EE2029: Introduction to Electrical Energy System

Induction Motors

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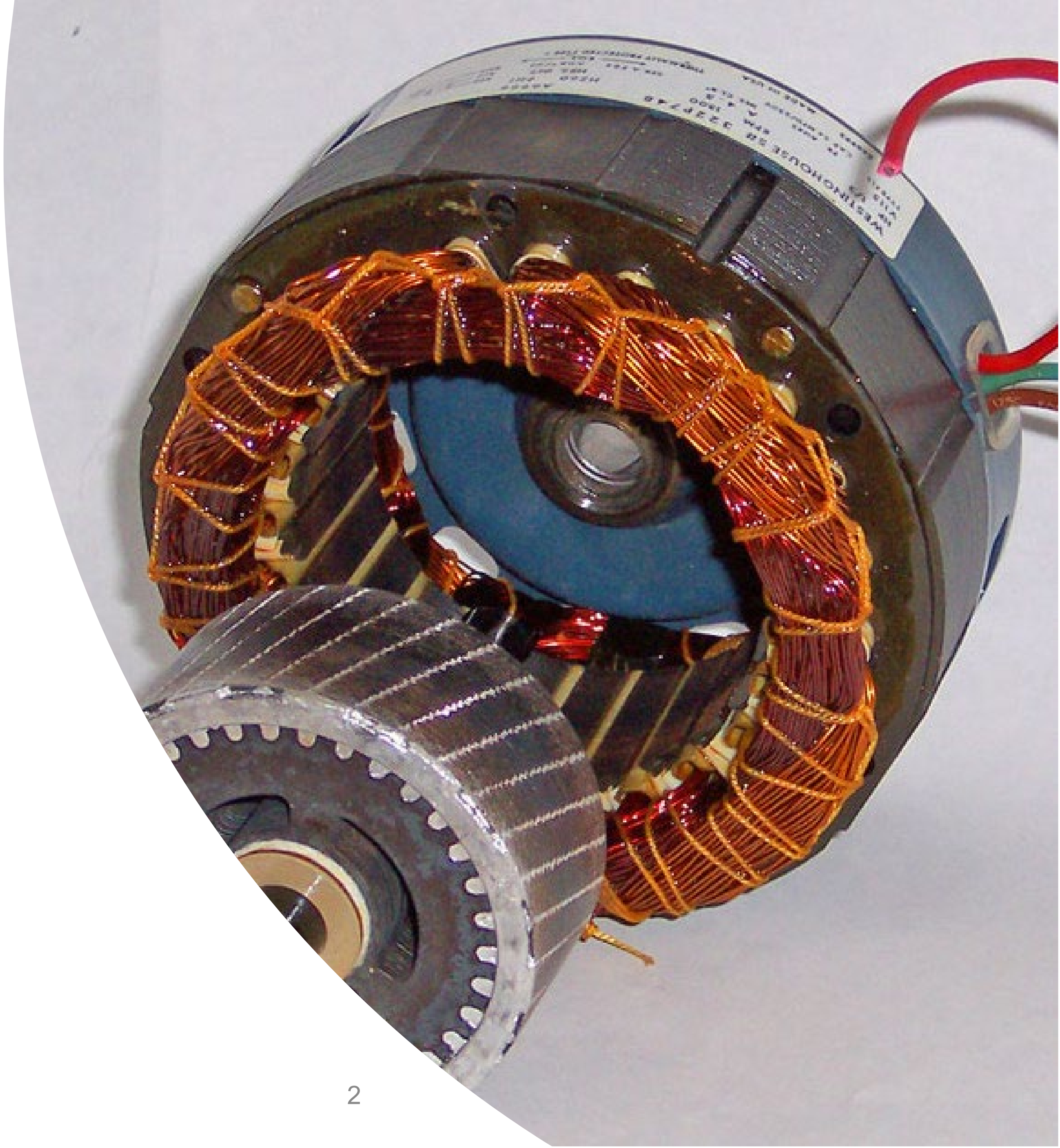
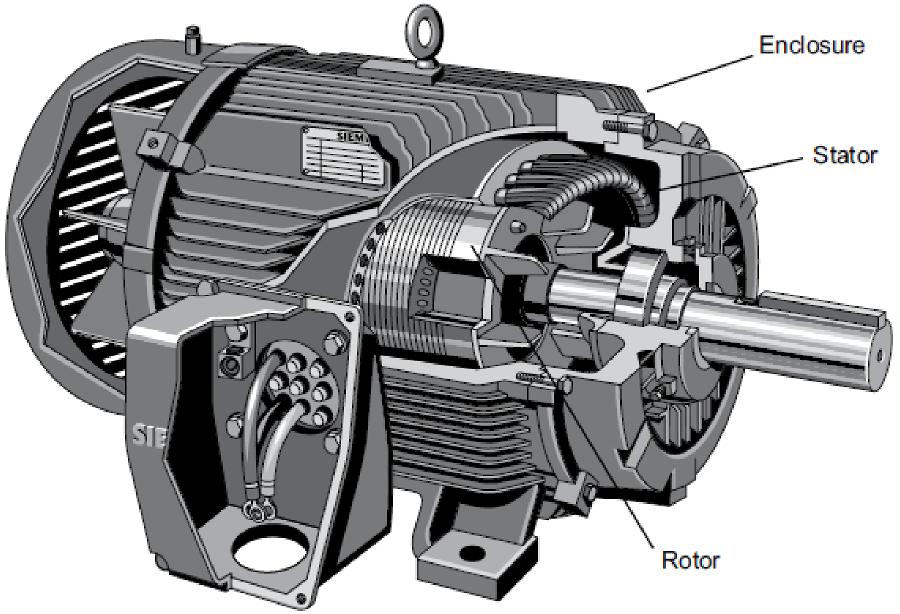
Learning Outcome

