NANYANG TECHNOLOGICAL UNIVERSITY

Lecture 5

EE3010: Electrical Devices and Machines

School of Electrical and Electronic Engineering

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Learning Objectives

By the end of this lecture, you should be able to:

- Describe how the speed of an induction motor can be controlled.
- Explain the various tests to be carried out to measure the induction motor circuit model parameters.
- Explain the techniques that may be used for induction motor starting.

Speed Control of Induction Motors

❖ Two approaches:

a) Vary the slip of the motor by:
   - Varying the rotor resistance
   - Varying the terminal voltage of the motor

b) Vary the synchronous speed by:
   - Changing the number of poles
   - Changing the electrical frequency

Vary the Slip of Motor

- Varying the rotor resistance
  - In wound-rotor types, the shape of the torque speed characteristics can be changed by inserting extra resistances in the rotor circuit. But this method is inefficient as the extra rotor resistances seriously reduce the efficiency of the machine.
- Varying the terminal voltage of the motor
  - The torque is proportional to the square of the applied voltage, hence the speed can be controlled.

Vary Synchronous Speed

$$n_{sync} = \frac{120 f_s}{p}$$

- Changing the number of poles
  - Changing the number of poles requires multiple stator windings, which increases the complexity and overall cost of the induction machine.

- Changing the electrical frequency (commonly used)
  - When running at speeds below the base speed, the stator voltage should be decreased linearly with decreasing stator frequency. This is known as derating. Else, the steel in the motor core will saturate and excessive magnetisation currents will flow.

Vary Synchronous Speed

- This is explained as follows:

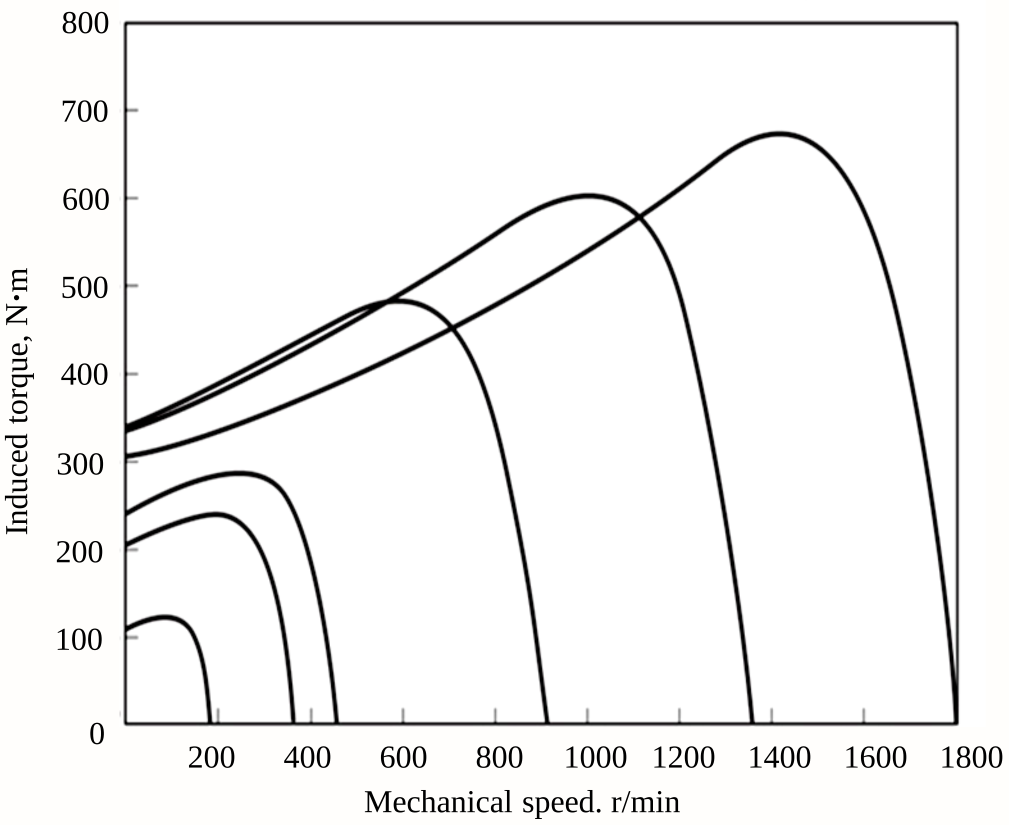
  If $(R_1 + jX_1)$ drop can be neglected, then

  $$V_\phi \approx E_1 = 4.44 N_1 \phi_{\max} f_s \Rightarrow \phi_{\max} = \frac{V_\phi}{4.44 N_1 f_s}$$

