Lecture Notes
EEE 360

TOPIC 5

Induction Machine

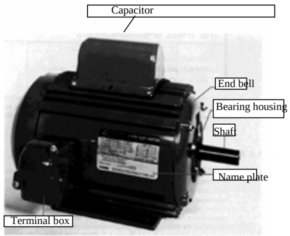
Read Chapter: **8**

INDUCTION MOTORS

General

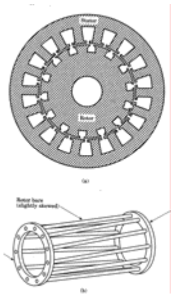
- The induction machine is used as a motor and as a generator. However, it is most frequently used as a motor. It is the Workhorse of industry.
- Majority of the motors used by industry are squirrel cage induction motors.
- Both three-phase and single-phase motors are widely used.
- The induction generators are seldom used. Their typical application is the wind power plant.

Single phase induction motor



INDUCTION MOTORS

- **Stator construction**
  - **Laminated iron core with slots**
  - **Coils are placed in the slots to form a three or single phase winding**
- **Squirrel-cage rotor construction**
  - **Laminated Iron core with slots**
  - **Metal bars are molded in the slots**
  - **Two rings short circuits the bars**
  - **The bars are slanted to reduce noise**

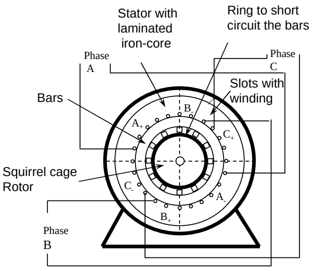


INDUCTION MOTORS

Construction

- The stator has a ring shape laminated iron core with slots.
- A three or single-phase winding is placed in the slots.
- The rotor has a ring-shape laminated iron core, with slots bolted to the shaft.
- Squirrel Cage Rotor: Conductor bars are placed in the slots and short circuited at both ends (Most frequently used).

Concept of squirrel cage motor



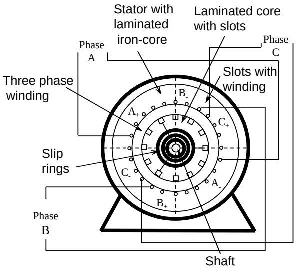
INDUCTION MOTORS

Construction

Wound-rotor:

- Three-phase windings are placed in the slots.
- The winding is wye or delta connected.
- The ends of each phase is connected to a slip ring.
- Three brushes contact the three slip-rings.
- The rotor winding may be loaded by variable resistance's or supplied by a separate power supply.

Concept of wound-rotor motor

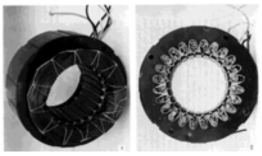


INDUCTION MOTORS

Stator Construction

- The figure shows a typical stator iron core.
- The laminated ring shaped core is bolted to the motor frame.
- The coils are placed in the slots. The slots are closed by a wedge.
- The coil ends are shaped to fit to the iron core and tied together by strings.
- High voltage motor coils are dried and impregnated.

Stator iron core construction

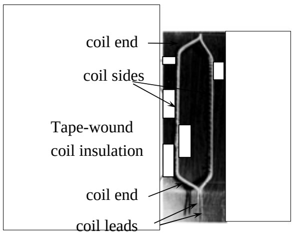


INDUCTION MOTORS

Stator Construction

- The figure shows typical stator coil construction.
- The coil is wound on a form using insulated (enamel) copper conductors.
- The coil is insulated by insulating tape.
- The insulated coil is placed in the stator slots.
- The two sides of the coil are approximately 180^o electrical degree apart.

Stator winding construction

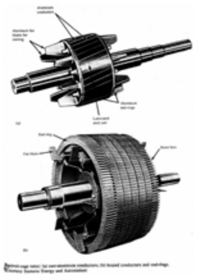


INDUCTION MOTORS

Squirrel-cage rotor

- The picture shows the rotor of a small and a large motor.
- Both rotors have laminated cores with slots, mounted on a shaft.
- The aluminum bars are slanted on the small rotor. This reduces the noise and improves performance.
- Fins are placed on the ring that shorts the bars. The fins work as a fan and improves cooling.
- The large rotor also has fins and bars. But the bars are not slanted.

