

METE 3100U
Actuators and Power Electronics

Lecture 16
Induction Machines 1/2

Outline of Lecture 16

By the end of today's lecture, you should be able to

- Understand the working principle of induction machines
- Model an induction machine
- Estimate the speed of an induction machine

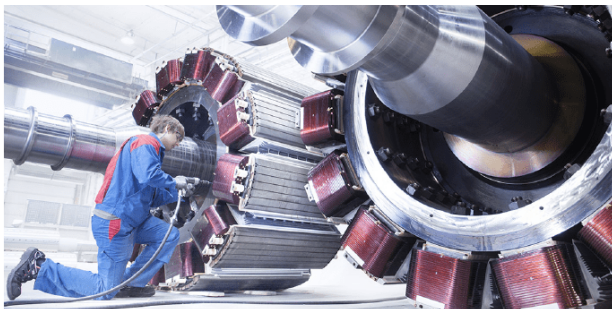
Applications

90 percent of motors used in industrial settings are induction motors. What are their advantages?



Applications

General Electric has developed one of the world's largest two-pole induction motor.



Applications

Miniature induction motors are used in blenders, lawn mowers, juice makers, washing machines, refrigerators, stereo turn tables, ...

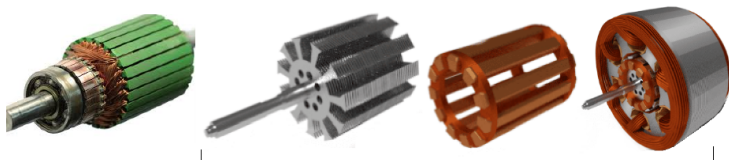


Induction machines

Stator: Laminations of high-grade steel with a 3-phase winding



Rotor: Squirrel-cage or wound type



Operating principle

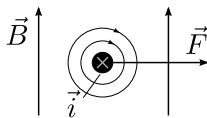
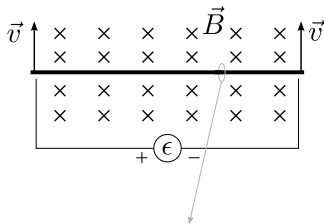
Faraday's law: A voltage is induced in the moving conductor:

$$\vec{\epsilon} = \ell \vec{v} \times \vec{B}$$

The interaction between the magnetic field B and the current generates a force

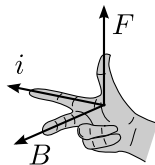
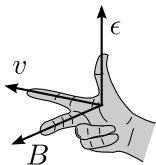
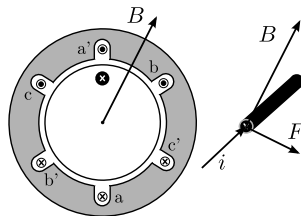
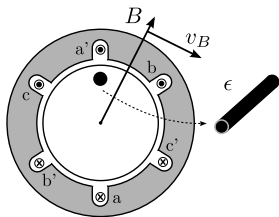
$$\vec{F} = i \vec{\ell} \times \vec{B}$$

A torque is produced as a result of the interaction of those two magnetic fields

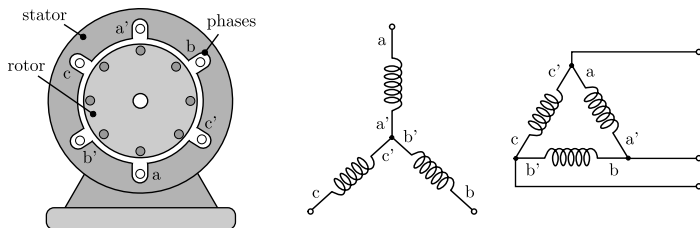


Torque

The torque is induced in the direction of the rotating field B



Induction machines



The current in each coil is shifted by 120° :