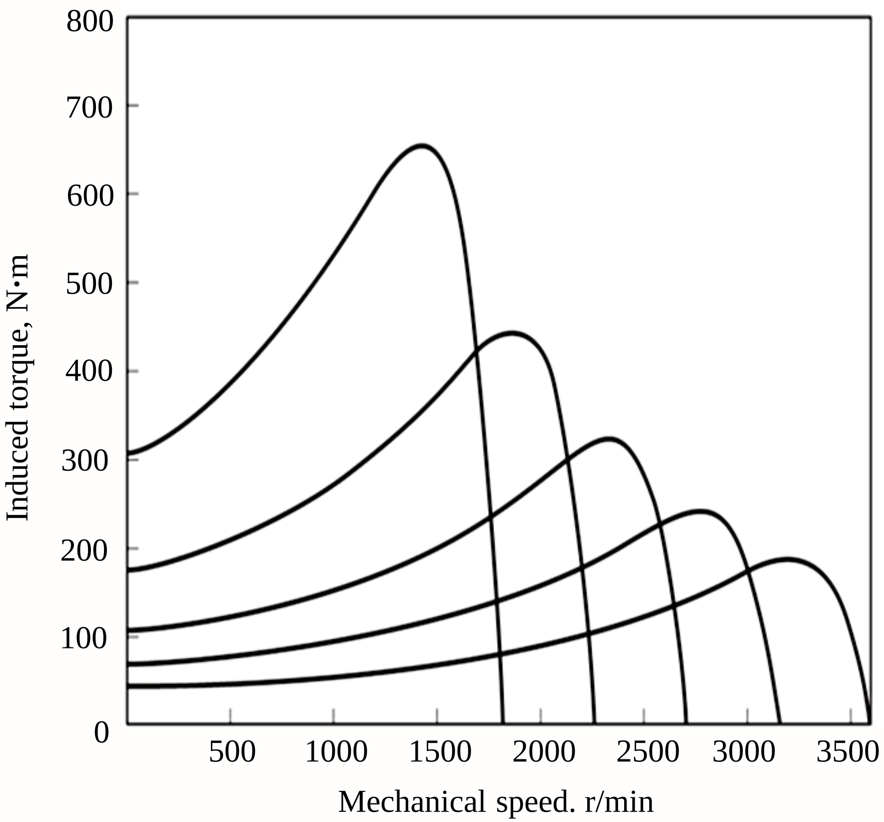
  If V_ϕ remains constant while $f_s \downarrow$, this $\Rightarrow \phi_{\max} \uparrow$

  which requires large increase in magnetisation current.

- Thus, it is customary to decrease the applied stator voltage in direct proportion to the decrease in frequency below rated frequency, to avoid excessive magnetisation currents. The method is also called *Variable Voltage Variable Frequency* control – using solid-state, power electronics, etc.

