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Unit: III- Control Strategies

Class-13:
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Presented by
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Subject Name
EE: Modelling and Control of Electric Drives

Discussed in the Previous Class

In the previous class discussed the following topics:

- ❖ Chopper Control of Separately Excited DC Motor
- ❖ Regenerative Braking of Chopper fed Separately Excited DC Motor
- ❖ Motoring and Regenerative Braking of DC Motor
- ❖ Dynamic Braking of DC Motor

Lecture Outcomes

- ❖ Three-phase Induction Motor
- ❖ Regenerative Braking of Chopper fed Separately Excited DC Motor
- ❖ Motoring and Regenerative Braking of DC Motor
- ❖ Dynamic Braking of DC Motor
- ❖ Lecture remarks: Key points of today’s class

Introduction: Three-phase Induction Motor

- The **induction motor** especially **three-phase induction motors** are widely used AC motors to produce mechanical power in industrial applications.

- Almost 80% of the motor is a three-phase induction motor all motors used in industries.

- Therefore, the induction motor is the most important motor among all other types of motor.

- The three-phase supply current produces an electromagnetic field in the stator winding which leads to generating the torque in the rotor winding of a phase induction motor having a magnetic field.

Introduction: Three-phase Induction Motor

The construction of an induction motor is very simple and robust. It has mainly two parts;

1. Stator
2. Rotor

1. Stator

As the name suggests, the stator is a stationary part of the motor. The stator of the induction motor consists of three main parts;

1. Stator Frame
2. Stator Core
3. Stator Winding

Introduction: Three-phase Induction Motor

Stator Frame

- The stator frame is the outer part of the motor.
- The function of the stator frame is to provide support to the stator core and stator winding. It provides mechanical strength to the inner parts of the motor.
- The frame has fins on the outer surface for heat dissipation and cooling of the motor.
- The frame is casted for small machines and it is fabricated for a large machine.
- According to the applications, the frame is made up of die-cast or fabricated steel, aluminum/ aluminum alloys, or stainless steel.

Introduction: Three-phase Induction Motor

Stator Core

- The function of the stator core is to carry the alternating magnetic flux which produces hysteresis and eddy current loss.
- *To minimize these losses, the core is laminated by high-grade steel stampings thickness of 0.3 to 0.6 mm.*
- These stampings are insulated from each other by varnish.
- All stampings stamp together in the shape of the stator core and fixed it with the stator frame.
- An inner layer of the stator core has a number of slots.

Introduction: Three-phase Induction Motor

Stator Winding

- The stator winding is placed inside the stator slots available inside the stator core. Three-phase winding is placed as a stator winding. And three-phase supply is given to the stator winding.

- The number of poles of a motor depends on the internal connection of the stator winding and it will decide the speed of the motor.

- If the number of poles is greater, the speed will less and if the number of poles is lesser than the speed will high.

- The poles are always in pairs. Therefore, the total number of poles always an even number.

Introduction: Three-phase Induction Motor

- The relation between synchronous speed and number poles is as shown in the below equation,

$$\mathbf{N_S = 120\mathit{f} / P}$$

Where;

f = Supply Frequency
P = Total Number of Poles
N_s = Synchronous Speed

Introduction: Three-phase Induction Motor

Rotor

- As the name suggests, the rotor is a rotating part of the motor.

- According to the type of rotor, the induction motor is classified as;

1. **Squirrel Cage Induction Motor**

2. **Phase Wound (Wound Rotor) Induction motor / Slip-ring Induction Motor**

Introduction: Three-phase Induction Motor

Squirrel Cage Induction Motor

- The shape of this rotor is resembling the shape of the cage of a squirrel.
- Therefore, this motor is known as a squirrel cage induction motor.
- The construction of this type of rotor is very simple and rugged.
- So, almost 80% of the induction motor is a squirrel cage induction motor.
- The rotor consists of a cylindrical laminated core and has slots on the outer periphery.
- The slots are not parallel but it is skewed at some angle.

Introduction: Three-phase Induction Motor

Squirrel Cage Induction Motor

- It helps to prevent magnetic locking between the stator and rotor teeth.
- It results in smooth operation and reduces the humming noise.
- It increases the length of the rotor conductor due to this the rotor resistance is increased.
- The squirrel cage rotor consists of rotor bars instead of the rotor winding.
- The rotor bars are made up of aluminum, brass, or copper.