- Model key components of power systems including transformer, induction motor load, static load, transmission line, cable, and rectifier load



AC Motors

- Consists of
  - Stator: Stationary Electrical Component
  - Rotor: Rotates the motor shaft
- Types of AC Motors:
  - Synchronous Motor
  - Induction Motor
  - Main difference between synchronous and induction motor is that the rotor of the induction motor travels at a varying speed as the rotating magnetic field.
- Types of Induction Motors:
  - Single Phase Induction Motor
  - Three Phase Induction Motor



- Advantages of Induction Motor
  - Over 70% of our industry uses induction motor.
  - Simple design
  - Inexpensive to construct
  - High power to weight ratio
  - Easy to maintain
  - Direct connection to AC power source

Operating Principle

- Single Supply Excited Motor
  - Supply is applied only to one part i.e. stator
- Faraday's Law of Electromagnetic Induction
  - (Hint: why it is called induction motor!!!)

Stator

- Electricity supplied to the stator → stator rotating magnetic field
- Rotating stator magnetic field (stator flux) cuts the rotor conductors inducing a voltage

Rotor

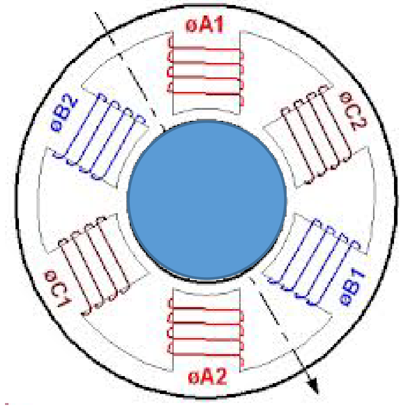
- Current is induced in the rotor conductors via this induced voltage (design of the rotor ensures this)
- Produces a secondary magnetic field (rotor flux) opposing the stator magnetic field