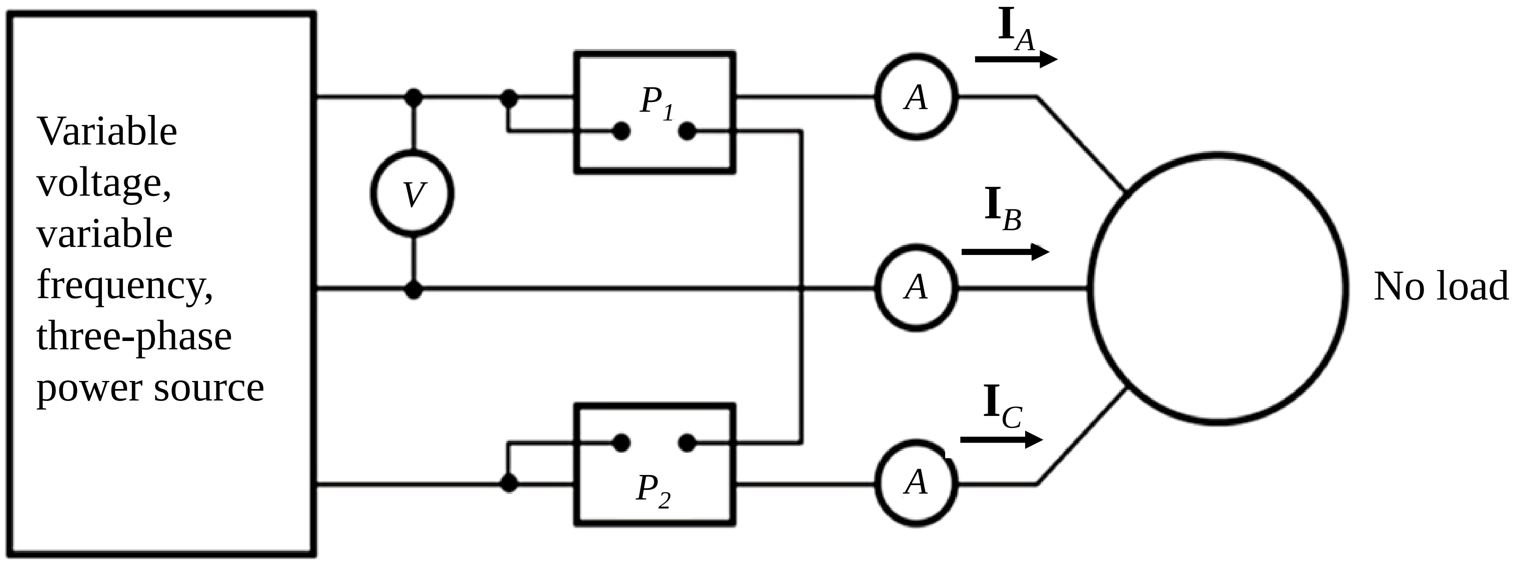


T-S characteristics for speeds below the base speed, assuming the stator voltage is derated linearly with frequency.

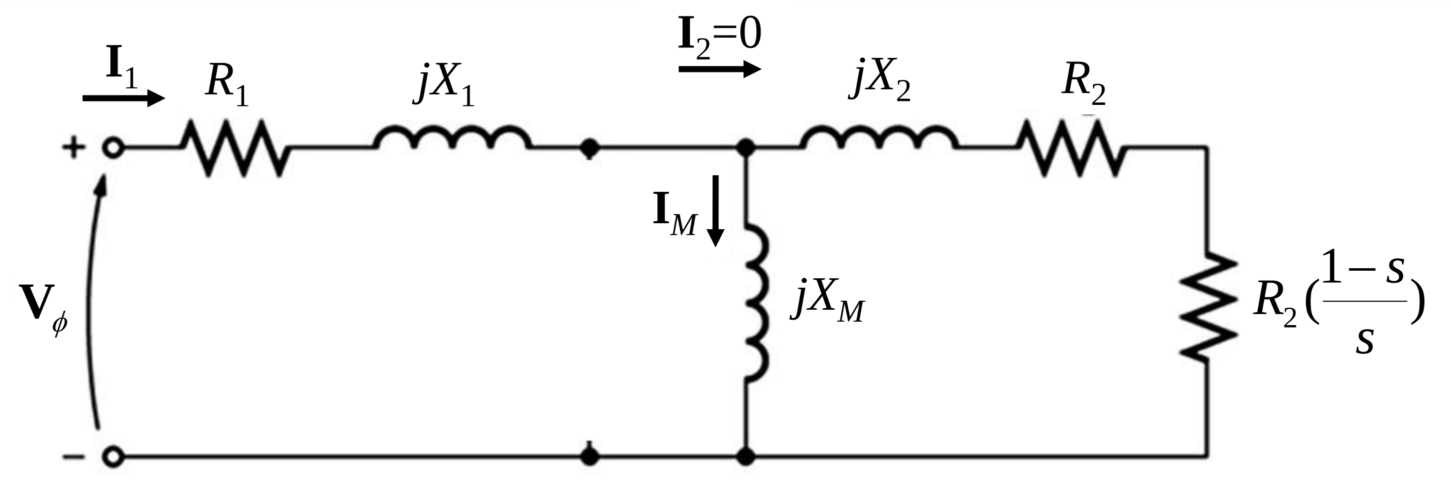


T-S characteristics for speeds above the base speed, assuming the stator voltage is held constant.

- How can R_1, R_2, X_1, X_2 and X_M be determined for a real motor?
- <u>No load test</u>: To determine the magnetising reactance and the combined core, friction and windage losses.



No-load test circuit.