Introduction: Three-phase Induction Motor

Squirrel Cage Induction Motor

- Rotor bars are permanently shorted by end rings.
- So, it makes a complete close path in the rotor circuit.
- The rotor bars are welded or braced with the end rings to provide mechanical support.
- The rotor bars are short-circuited.
- Therefore, it is not possible to add external resistance to the rotor circuit.
- In this type of rotor, the slip rings and brushes are not used.
- Hence, the construction of this type of motor is simpler and more robust.

Introduction: Three-phase Induction Motor

Slip-ring or Wound Rotor Induction Motor

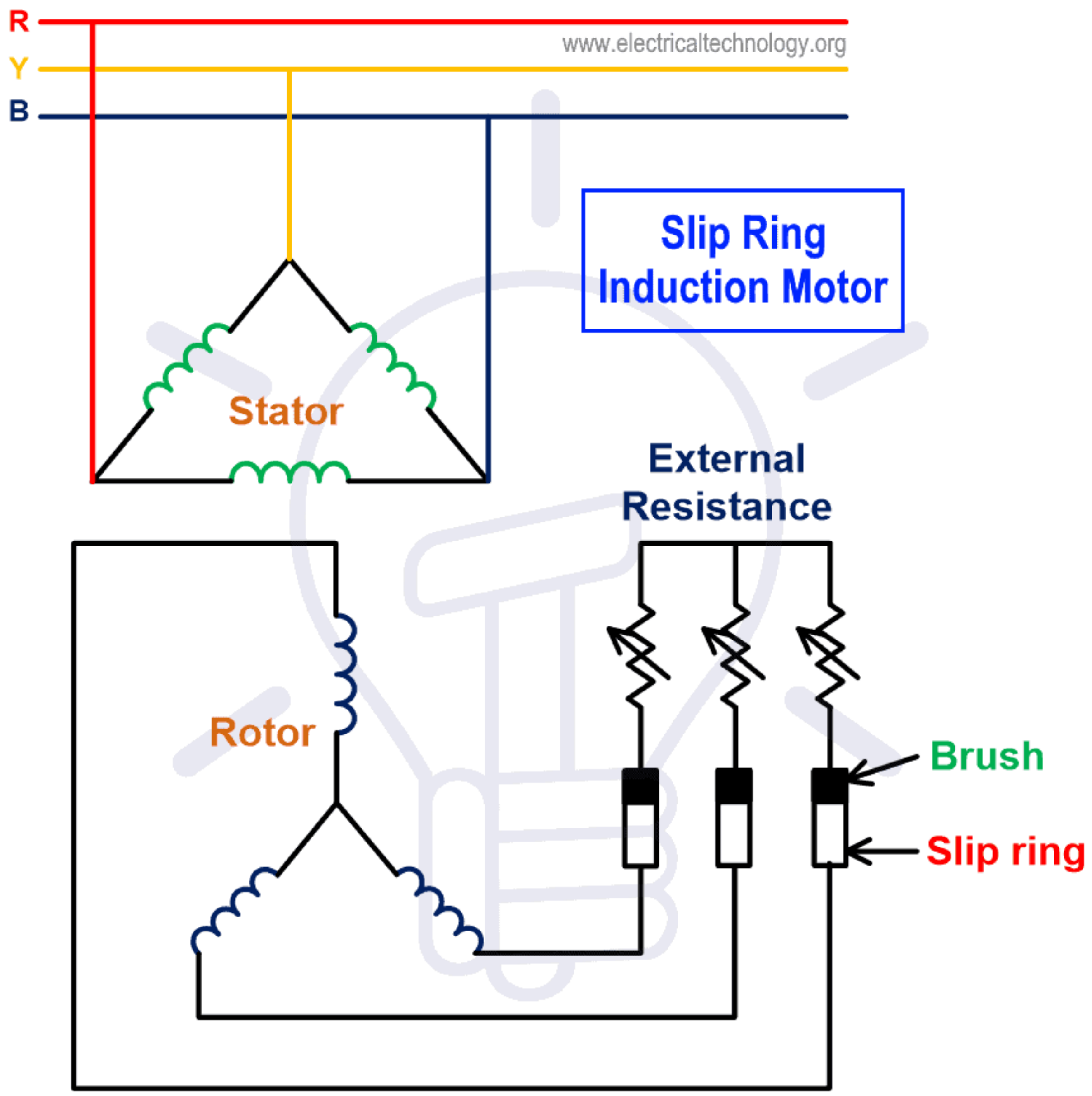
- Slip-ring induction motors are also known as wound rotor motor.
- The rotor consists of a laminated cylindrical core with slots on the outer periphery.
- The rotor winding is placed inside the slots.
- In this type of rotor, the rotor winding is wounded in such a way that, the number of poles of rotor winding is the same as the number of poles of the stator winding.
- The rotor winding can be connected as a star or delta.