$$i_a = I_m \cos(\omega t)$$

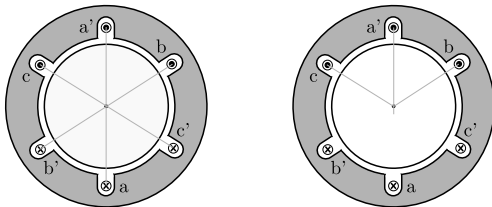
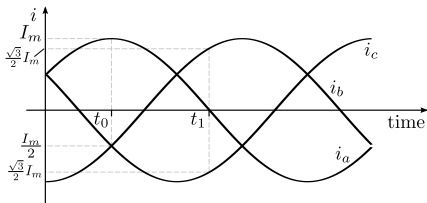
$$i_b = I_m \cos(\omega t - 120^\circ)$$

$$i_c = I_m \cos(\omega t + 120^\circ)$$

where I_m is the maximum current.

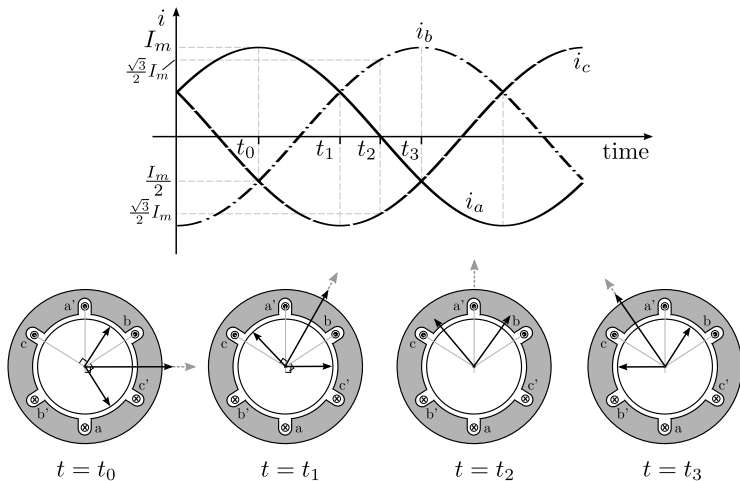
Rotating magnetic field

The current in each coil produces a rotating mmf wave

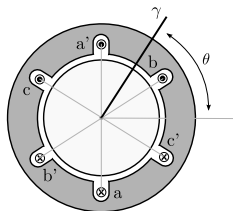
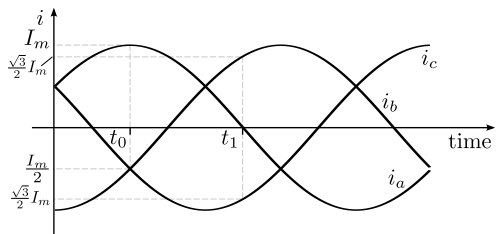


Rotating magnetic field

The current in each coil produces a rotating mmf wave



Rotating magnetic field



The contribution of each phase on the mmf along an axis γ is

$$F_a(\theta) = Ni_a \cos(\theta)$$

$$F_b(\theta) = Ni_b \cos(\theta - 120^\circ)$$

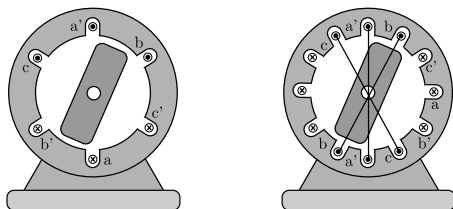
$$F_c(\theta) = Ni_c \cos(\theta + 120^\circ)$$

The resultant mmf along γ is

$$F(\theta) = F_a + F_b + F_c \quad (1)$$

Synchronous speed

Synchronous speed: The speed at which the magnetic field revolves



$$\underbrace{\text{cycles of current}}_f = \frac{p}{2} \times \text{revolutions of field} \quad (2)$$

The speed (rpm) of a p pole machine is

$$n_s = \frac{2}{p} f 60 = \frac{120f}{p} \quad (3)$$

f is the current frequency.