- At no load, motor speed ≈ synchronous speed. Hence $s \approx 0$ and $\frac{R_2}{s}$ will be very high.
- The reactance of the parallel combination of X_M and the rotor circuit will, therefore, be very nearly equal to X_M and the overall input power factor will be very small.
- Most of the voltage drop will be across the inductive components in the circuit.

Determining Circuit Model Parameters of Induction Motors

- The equivalent input impedance at no load is thus approximately

$$\frac{V_\phi}{I_1} \simeq X_1 + X_M$$

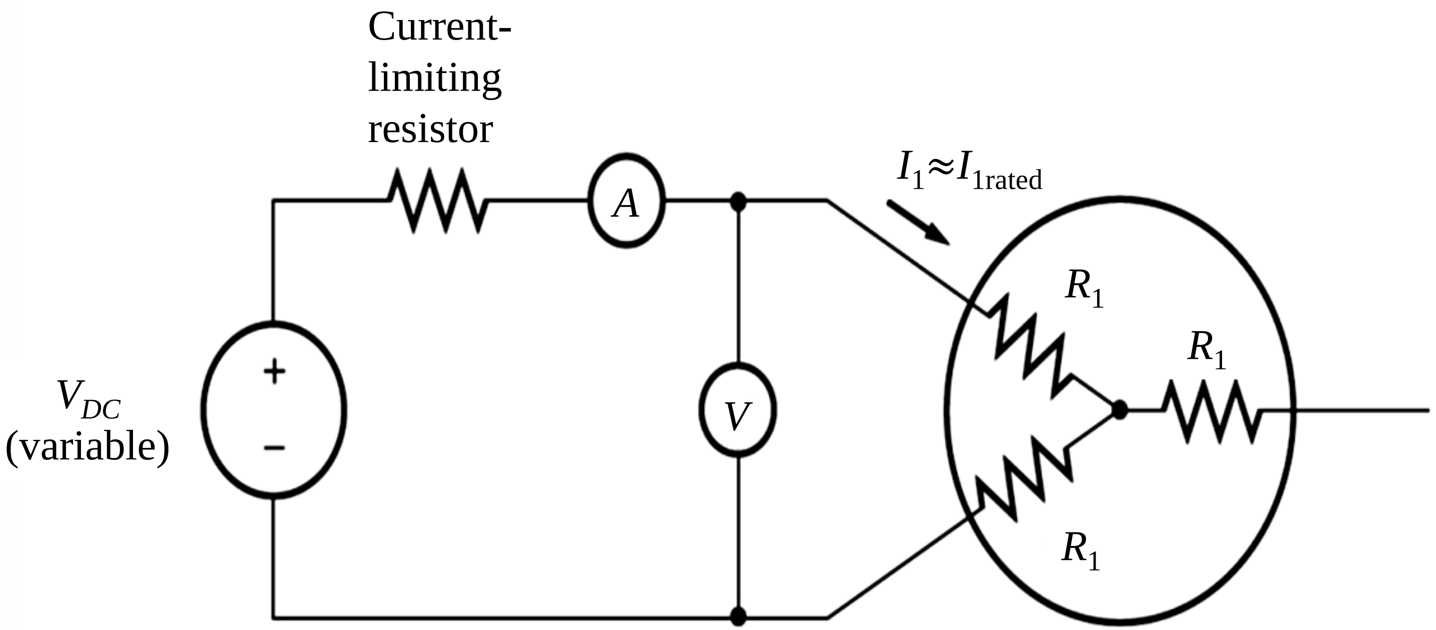
$\Rightarrow X_M$ can be obtained, as X_1 can be found from the blocked-rotor test.

- At no load, P_{in} measured must equal to the losses in the motor.
The rotor copper losses are negligible as the rotor current is almost zero.

- The stator copper losses $P_{SCL} = 3I_1^2 R_1$, where R_1 is obtained from the DC test.
Hence, the rotational losses of the machine can be obtained.

