counter-torque
  - the speed will be stable
Slip

- Slip is the ratio of the speed difference between the synchronous speed and the actual rotor speed to the synchronous speed
  
  \[ s = \frac{n_s - n}{n_s} \]

where

- \( s = \text{slip} \)
- \( n_s = \text{synchronous speed} \)
- \( n = \text{rotor speed} \)

- for a rotor at standstill, the slip is unity
- for a rotor spinning at the synchronous speed, the slip is zero
- in most cases the motor slip ranges between 0 and 1
Slip

• Example
  – a one-half horsepower, 6-pole, 3-phase induction motor is connected to a 60 Hz power supply
  – the full-load speed is 1140 rpm
  – calculate the slip
Rotor Circuit

- The voltage and frequency induced in the rotor both depend upon the slip

\[ f_2 = s \cdot f \quad E_2 \approx s \cdot E_{oc} \]

where

- \( f_2 \) = frequency of the voltage in the rotor
- \( f \) = frequency of the power source
- \( s \) = slip
- \( E_2 \) = voltage induced in the rotor at slip \( s \)
- \( E_{oc} \) = open-circuit voltage induced in the rotor when at rest
Rotor Circuit

• Example
  – a one-half horsepower, 6-pole, 3-phase induction motor is connected to a 60 Hz power supply
  – calculate the frequency of the rotor current under the following conditions
    • at standstill
    • at a shaft speed of 500 rpm rotating in the same direction as the revolving field
    • at a shaft speed of 500 rpm rotating in the opposite direction of the revolving field
    • at a shaft speed of 2000 rpm rotating in the same direction as the revolving field
Three-phase Induction Motors

• Homework