Rotor construction

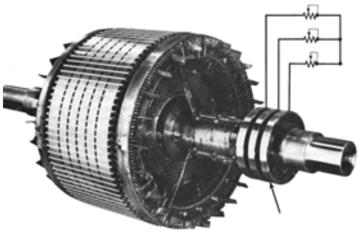


INDUCTION MOTORS

Wound-rotor

- The picture shows the rotor of a large **wound-rotor motor**
- The ends of each phase is connected to a slip ring.
- Three brushes contact the three slip-rings to three wye connected resistances.

Rotor construction



INDUCTION MOTORS

Three-phase motors. Operation principles.

- The stator is supplied by three-phase voltages that drive three-phase balanced current through the windings.
- The three-phase currents generate a rotating magnetic field.
- The field rotates at synchronous speed. Synchronous speed is determined by the frequency of the supply voltage and the number of poles: $n_s = f / p/2 = 2 f / p$. The unit is rpm.
- The rotating field induces a voltage in the short-circuited rotor conductors.
- The induced voltage generates current in the bars.

INDUCTION MOTORS

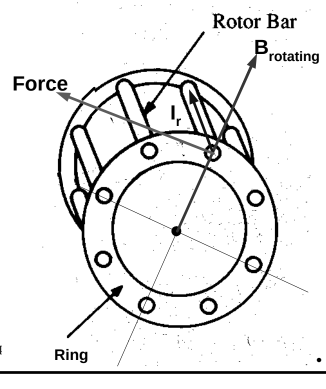
Three-phase motors. Operation principles

- The interaction between the rotor current and the stator field produces a force that drives the motor: $\text{Force} = B\ I\ L \sin \phi$
- The induced voltage magnitude is dependent upon the speed difference between the rotating stator field and the rotor.
- The speed difference is maximum during starting when the motor draws large current. The frequency of the rotor current is 60 Hz when the rotor is stationary.
- As the motor starts to rotate the speed difference is reduced, which results in:
  - reduction on the frequency of the induced voltage in the rotor.
  - reduced magnitude of rotor current and induced voltage.

INDUCTION MOTORS

Force generation.

- **Rotating field induces current in the bar .**
- **The current and field interaction generates the driving force.**
- **Force = $B_{rotating}$ L I_r**
- **The force drives the motor.**
- **L is the length of the rotor**



INDUCTION MOTORS

Three-phase motors. Operation principles.

- If the rotor speed is equal to the angular speed of the stator field, the induced voltage, current and torque become zero. Therefore the **motor speed must be less than the synchronous speed.**
- Motor operation requires speed difference between the stator generated rotating field and the actual rotor speed. The speed difference is called **slip (s)** and defined as:

  $s = (n_s - n_r) / n_s$ where $n_s = 2 f / p$
- The frequency of the rotor current is: $f_r = s f$
- The slip in normal operation is between 1 and 5 %
- **For demonstration of operation open "Squirrel Cage Rotor" animation program.**

INDUCTION MOTORS

Three phase motors.
Student class room numerical exercise

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

Calculate:

a) Synchronous speed
b) Rotor speed
c) Frequency of rotor current

Solution

- Synchronous speed: $n_s = 2 f / p = (120) / 6 = 20$ rev/sec =1200 rpm
- Rotor speed: $n_r = (1\text{-}s)\ n_s = (1\text{-} 0.05)\ (1200) = 1140$ rpm
- Frequency of rotor current: $f_r = s f = (0.05)\ (60) = 3$ Hz

INDUCTION MOTORS

Three phase motors. Development of equivalent circuit

- The induction motor consists of a two magnetically connected systems: Stator and rotor.
- This is similar to a transformer that also has two magnetically connected systems: primary and secondary windings.
- The stator is supplied by a balanced three-phase voltage that drives a three-phase current through the winding. This current induces a voltage in the rotor.
- The applied voltage (V_1) across phase A is equal to the sum of the
  - induced voltage (E_1).
  - voltage drop across the stator resistance ($I_1 R_1$).
  - voltage drop across the stator leakage reactance ($I_1\ j\ X_1$).