Introduction: Three-phase Induction Motor

Slip-ring or Wound Rotor Induction Motor

- End terminals of rotor windings are connected to the slip-rings.
- So, this motor is known as a slip-ring induction motor.
- The external resistance can easily connect with the rotor circuit through the slip-ring and brushes.
- And it is very useful for controlling the speed of the motor and improving the starting torque of the three-phase induction motor.
- An electrical diagram of slip-ring three-phase induction motor with external resistance is shown in the below figure.

Introduction: Three-phase Induction Motor



Introduction: Three-phase Induction Motor

- The external resistance is used only for the starting purpose. If it is remains connected during the running condition, it will increase the rotor copper loss.

- High rotor resistance is good for the starting condition. So, the external resistance is connected with the rotor circuit during the starting condition.

- When motor running near the speed of the actual speed, the slip-rings are short-circuited by the metal collar.

- By this arrangement, the brushes and external resistance is removed from the rotor circuit.

Introduction: Three-phase Induction Motor

- This reduces the rotor copper loss as well as friction in brushes.

- The rotor construction is a little bit complicated compared to the squirrel cage motor due to the presence of brushes and slip-rings.

- The maintenance of this motor is more. So, this motor only used when variable speed control and high starting torque are needed.

- Otherwise, the squirrel cage induction motor is more preferred over slip-ring induction motor.

Introduction: Three-phase Induction Motor

Why the slip is never zero in an induction motor?

- When the actual speed of the rotor is equal to the synchronous speed, the slip is zero. For the induction motor, this condition will never happen.
- Because when the slip is zero, both speeds are equal and there is no relative motion. Therefore, no EMF induced in the rotor circuit and rotor current is zero. Hence, the motor cannot run.
- The induction motor is a widely used motor in industries. Because it has more advantages than disadvantages.

Introduction: Three-phase Induction Motor

The advantages of induction motor

- The construction of a motor is very simple and robust.
- The working of an induction motor is very simple.
- It can operate in any environmental condition.
- The efficiency of the motor is very high.
- The maintenance of an induction motor is less compared to other motors.
- It is a single excited motor. Hence, it needs only one supply of source. It does not require external DC supply for excitation like a synchronous motor.
- The induction motor is a self-starting motor. So, it does not require any extra auxiliaries for the starting purpose for normal operation.
- The cost of this motor is very less compared to other motors.
- The life span of this motor is very high.
- Armature reaction is less.

Introduction: Three-phase Induction Motor

The disadvantages of the motor

- During light load condition, the power factor is very less. And it draws more current. So, the copper loss is more which reduce the efficiency during light load condition.

- The starting torque of this motor (squirrel cage induction motor) is not less.
- The induction motor is a constant speed motor. For the application where variable speed requires, this motor is not used.

- Speed control of this motor is difficult.

- The induction motor has a high starting inrush current. This causes a reduction in voltage at the time of starting.

Introduction: Three-phase Induction Motor

The induction motor is mostly used in industrial applications. The **squirrel cage induction motors** are used in residential as well as industrial applications especially where the speed control of motors is not needed such as:

- Pumps and submersible
- Pressing machine
- Lathe machine
- Grinding machine
- Conveyor
- Flour mills
- Compressor
- And other low mechanical power applications

Introduction: Three-phase Induction Motor

The **slip ring motors** are used in heavy load applications where the high initial torque is needed such as:

- Steel mills
- Lift
- Crane Machine
- Hoist
- Line shafts
- and other heavy mechanical workshops etc.

Analysis and Performance of 3-phase Induction Motor

Analysis and Performance of 3-phase Induction Motor

- Per-phase equivalent circuit of Three three-phase induction motors is shown in Fig. 1.

- R'_r and X'_r are the stator referred values of rotor resistance R_r and rotor reactance X_r.