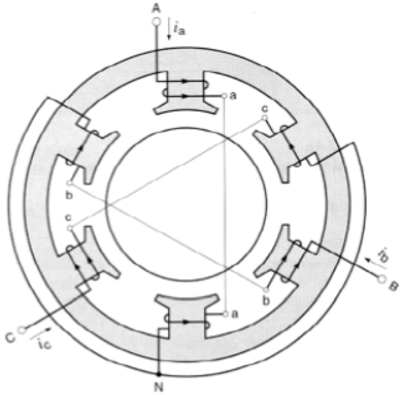
Flux

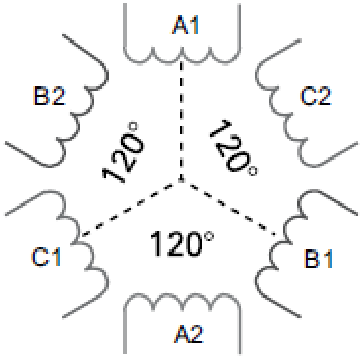
- Rotor flux is lagging with respect to the stator flux
- Rotor will feel a torque to rotate in the direction of the rotating stator magnetic field (rotor current +rotor flux → rotation)

Three-phase Induction Motor

- Poles
  - Winding(s) that produce the magnetic field(s) necessary to cause the rotor to turn
- Three-phase Rotating Field
  - AC currents I_a, I_b and I_c will flow in the windings, but will be displaced in time by 120°
  - Each winding produces its own MMF, which creates a flux across the hollow interior of the stator
  - The 3 fluxes combine to produce a magnetic field that rotates at the same frequency as the supply



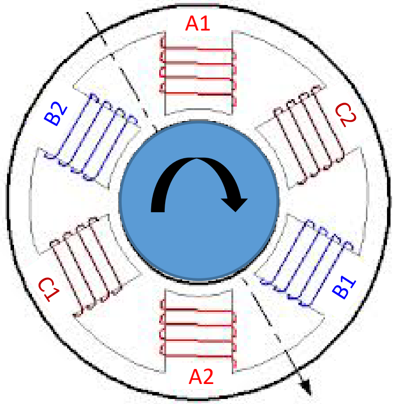


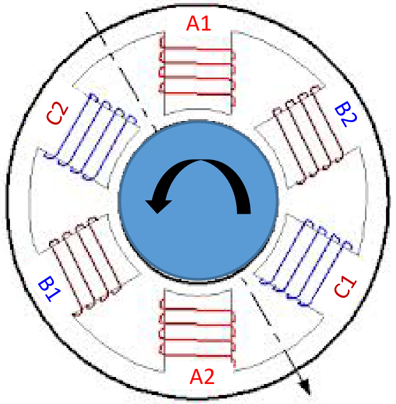


2-Pole Stator Winding

Three-phase Induction Motor

- Rotating Field - Direction of Rotation
  - Phase current waveforms follow each other in the sequence A-B-C
  - This produces a clockwise rotating magnetic field
  - If we interchange any two of the lines connected to the stator, the new phase sequence will be A-C-B
  - This will produce a counterclockwise rotating field, reversing the motor direction





- Number of Poles – Synchronous Speed
  - The rotating speed of the revolving stator flux can be reduced by increasing the number of poles (in multiples of two)
  - In a four-pole stator, the phase groups span an angle of 90°
  - In a six-pole stator, the phase groups span an angle of 60°
- This leads to the definition of synchronous speed, i.e. the speed of the rotating stator flux:
  - $N_s = 120 \frac{f}{p}$
  - $N_s = synchronous\ speed\ (rpm)$
  - $f = frequency\ of\ the\ supply\ (Hz)$
  - $p = number\ of\ poles$

Slip of an Induction Motor

- Difference between synchronous speed and rotor speed can be expressed as a percentage of synchronous speed, known as the slip

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

  - where,
    - $s \ = \ slip,$
    - $N_s \ = \ synchronous\ speed\ (rpm),$
    - $N_R \ = \ rotor\ speed\ (rpm)$
- At no-load, the slip is nearly zero (<0.1%)
- At full load, the slip for large motors rarely exceeds 0.5%
- For small motors at full load, it rarely exceeds 5%
- Slip is 100% for locked rotor (Motor Standstill)
- Can slip be equal to zero?