INDUCTION MOTORS

Three phase motors. Development of equivalent circuit

- The stator voltage equation is:

  $V_1 = E_1 + I_1 (R_1 + j X_1)$

- The E_1 induced voltage generates a voltage E_2 in the rotor through the magnetic coupling.
  - If the rotor is at stand still, the induced voltage E_2 is proportional to E_1 times the turn ratio. $T = N_{stat} / N_{rot} = N_1 / N_2$. The value is:

    $E_2 = E_1 (N_2 / N_1) = E_1 / T$
  - If the rotor is rotating, the voltage induced in the rotor is multiplied by the slip s, because the induced voltage is proportional to the speed difference between the stator field and rotor.

    $E_2 = s E_1 / T$

INDUCTION MOTORS

Three phase motors. Development of equivalent circuit.

- The rotor induced voltage is equal to the sum of the voltage drop across the rotor resistance ($I_2 R_2$), and the leakage inductance ($I_2 X_2$).
- The voltage drop across the secondary leakage inductance L_2 is:

$$I_2\ j\,\omega_r\ L_2 = I_2\ j\,\underbrace{(2\,\pi\,f_r)}_{\omega_r} L_2 = I_2\ j\,\underbrace{(2\,\pi\,f\,)}_{\omega} s\,L_2 = I_2\,j\,s\,\underbrace{(\omega\,L_2)}_{X_2} = I_2\,j\,s\,X_2$$

- The rotor voltage equation is:

  $E_2 = I_2 (R_2 + j\,s\,X_2)$

INDUCTION MOTORS

Three phase motors. Development of equivalent circuit.

- The equations derived for the induction motors are:

$$\begin{array}{lcl} V_1 = E_1 + I_1 (R_1 + j\,X_1) & \nearrow & E_2 = s\,E_1 / T \\ E_2 = I_2 (R_2 + j\,s\,X_2) & \longleftarrow & I_2 = I_1 (N_1 / N_2) = I_1\,T \end{array}$$

- Combining the equations we have:

$$E_1 = E_2\,T / s = T\,I_2 (R_2 + j\,s\,X_2)/s = I_1\,T^2 (R_2/s + j\ X_2)$$
$$= I_1 [(R_2\,T^2/s) + j\,(T^2\ X_2)] = I_1 (R^*_2/s) + j\ X^*_2)$$

where: $R^*_2 = R_2\,T^2$ and $X^*_2 = T^2\ X_2$ are rotor resistance and reactance referred to the stator.

INDUCTION MOTORS

Three-phase motors. Development of equivalent circuit.

- The derivation results in the following equations:

  $V_1 = E_1 + I_1 (R_1 + j X_1)$ $E_1 = I_1 (R_2^* / s + j X_2^*)$

- We substitute the second equation into the first one to obtain the following equation for the induction motor:

  $V_1 = I_1 (R_2^* / s + j X_2^*) + I_1 (R_1 + j X_1) = I_1 [(R_1 + R_2^* / s) + j (X_1 + X_2^*)]$

- The final equation is:

  $V_1 = I_1 [(R_1 + R_2^* / s) + j (X_1 + X_2^*)]$

INDUCTION MOTORS

Three-phase motors. Development of equivalent circuit.

- The induction motor equation is:

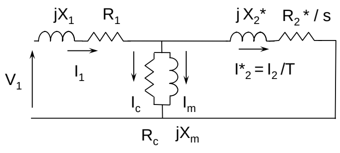
  $V_1 = I_1 [(R_1 + R_2^* / s) + j (X_1 + X_2^*)]$

- This equations suggests that the induction motor equivalent circuit contains two resistances and reactances connected in series.
- The magnetizing current can be represented by a resistance R_c and a reactance X_m connected in parallel.
  - The resistance represents the hysteresis and eddy current losses.
  - The reactance represents the magnetizing current that generates the air-gap magnetizing flux.

INDUCTION MOTORS

Three-phase motors.
Development of equivalent circuit.