$$P_{rot} = P_{in} - P_{SCL}$$

DC Test for Stator Resistance



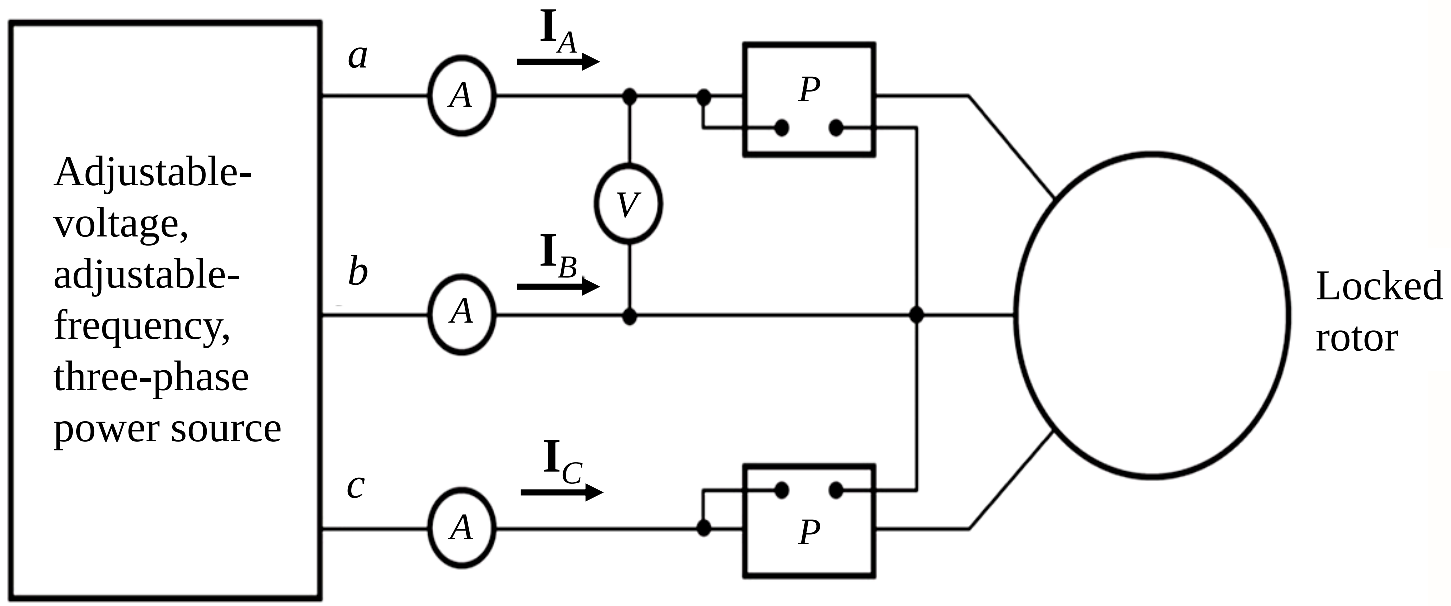
$$R_1 = \frac{V_{DC}}{2I_{DC}}$$

DC resistance test circuit.

❖ Because the current is dc, there is no induced voltage in the rotor circuit and no resulting current flow. Also, the reactances are zero at dc.

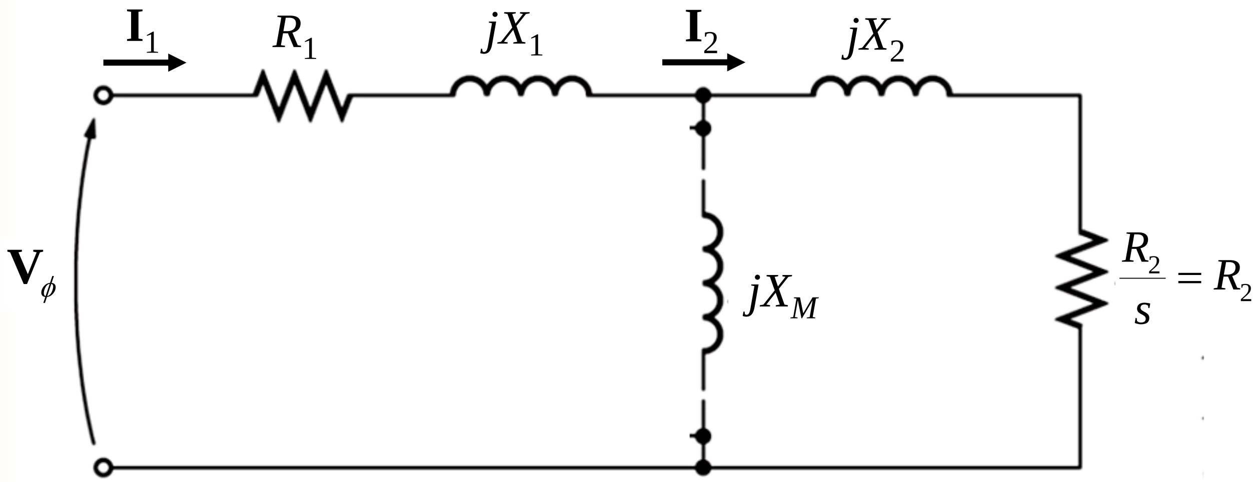
Locked-rotor or Blocked-rotor Test

- The rotor is locked or blocked. An AC voltage is applied to the stator, and the current flow is adjusted to be approximately full-load value.
- For finding R_2, X_1 and X_2.