Frequency Induced In the Rotor

- The induced frequency in the rotor depends on the slip:

$$f_R = sf$$

$$f_R = \frac{N_s - NR}{N_s} f$$

  - $f_R = frequency\ of\ voltage\ and\ current\ in\ the\ rotor,\ slip\ frequency$
  - $f = frequency\ of\ the\ supply\ and\ stator\ field$
  - $s = slip$
- Induction motor is a common form of an asynchronous motor
- Basically, an AC transformer with a rotating secondary side

Example 1: A 208 V, 10 hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip
of 5 percent. Answer the following questions:

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

Equivalent Circuit

- Induction motor is an AC transformer with a rotating secondary side
- Equivalent model can be derived from existing per-phase transformer equivalent circuit
- View it as a variable frequency transformer!
  - Stator Circuit Model
  - Rotor Circuit Model
  - Approximate Equivalent circuit of an Induction Motor

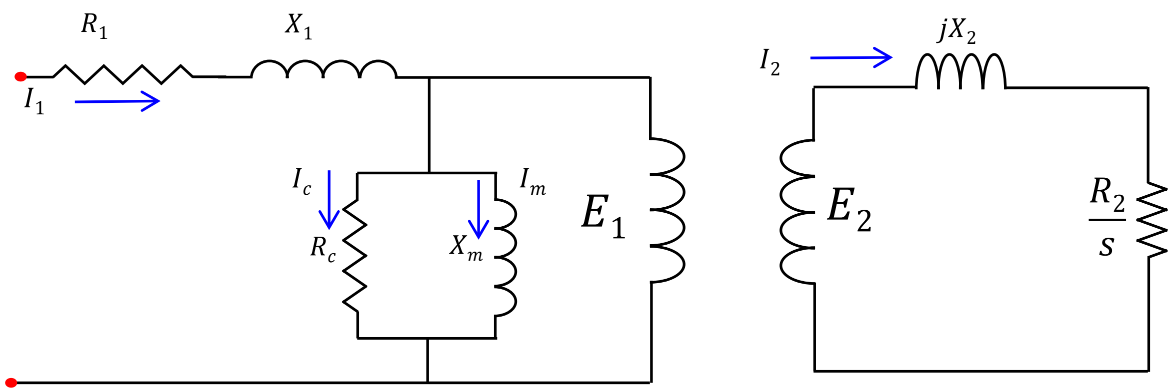
Equivalent Circuit

- Induction Motor Losses
- Copper losses (conductor losses, I^2R losses)
  - Stator conductor loss
  - Rotor conductor loss
- Iron losses (core losses)
  - Hysteresis
  - Eddy current loss
- Mechanical losses
  - Windage loss
  - Friction loss

- Impact of Air Gap
  - The magnetizing reactance indicates the amount of flux that is not linked to the rotor (X_M)
  - Air gap in an induction motor greatly increases the reluctance of flux path
    - This reduces the coupling between primary and secondary windings
  - Higher reluctance ➔ higher magnetizing reactance, X_M, in the equivalent circuit than in an ordinary transformer act of Air Gap

Equivalent Circuit

- Stator Circuit Model
  - The stator circuit model of an induction motor consists of a stator phase winding resistance R_1, stator phase winding leakage reactance X_1
  - It also consists of the core losses (R_c) and the magnetising inductance (X_M)



- Rotor Circuit Model
  - Let E_2 and X_2 be the induced voltage and rotor reactance of the rotor in standstill condition
  - Induced voltage at any slip is

$$E_{2s} = sE_2$$

  - If L_2 is the inductance of rotor, the rotor reactance is given by :

$$X_{2s} = 2\pi f_2 L_2 \Rightarrow X_{2s} = 2\pi s f_1 L_2 \quad since\ f_2 = sf_1$$