Induced voltage

The rotor current creates a rotating field density

$$B(\theta) = B_{max} \cos(\theta)$$

The air gap flux per pole with area A is

$$\Phi_p = BA$$

Thus, the flux linkage in coil a is

$$\lambda_a(\omega t) = N\Phi_p \cos(\omega t)$$

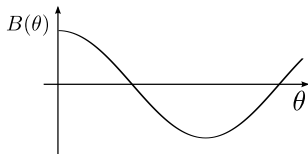
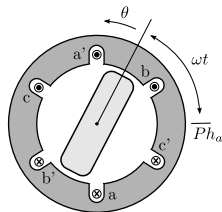
and the induced voltage is

$$\epsilon_a = -\frac{d\lambda_a}{dt} = \omega N\Phi_p \sin(\omega t) = E_{max} \sin(\omega t)$$

In the other coils, the voltages are

$$\epsilon_b = E_{max} \sin(\omega t - 120^\circ)$$

$$\epsilon_c = E_{max} \sin(\omega t + 120^\circ)$$



Induced voltage

The instantaneous induced voltage is

$$\epsilon_a = \omega N \Phi_p \sin(\omega t) = E_{max} \sin(\omega t)$$

Thus, the rms voltage is

$$\epsilon_{rms} = \frac{\omega N \Phi_p}{\sqrt{2}} = \frac{2\pi f N \Phi_p}{\sqrt{2}} \quad (4)$$

where f is the frequency in Hertz. Thus:

$$\epsilon_{rms} = 4.44 f N \Phi_p \quad (5)$$

Φ_p is the maximum flux per pole. For a distributed phase winding:

$$\epsilon_{rms} = 4.44 f N \Phi_p K_w \quad (6)$$

with a correction factor $0.85 \leq k_w \leq 0.95$.

Rotor speed

The rotor rotates at a lower speed than that of the rotating magnetic field. Why?

Rotor speed: n

Rotating field speed: n_s

Slip factor:

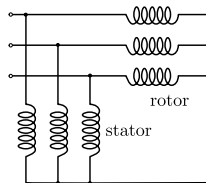
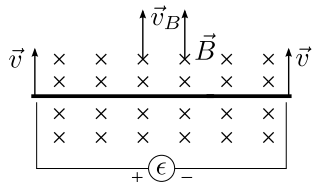
$$s = \frac{n_s - n}{n_s} \quad (7)$$

The electrical frequency in the winding is

$$\begin{aligned} f_1 &= \frac{p}{120} (n_s - n) = \frac{p}{120} s n_s \\ &= s f \end{aligned}$$

The voltages induced in the rotor are

$$\epsilon_{rms} = 4.44 f_1 N \Phi_p K_w \quad (8)$$



Standstill vs slip operation

For $s = 1$ (the rotor does not move) the rotating field induces a voltage in the stator and rotor coils:

$$\epsilon_1 = 4.44fN_1\Phi_p K_1$$

$$\epsilon_2 = 4.44fN_2\Phi_p K_2$$

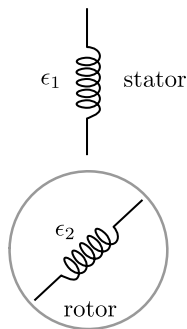
If the rotor and stator coils have each N turns:

$$\frac{\epsilon_1}{\epsilon_2} = \frac{N_1 k_1}{N_2 k_2}$$

with $k_1 \approx k_2$.

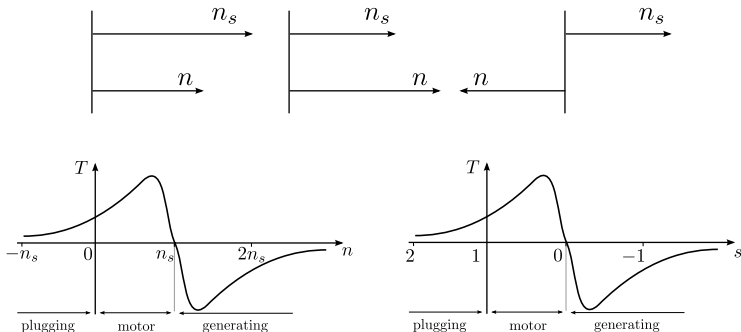
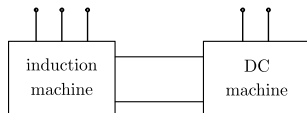
As the rotor moves, the frequency in the stator is $f_1 = sf$, thus

$$\begin{aligned}\epsilon_{2s} &= 4.44(f_1)N_2\Phi_p K_2 \\ &= 4.44(fs)N_2\Phi_p K_2 \\ &= \end{aligned}$$



Operating modes

- Motor: $n < n_s$
- Generator: $n > n_s$
- Braking: $\text{sign}(n) \neq \text{sign}(n_s)$



Exercise 75

A 3-phase, 4 pole, 400 V, 60 Hz induction motor delivers rated output power at a slip of $s = 0.05$.