Locked-rotor test circuit.

Locked-rotor or Blocked-rotor Test



Motor equivalent circuit under locked-rotor test.

- Since rotor is not moving, $s = 1$. Since R_2 and X_2 are small, almost all the input current will flow through them, instead of through the much larger magnetising reactance X_M.

- Under these conditions, the circuit looks like a series combination of R_1, X_1, R_2 and X_2.

Locked-rotor or Blocked-rotor Test

- The input power to the motor $P = 3I_1^2(R_1 + R_2)$

  $\Rightarrow R_2$ can be obtained since R_1 found from DC test.

- $$Z_{LR} = \frac{V_\phi}{I_1} = \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}$$

  $\Rightarrow (X_1 + X_2)$ can be obtained.

- It is not uncommon to have equal division between X_1 and X_2. Thus,

  $\Rightarrow X_1 = X_2 = \dfrac{(X_1 + X_2)}{2}$ can be obtained.

Example 1

The following test data were taken on a 7.5-hp, four-pole, 208 V, 60-Hz, wye-connected induction motor having a rated current of 28 A.

DC test: $V_{DC} = 13.6 \text{ V}, I_{DC} = 28.0 \text{ A}$

No-load test: $V_{line} = 208 \text{ V}, \ f = 60 \text{ Hz}, I_{line} = 8.17 \text{ A}, P_{in} = 420 \text{ W}$

Locked-rotor test: $V_{line} = 25 \text{ V}, \ f = 15 \text{ Hz}, I_{line} = 27.9 \text{ A}, P_{in} = 920 \text{ W}$

a) Sketch the per-phase equivalent circuit for this motor.

b) Find the slip at the pullout torque and find the value of the pullout torque.

(Solutions →)

Example 1 – Solutions

a) i. DC test: $V_{DC} = 13.6\text{ V}, I_{DC} = 28.0\text{ A}$

$$\Rightarrow 2R_1 = \frac{V_{DC}}{I_{DC}} \Rightarrow R_1 = 0.243\Omega$$

ii. Locked-rotor test: $V_{line} = 25\text{ V},\ f = 15\text{ Hz},$

$$I_{line} = 27.9\text{ A}, P_{in} = 920\text{ W}$$

$$\Rightarrow 920 = 3(I_1^2)(R_1 + R_2) \Rightarrow R_2 = 0.151\Omega$$

and $Z_\varphi = \frac{25}{\sqrt{3}} = \left(\frac{1}{27.9}\right) = \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}$

$\Rightarrow X_1 = X_2 = 0.168\Omega$ at a test frequency of 15 Hz.

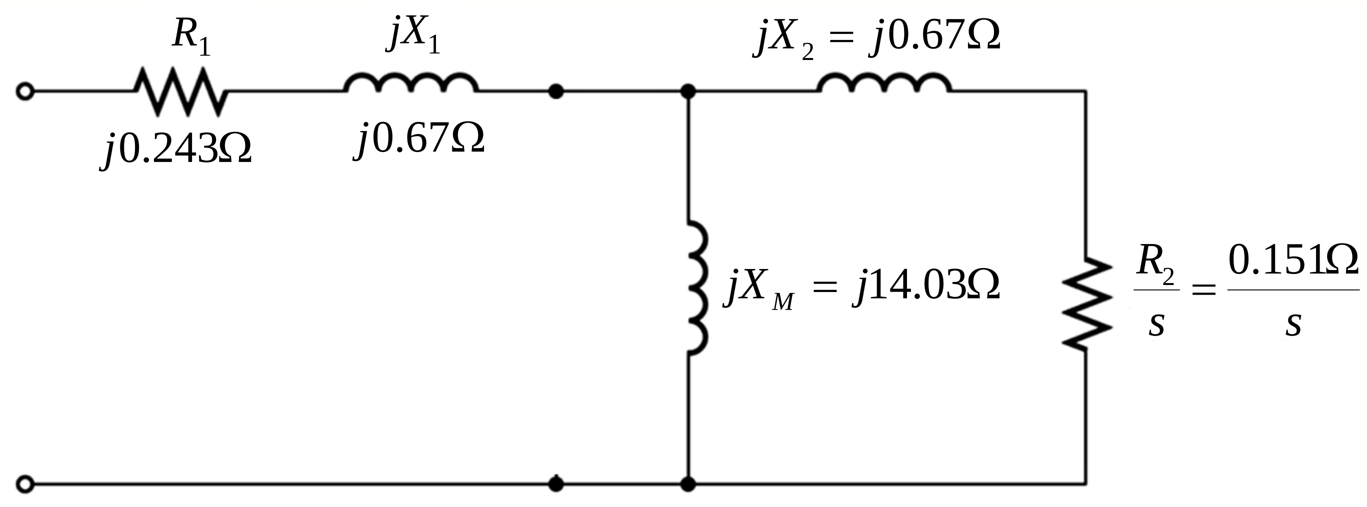
Hence, $X_1 = X_2 = 0.168\left(\frac{60}{15}\right)\ \Omega = 0.672\ \Omega$ at 60 Hz.