- The induction motor equivalent circuit is:



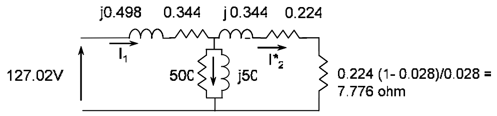
INDUCTION MOTORS

Three-phase motors. Application of equivalent circuit
Student class room exercise.

A three-phase, 20 hp, 220V, 60 Hz, 4 pole, induction motor has the following parameters:

- R_1 = 0.344 ohm X_1 = 0.498 ohm X_m = 50 ohm
- R_2* = 0.224 ohm X_2* = 0.344 ohm R_c = 500 ohm

Draw the equivalent circuit.



INDUCTION MOTORS

- **Draw the equivalent circuit**
- **Calculate motor impedance vs. slip**
- **Calculate motor stator and rotor current vs. slip**
- **Calculate and plot input and output power and efficiency vs. slip**
- **Calculate motor speed and torque vs. motor speed**
- **Determine the maximum value of torque, efficiency**
- **Calculate starting torque**

LECTURE 18

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test

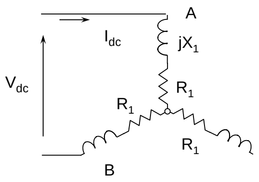
- The motor parameters are determined from three tests:
    - **No-load test**. Provides the magnetizing reactance and core resistance (R_c and X_m).
    - **Blocked-Rotor Test** (Short circuit test). Provides ($R_1 + R_2^*$) and ($X_1 + X_2^*$).
    - **Stator DC resistance measurement**. Determines the stator resistance value (R_1).

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test

- **Stator DC resistance measurement**
    - The motor is supplied by DC voltage between two terminals (A and B at the figure).
    - The dc voltage and current are measured.
    - The resistance is:

$$R_1 = \frac{V_{dc}}{2 \cdot I_{dc}}$$



INDUCTION MOTORS

Three-phase motors. Determination of parameters from test

- **No-load test**
    - The motor is supplied by rated line -to -line voltage (V_{ml}) and the no-load current I_{nl} and the no load input power P_{nl} are measured.
    - The no-load input power includes magnetizing and rotational losses.
    - Using the measured values, the admittance and resistance are calculated if the winding leakage impedance is neglected:

$$R_c = \frac{V_{nL}^{\ 2}}{P_{nL}} \quad \text{and} \quad Y_{nL} = \frac{I_{nL}}{\frac{V_{nL}}{\sqrt{3}}}$$

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test.

- **No-load test**
  - The approximate magnetizing reactance is:

$$X_m = \frac{1}{\sqrt{Y_{nl}^2 - \frac{1}{R_c^2}}}$$

Rotational losses (friction, ventilation etc.) :

  - At no-load conditions the slip is very low. Therefore, the rotor copper losses are negligible.
  - input power P_{nl} is equal to the core loss and the rotational losses.

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test.

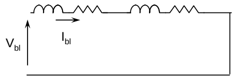
- **Blocked-Rotor Test**
  - The motor is supplied by reduced voltage V_{br} (line-to-line) and lower frequency voltage. Approximate frequency value is: $f_{test} = (0.258)(60) = 15$ Hz. Reduced frequency simulates that rotor current frequency is small in normal operation.
  - The voltage V_{br} , current I_{br}, the input power $P_{b\,r}$ are measured.
  - The rotor is blocked slip is $s = 1$. Magnetizing reactance and resistance are neglected because of reduced supply voltage.

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test.

- **Blocked-Rotor Test**

The approximate equivalent circuit is:



- Blocked rotor resistance is:

$$R_{br} = \frac{P_{br}}{3 I_{br}^2}$$

- \- Blocked rotor impedance is: $Z_{br} = \frac{V_{br}}{\sqrt{3}\, I_{br}}$

INDUCTION MOTORS

Three-phase motors. Determination of parameters from test.

- **Blocked-Rotor Test**
  - Blocked rotor reactance at the test frequency f_{test} is:
    $X_{br_{test}} = \sqrt{Z_{br}^{2} - R_{br}^{2}}$
  - Blocked rotor reactance at the rated frequencies:
    $X_{br} = X_{br,\ test}\ (f_{rated} / f_{test})$
  - The equivalent circuit parameters are calculated from:
    $R_{br} = R_1 + R_2$ and $X_{br} = X_1 + X_2$
  - R_1 is determined by stator resistance measurement.