$$X_{2s} = sX_2$$

  - Let Z_{2s} be the rotor impedance at any slip s

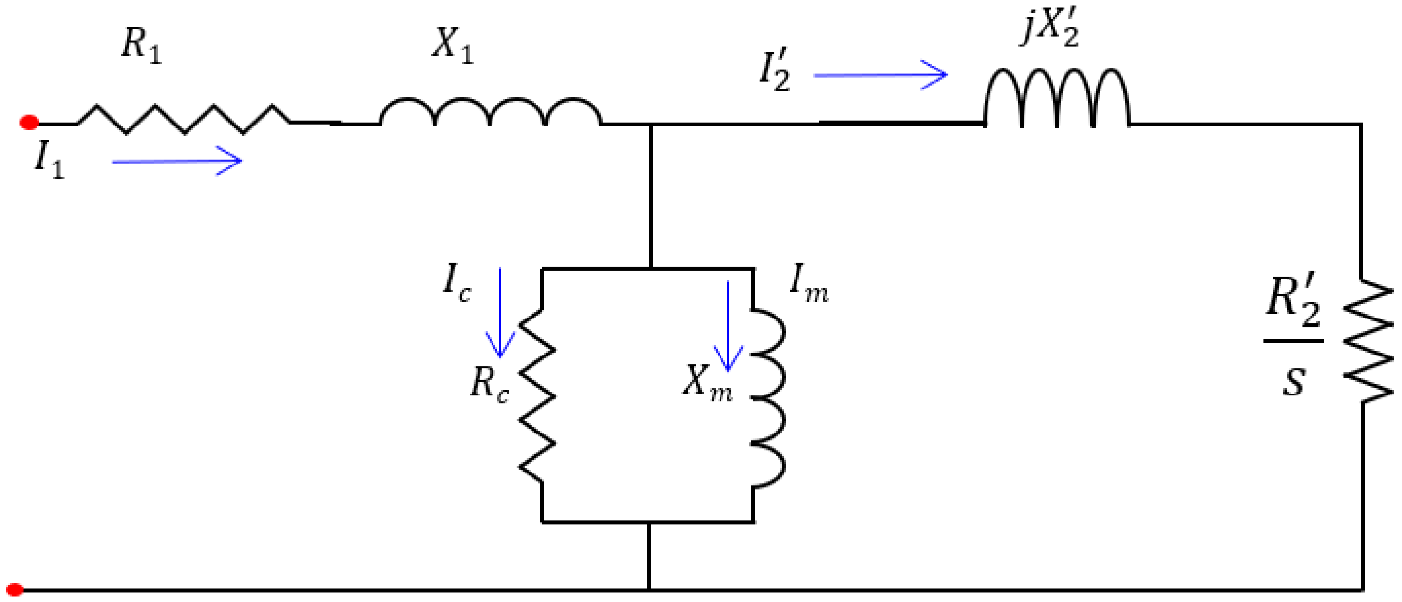
$$Z_{2s} = R_2 + jX_{2s} = R_2 + jsX_2$$

  - The rotor current per phase is given by

$$I_2 = \frac{E_{2s}}{Z_{2s}} = \frac{sE_2}{R_2 + jsX_2} = \frac{E_2}{\frac{R_2}{s} + jX_2}$$