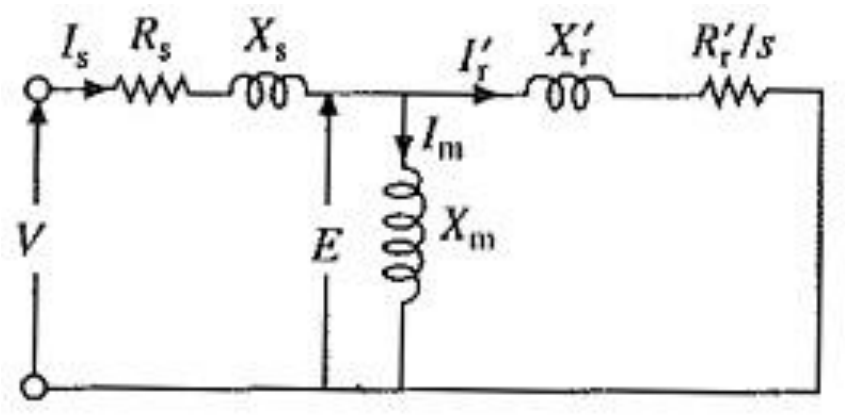


Fig. 1. Per phase equivalent circuit of IM.

Analysis and Performance of 3-phase Induction Motor

Slip is defined by (1)

$$s = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} \qquad (1)$$

where ω_m and ω_{ms} are rotor and synchronous speeds, respectively.

Further

$$\omega_{ms} = \frac{4\pi f}{p} \text{ rad/sec} \qquad (2)$$

where f and p are supply frequency and number of poles, respectively.

Analysis and Performance of 3-phase Induction Motor

- Since, stator impedance drop is generally negligible compared to terminal voltage V, the equivalent circuit can be simplified to that shown in Fig. 2.

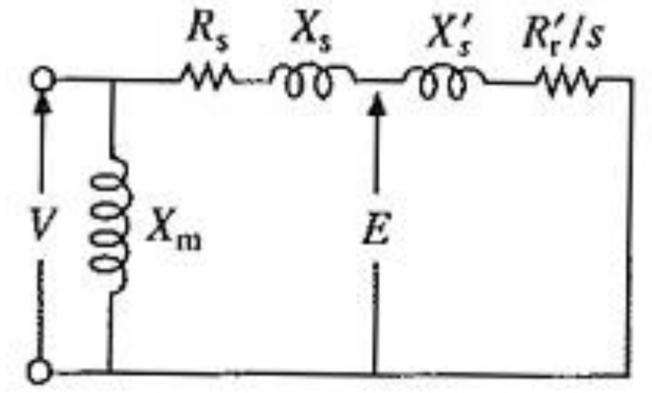


Fig. 2. Per phase equivalent circuit of IM.

Analysis and Performance of 3-phase Induction Motor

Also, from Eq. (1)

$$\omega_m = \omega_{ms}(1 - s) \qquad (3)$$

From Fig. 2,

$$\bar{I}_r' = \frac{V}{\left(R_s + \frac{R_r'}{s}\right) + j(X_s + X_r')} \qquad (4)$$

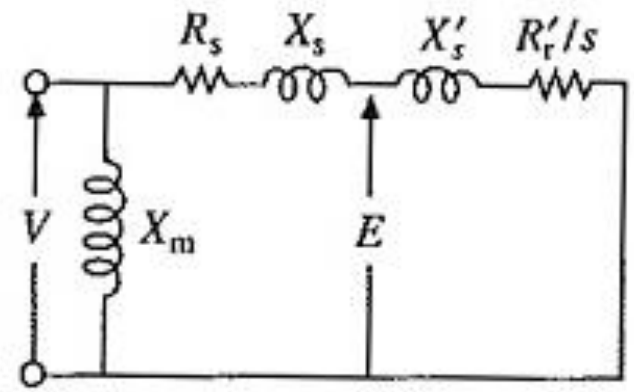


Fig. 2. Per phase equivalent circuit of IM.

Analysis and Performance of 3-phase Induction Motor

Power transferred to rotor (or air-gap power)

$$P_g = 3I_r'^2 R_r'/s \qquad (5)$$

Rotor copper loss is

$$P_{cu} = 3I_r'^2 R_r' \qquad (6)$$

Electrical power converted into mechanical power

$$P_m = P_g - p_{cu} = 3I_r'^2 R_r' \left(\frac{1-s}{s} \right) \qquad (7)$$

Analysis and Performance of 3-phase Induction Motor

Torque developed by motor

$$T = P_m/\omega_m \qquad (8)$$

Substituting from Eqs. (3) and (7) yields

$$T = \frac{3}{\omega_{ms}} I_r'^2 \frac{R_r'}{s} \qquad (9)$$

Substituting from Eq. (4) gives

$$T = \frac{3}{\omega_{ms}} \left[\frac{V^2 R'_{r/s}}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2} \right] \qquad (10)$$

Analysis and Performance of 3-phase Induction Motor

A comparison of Eqs. (5) and (9) suggests that

$$T = P_g/\omega_{ms} \qquad (11)$$

- Motor output torque at the shaft is obtained by deducting friction windage and core-loss torques from the developed torque.
- The developed torque is a function of slip only (Eq. (10)).