INDUCTION MOTORS

Determination of motor parameters from test

A three-phase, 30 hp, 208 V, 4 pole, 60 Hz, wye-connected induction motor was tested, obtaining the following data:

- No load at 60 Hz:	V_{nl} **= 208 V**	I_{nl} **=22 A**	P_{nl} **= 1600 W**
- Blocked Rotor at 15 Hz:	V_{br} **= 21 V**	I_{br} **=71 A**	P_{br} **= 2100 W**
- DC test:	V_{dc}**= 12 V**	I_{dc} **=75 A**	

a) Calculate:
  - **the equivalent circuit parameters**
  - **the rated current and synchronous speed**

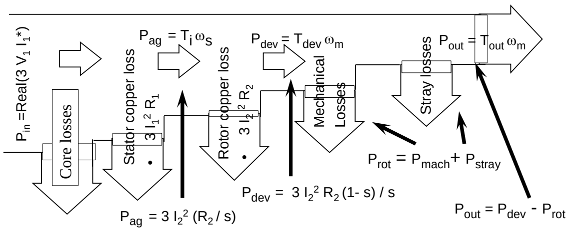
b) Draw the equivalent circuit with the parameter values.

LECTURE 19

INDUCTION MOTORS

Three-phase motors. Performance Analysis.

- **The induction motor performance is evaluated using the equivalent circuit.**
- **The power flow diagram is shown in the figure:**



$P_{in} = Real(3\, V_1\, I_1^*)$

Core losses

Stator copper loss $3\, I_1^2\, R_1$

$P_{ag} = T_i\, \omega_s$

Rotor copper loss $3\, I_2^2\, R_2$

$P_{dev} = T_{dev}\, \omega_m$

Mechanical Losses

Stray losses

$P_{out} = T_{out}\, \omega_m$

$P_{rot} = P_{mach} + P_{stray}$

$P_{dev} = 3\, I_2^2\, R_2\, (1\text{-}\, s) / s$

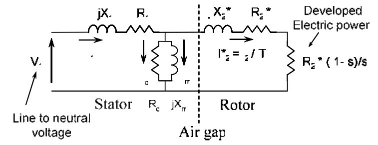
$P_{ag} = 3\, I_2^2\, (R_2 / s)$

$P_{out} = P_{dev} - P_{rot}$

INDUCTION MOTORS

Three-phase motors. Torque speed characteristics.

- **The torque speed relation is calculated from the equivalent circuit**.



The electric output or developed power is:

$$\mathbf{P}_{\mathbf{Dev}} = 3\mathbf{I}_2{}^2 \frac{1-\mathbf{s}}{\mathbf{s}} \mathbf{R}^*{}_2$$

INDUCTION MOTORS

Three-phase motors. Torque speed characteristics

- **The air gap power is:**

$$P_{ag} = 3I_2{}^2 \frac{R^*{}_2}{s}$$

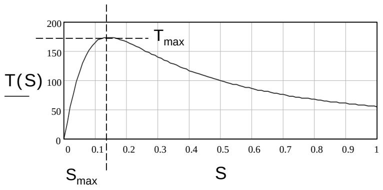
- **The synchronous ω is**: $\omega_s = 2\, \pi\, n_s = 2\, \pi\, f\, [2/p]$
- **The electromagnetic torque applied to the rotor is:**

$$T_e = \frac{P_{ag}}{\omega_s}$$

INDUCTION MOTORS

Three-phase motors. Torque speed characteristics.

- **The $T_e(s)$ function can be plotted using the MathCad program**.
- **The figure shows that the torque has a maximum value.**
- **The normal operation is between s = 0 and s_{max}**



INDUCTION MOTORS

Three-phase motors. Torque speed characteristics

- **The output mechanical power is:**

$$P_{mech} = 3I_2^{2}\frac{1-s}{s}R^{*}_2 - P_{Rotation}$$

$P_{rotation}$ are the rotational losses.