Example 1 – Solutions

iii. No-load test: $V_{line} = 208\text{ V},\ f = 60\text{ Hz},\ I_{line} = 8.17\text{ A},\ P_{in} = 420\text{ W}$

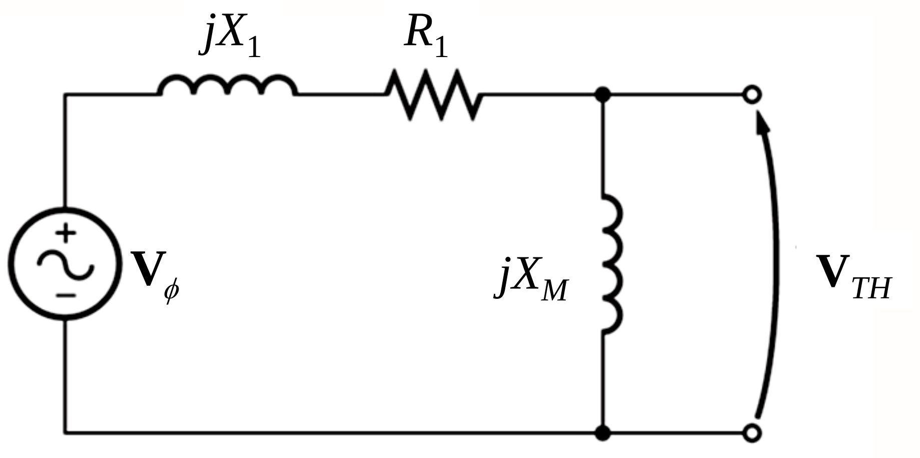
$$\Rightarrow \frac{208}{\sqrt{3}}\left(\frac{1}{8.17}\right) \simeq X_1 + X_M \Rightarrow X_M = 14.03\Omega$$

$$P_{SCL} = 3I_1^2 R_1 = 48.7\text{ W} \Rightarrow P_{rot} = 420 - P_{SCL} = 371.3\text{ W}$$

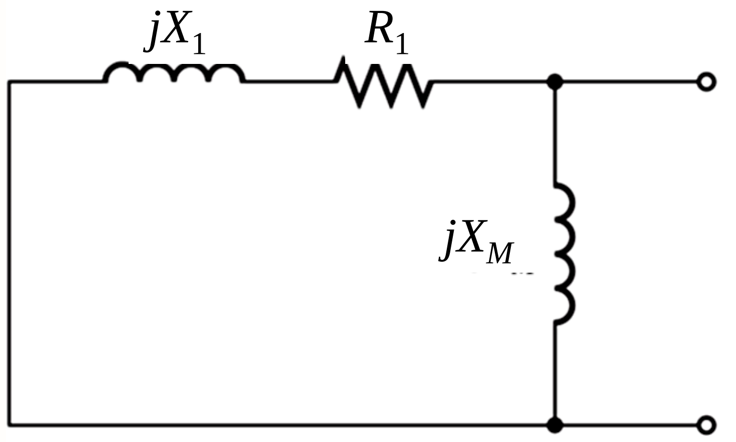


Motor per phase equivalent circuit.