Equivalent Circuit

- Combining the stator and rotor circuits



$R_2' = Rotor\ resistance\ referred\ to\ stator$

$X_2' = Rotor\ reactance\ referred\ to\ stator$

$I_2' = Rotor\ current\ referred\ to\ stator$

Power and Torque

- Supply Power is

$$P_{in} = 3V_1 I_1 Cos\theta$$

- Stator Copper Losses (SCL) and Core Losses

$$P_{SCL} = 3I_1^2 R_1;\ P_{core} = 3\frac{E_1^2}{R_c}$$

- Air gap power is

$$P_{AG} = P_{in} - P_{SCL} - P_{core}$$

- Air gap power is transferred to the rotor so

$$P_{AG} = 3I_2'^2 \frac{R_2'}{s}$$

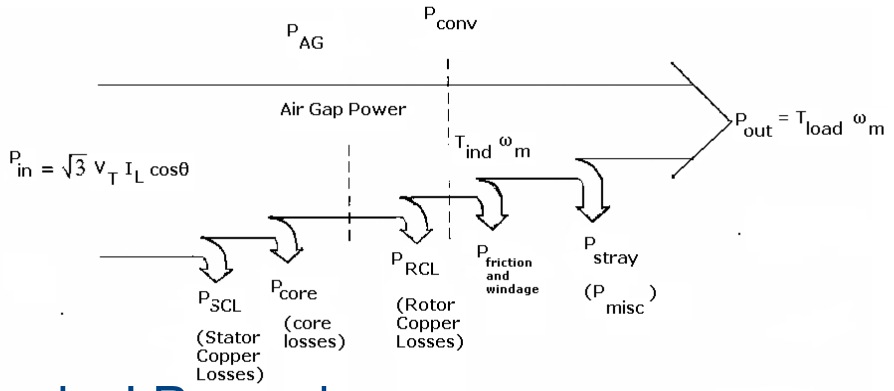
- Rotor copper losses (RCL)

$$P_{RCL} = 3I_2'^2 R_2'$$

- Electrically developed power (P_{elec}) is the difference between air gap power (P_{AG}) and rotor copper loss

$$P_{elec} = P_{AG} - P_{RCL} = 3I_2'^2 \frac{R_2'}{s} - 3I_2'^2 R_2'$$

$$P_{elec} = 3I_2'^2 R_2' \left(\frac{1-s}{s}\right)$$



- Mechanical Power is

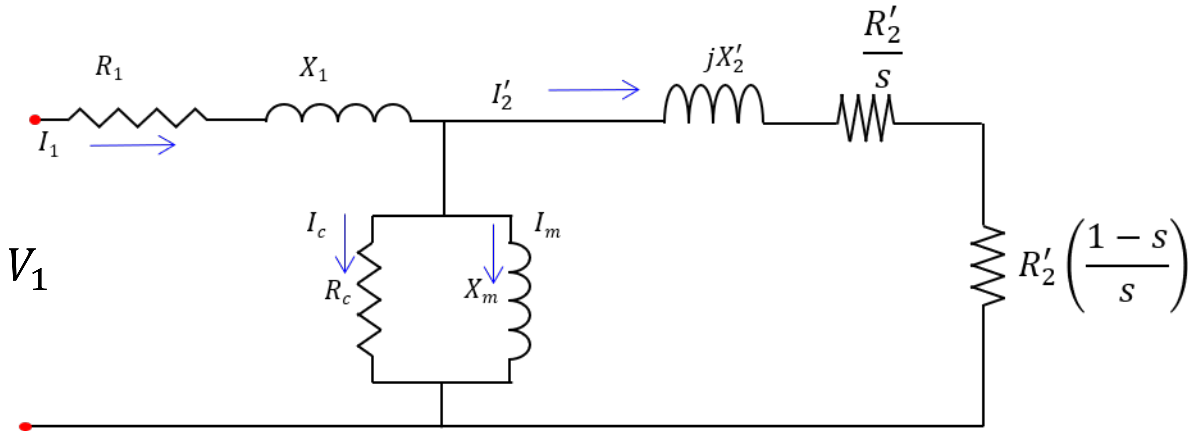
$$P_{out} = P_{elec} - P_{mech-lossRCL} = \tau_m \omega_m$$