- **The motor speed ω is:** $\omega_m = 2\pi n_m = 2\pi n_s(1-s)$
- **The output torque is:**

$$T_e = \frac{P_{mech}}{\omega_m}$$

INDUCTION MOTORS

Three-phase motors. Torque speed characteristics.

- **The maximum torque is calculated by numerical analysis, or by finding the maximum of the torque function. The steps of the calculation are:**
  - **Calculation of the torque derivative with respect to slip (s).**
  - **Setting the derivative to zero and solving the equation for s.**
- **The result of this calculation is the slip value when the maximum occur**.

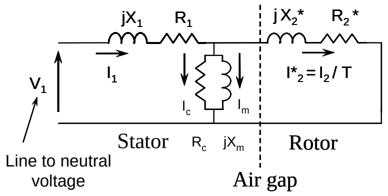
$$S_{max} = \frac{R_2}{\sqrt{R_1^{\ 2} + (X_1 + X_2)^2}}$$

- **The maximum torque is calculated by substituting s_{max} into the torque equation.**

INDUCTION MOTORS

Three-phase motors. Starting Torque

- **The slip is s =1 at starting**.
- **The figure show the equivalent circuit at starting.**



INDUCTION MOTORS

Three-phase motors. Starting Torque

- **The torque is generated by the air-gap power that produces the electromagnetic torque.**
- **The starting current is the supply voltage divided by the motor impedance. This current is generally 5-6 times the rated current.**
- The air gap power is: $P_{ag,\ start} = 3\ R_2\ (I_{2start})^2$
- The starting torque is: $T_{start} = P_{ag,\ start} / \omega_s$

INDUCTION MOTORS

Three-phase motors. Performance Analysis. Example.

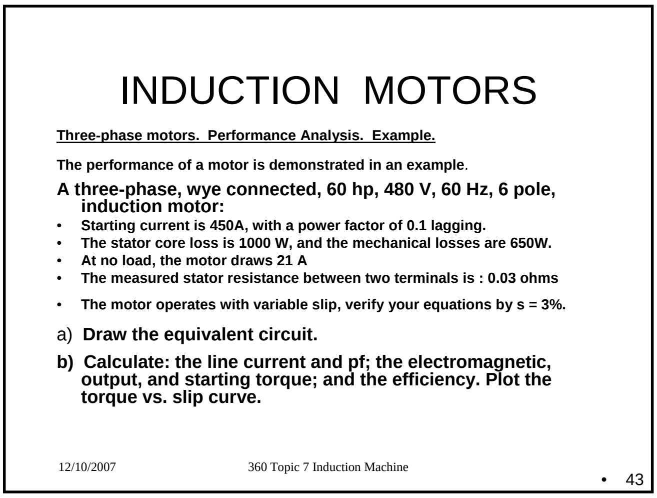
The performance of a motor is demonstrated in an example.

A three-phase, wye connected, 60 hp, 480 V, 60 Hz, 6 pole, induction motor drives a fan. The motor and fan data are:

- **Starting current is 450A, with a power factor of 0.1 lagging.**
- **The stator core loss is 1000 W, and the mechanical losses are 650W.**
- **At no load, the motor draws 21 A**
- **The measured stator resistance between two terminals is : 0.03 ohms**
- **The fan torque speed characteristics Is:**
- **The motor operates with variable slip, verify your equations by s = 3%.**

a) **Draw the equivalent circuit.**

b) Calculate: the line current and pf; the electromagnetic, output, and starting torque; and the efficiency. Plot the torque vs. slip curve.



INDUCTION MOTORS

Three-phase motors. Performance Analysis. Example.

The performance of a motor is demonstrated in an example.

A three-phase, wye connected, 60 hp, 480 V, 60 Hz, 6 pole, induction motor:

- **Starting current is 450A, with a power factor of 0.1 lagging.**
- **The stator core loss is 1000 W, and the mechanical losses are 650W.**
- **At no load, the motor draws 21 A**
- **The measured stator resistance between two terminals is : 0.03 ohms**
- **The motor operates with variable slip, verify your equations by s = 3%.**

a) **Draw the equivalent circuit.**

b) Calculate: the line current and pf; the electromagnetic, output, and starting torque; and the efficiency. Plot the torque vs. slip curve.