- Differentiating T in (10) with respect to s and equating to zero gives the slip for maximum torque

$$s_m = \pm \frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}} \qquad (12)$$

Analysis and Performance of 3-phase Induction Motor

Substituting from Eq. (12) into (10) yields an expression for maximum torque

$$T_{max} = \frac{3}{2\omega_{ms}}\left[\frac{V^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}}\right] \qquad (13)$$

Maximum torque is also known as breakdown torque. While it is independent of rotor resistance, S_m is directly proportional to rotor resistance.

Analysis and Performance of 3-phase Induction Motor

- The natures of speed-torque and speed-rotor current characteristics are shown in Fig. 2.
- Both rotor-current and torque are zero at synchronous speed. With decrease in speed, both increase.
- While torque reduces after reaching breakdown value, the rotor-current continues to increase, reaching a maximum value at zero speed. Drop in speed from no load to full load depends on the rotor resistance.
- When rotor resistance is low, the drop is quite small, and therefore, motor operates essentially at a constant speed.
- The breakdown torque is a measure of short-time torque overload capability of the motor.

Analysis and Performance of 3-phase Induction Motor

- Motor runs in the direction of the rotating field.

- Direction of rotating field, and therefore, motor speed can be reversed by reversing the phase sequence. Phase sequence can be reversed by interchanging any two terminals of the motor.

- Sometime, torque is expressed in terms of s_m and T_{max}, which not only facilitates calculations, but also enables a quick appreciation of nature of speed-torque characteristics.

- Dividing Eq. (10) by (13) and then substituting from (12) yields

$$\frac{T}{T_{max}} = \frac{2\left(1 + \frac{R_s}{R_r'} s_m\right)}{\frac{s}{s_m} + \frac{s_m}{s} + 2\frac{R_s}{R_r'} s_m} \qquad (14)$$

Analysis and Performance of 3-phase Induction Motor

The nature of speed-torque characteristics (Fig. 3) can now be readily explained from Eq. (14).

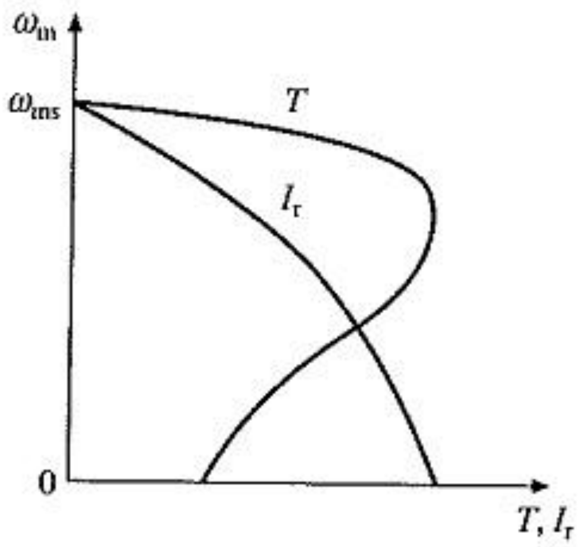


Fig. 3. Speed torque and speed rotor current characteristics of an induction motor.

Analysis and Performance of 3-phase Induction Motor

- For slips much smaller than s_m, the second term of the denominator dominates.

- Therefore, the speed-torque relation from 0 to rated torque is approximately represented by a straight line.

- For slips much larger than s_m, the first term of the denominator dominates and the speed-torque relation takes a hyperbolic shape in this region.

- In the whole region of motor operation, the term $(R_s s_m/R'_r)$ is small compared to 1 and the dominating term in the denominator. Therefore, it can be dropped from Eq. (14). Thus

$$\frac{T}{T_{max}} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}} \qquad (15)$$

Key Points from Today's Class

- Chopper Control of Separately Excited DC Motor
- Regenerative Braking of Chopper fed Separately Excited DC Motor
- Motoring and Regenerative Braking of DC Motor
- Dynamic Braking of DC Motor

Key Points from Next Class

In the next class, we will be discussing on the

- ❖ Three-Phase Induction Motor
- ❖ Speed Control of Three Phase Induction Motors

Thank you so much for your attentions

Q & A