- Motor Efficiency is

$$\eta = \frac{P_{out}}{P_{in}}$$

- Motor torque is

$$\tau_m = \frac{P_{out}}{\omega_m}$$



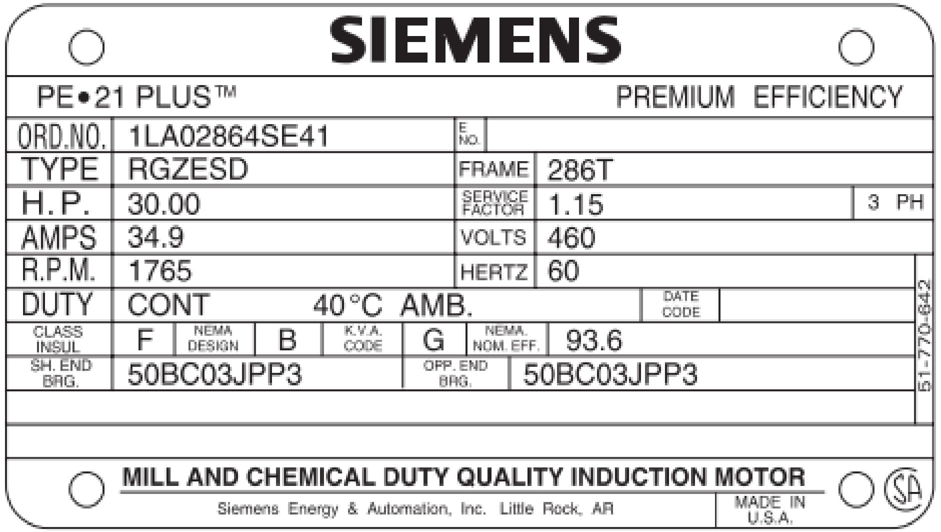
Example 2: A 460-V, 25-hp, 60 Hz, four-pole, Y-connected induction motor has the following impedances in ohms per phase referred to the stator circuit:

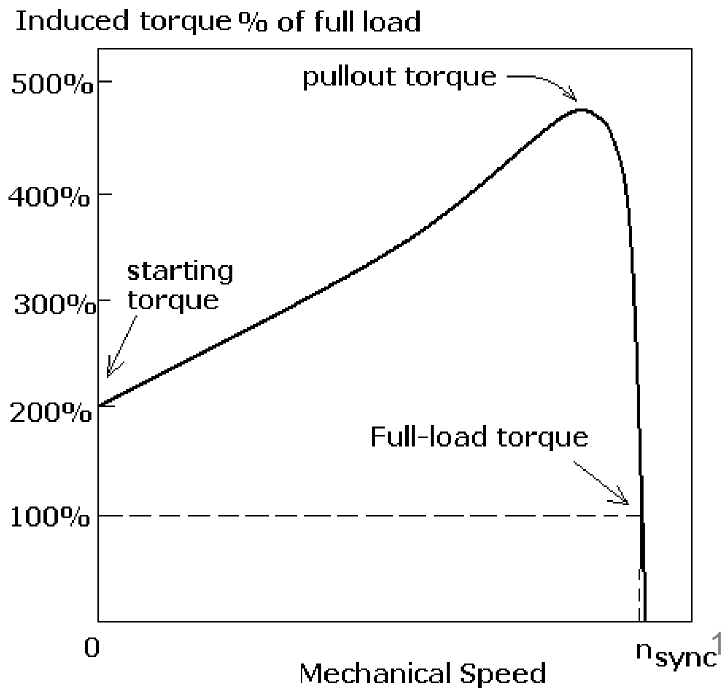
$R_1 = 0.641\ \Omega, R'_2 = 0.332\ \Omega, X_1 = 1.106\ \Omega, X'_2 = 0.464\ \Omega, X_m = 26.3\ \Omega$

Find the equivalent impedance of the induction motor with respect to the stator side. Assume a slip of 2.2%.