Determine:

- (a) The synchronous and rotor speeds
- (b) The frequency of the rotor current

Exercise 75 - continued

Exercise 76

A 3-phase, 460 V, 60 Hz, 4-pole Y-connected wound-rotor induction machine has 230 V between the slip rings at standstill. The rotor is connected to a DC motor whose speed can be changed. Determine the magnitude and frequency of the voltage between the slip rings when the induction machine is driven at the following speeds:

- (a) 1620 rpm in the same direction as the rotating field
- (b) 1620 rpm in the opposite direction to the rotating field
- (c) 1800 rpm in the same direction as the rotating field
- (d) 1800 rpm in the opposite direction to the rotating field
- (e) 3600 rpm in the same direction as the rotating field

Exercise 76 - continued

Exercise 76 - continued

Exercise 77

A 3-phase, 208 V, 60 Hz, induction machine runs at 1746 rpm when it delivers rated output power. Determine:

- (a) The number of poles of the machine
- (b) The slip at the full load
- (c) The frequency of the rotor current
- (d) The speed of the rotor field

Exercise 77 - continued

(a) The number of poles of the machine

(b) The slip at the full load

Exercise 77 - continued

(c) The frequency of the rotor current

(d) The speed of the rotor field

Exercise 78

A 3-phase, 460 V, 60 Hz, six-pole induction machine runs at 3% slip (positive) at full load. Determine:

- (a) The speed of the motor
- (b) The rotor frequency
- (c) The speed of the rotor field relative to the rotor structure

Exercise 78 - continued

(a) The speed of the motor

(b) The rotor frequency

(c) The speed of the rotor field relative to the rotor structure

Quiz

Q1 - When an induction motor is at standstill, the slip of the machine will be:

(a) ∞

(b) 1

(c) 0

(d) -1

(e) π

Quiz

Q2 - When an induction motor runs above its synchronous speed, it operates as:

- (a) an induction generator
- (b) and induction reactor
- (c) a motor
- (d) a brake
- (e) an induction reactor

Quiz

Q3 - Which of the following power is supplied to the rotor winding of a 3-phase induction motor

- (a) Single-phase AC supply
- (b) 3-phase AC supply
- (c) DC supply
- (d) PWMed voltage
- (e) No power is given

Quiz

Q4 - A 3-phase induction motor will have a _____ starting torque and a _____ starting current.

- (a) Low, low
- (b) High, high
- (c) High, low
- (d) Low, high
- (e) negative, high

Quiz

Q5 - The rotation direction of a 3-phase induction motor can be reversed by reversing:

- (a) Any two phase connections of the supplying power
- (b) All phase connections of the supplying power
- (c) One phase connection of the supplying power
- (d) The frequency of the supplying power
- (e) The magnitude of the supplying power

Quiz

Q6 - The slip of a 3-phase induction motor should always be:

- (a) Zero
- (b) Greater than 1
- (c) Less than 1
- (d) Equal to 1
- (e) Between -1 and 1

Quiz

Q7 - What happens when an induction motor runs at the synchronous speed?

- (a) It delivers no torque
- (b) It stops
- (c) It generates energy
- (d) It creates reactive power
- (e) It blows up

Next class...

- Synchronous motors

Additional supporting materials for Lecture 16:

Linear induction motors: <https://goo.gl/ayW1YF>

Induction motors for kids: <https://goo.gl/ME71yS>

Induction motors start torque: <https://youtu.be/JPn50u-N0b0>