Torque-Speed Characteristic

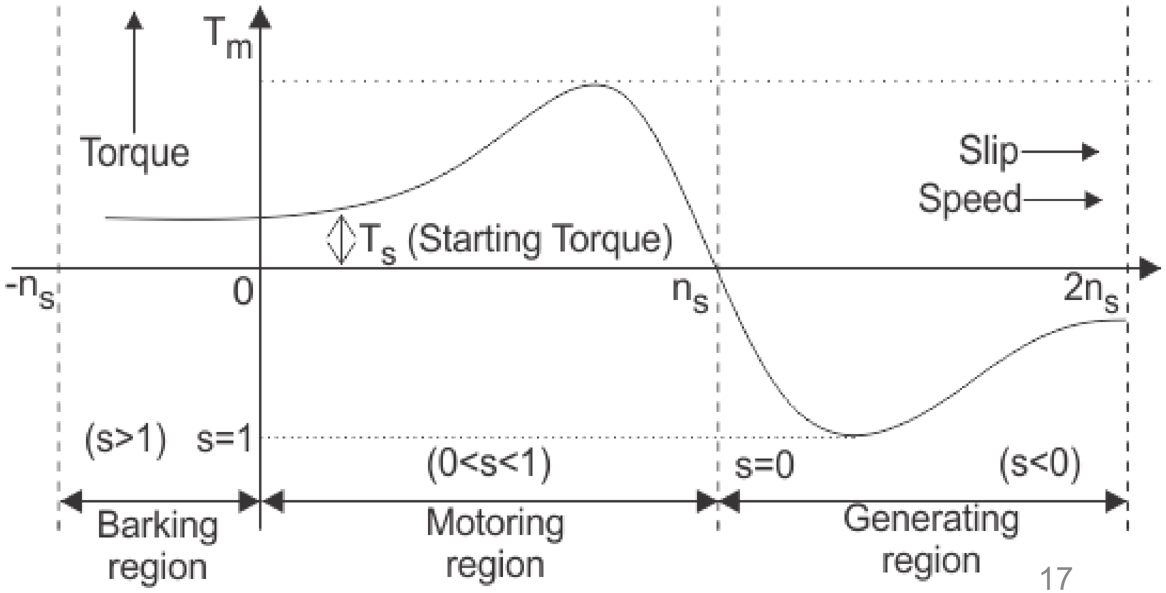
- **Light loads**: The rotor slip is very small, i.e. close to synchronous speed
- **Heavy loads**: As load increase, the slip increase. The rotor speed falls down as a result.
- **Starting torque**: About 200-250% of the full load torque (rated torque)
- **Pullout torque**: Maximum torque the motor can produce at full rated voltage and frequency (Usually 2 to 3 times of the rated full-load torque of motor) Motor will stall beyond this limit.
- Speed (rpm) of motor on the nameplate refers to the speed at full-load





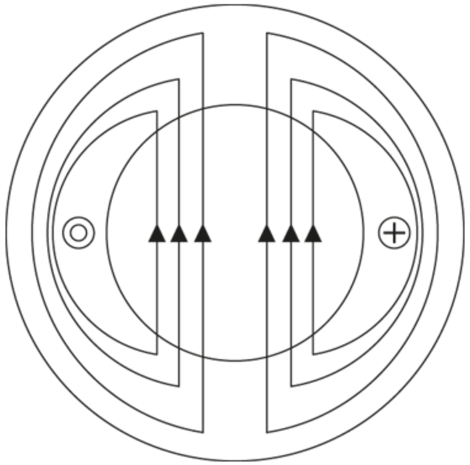
Torque-Speed Curve Regions

- Low slip region: Slip increases linearly with increased load
  - Rotor mechanical speed decreases approximately linearly with load
  - Rotor reactance is negligible, so rotor power factor is approximately unity, while rotor current increases linearly with slip
  - The entire normal steady-state operating range of an induction motor is included in this linear low-slip region
- Moderate slip region: Rotor current no longer increases as rapidly as before
  - Power factor starts to drop
  - Peak torque (pullout torque) of motor occurs at point where, for an incremental increase in load, increase in rotor current is exactly balanced by decrease in rotor power factor
- High slip region: Induced torque decreases with increased load due to decreasing power factor at rotor
  - Starting torque (at zero speed) is about 150% of full-load torque
  - Unlike synchronous motor, induction motor can start with a full-load attached to its shaft



Single-Phase Induction Motor

- Single-phase power supply:
- Commonly use in household appliances:
  - fans, washing machines, dryers
- Require a device to start motor



- Three Types of Capacitor-Start Motor
  - Capacitor-Start: disconnects capacitor after motor speed picks up
  - Capacitor-Run: Keeps the capacitor connected during the operation of the motor, in order to keep the electric power consumption low
  - Capacitor-Start-Run: uses two capacitors, one for starting and one for running (This further improves Power Consumption)

Questions