Example 1 – Solutions

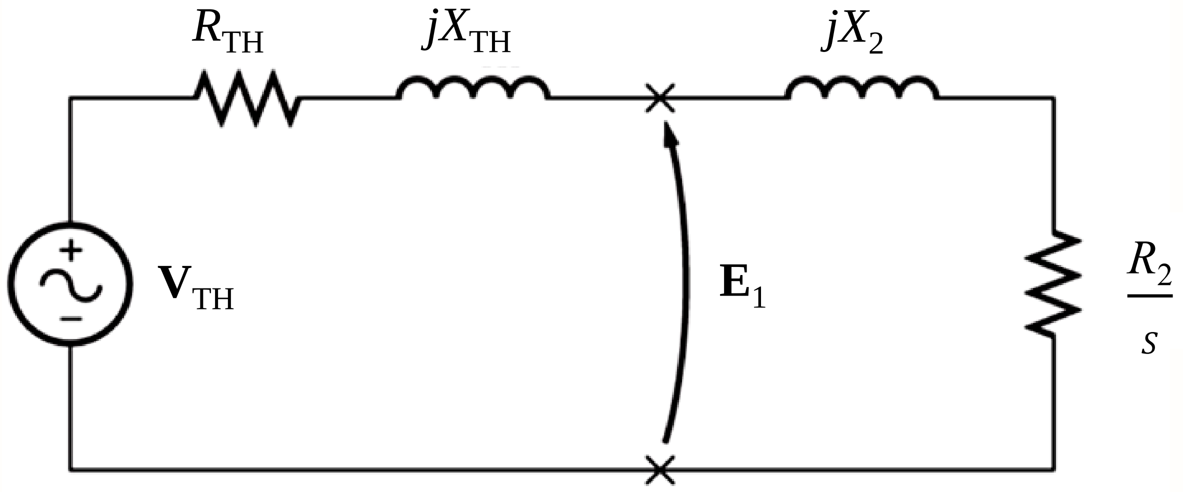


$$\mathbf{V}_{TH} = \frac{jX_M}{R_1 + jX_1 + jX_M}\mathbf{V}_\varphi$$
$$= 114.58\angle 0.95°$$



$$\mathbf{Z}_{TH} = \frac{jX_M(R_1 + jX_1)}{R_1 + jX_1 + jX_M}$$
$$= 0.2212 + j0.6449$$
$$= 0.682\angle 71.06°\Omega$$

Example 1 – Solutions



Max power transfer to $\frac{R_2}{s}$ when

$$\frac{R_2}{s_{\max}} = \left| \mathbf{Z}_{TH} + jX_2 \right| \Rightarrow s_{\max} = 0.1131$$

Example 1 – Solutions

$$\left(\begin{array}{l}\text{Recall that } T_{ind} = \dfrac{P_{AG}}{\omega_{sync}} \text{ and since } P_{AG} = 3I_2^2\left(\dfrac{R_2}{s}\right), \text{ then max } T_{ind} \\ \text{occurs when the power consumed by } \dfrac{R_2}{s} \text{ is a maximum.}\end{array}\right)$$

$$\text{At } s_{\max}, \mathbf{I}_2 = 56.2\angle -39.29^\circ \text{ A}$$

$$\Rightarrow \max P_{AG} = 3(56.2)^2\left(\frac{0.151}{0.1131}\right) = 12650.5 \text{ W}$$

$$n_{sync} = \frac{120 f_s}{p} = 1800 \text{ r/min}$$

$$\Rightarrow T_{\max} = \frac{\max P_{AG}}{\omega_{sync}} = 67.11 \text{ N.m}$$

Starting of Induction Motors

- In many cases, induction motors can be started by connecting them to power supply directly. But the resulting starting current may cause a dip in power supply voltage, and hence, result in undesirable effects such as dimming of lamps, etc.

- If necessary, the starting current of an induction motor may be reduced by a starting circuit.

- One way is to change a normally delta connected motor to a star-connected motor during starting of induction motor. Phase voltage and hence starting current is reduced. When at full speed, reconnect back in a delta configuration.

Starting of Induction Motors

- Another way to reduce starting current is to insert extra inductors or resistors into the power line during starting. This approach is rare today.

- Some may reduce the motor’s terminal voltage during starting by using autotransformers to step it down, and once full speed is reached, full line voltage is applied back.

- For wound-rotor induction motor, starting can be achieved at relatively low currents by inserting extra resistance in the rotor circuit during starting. The extra resistance not only increases starting torque, but also reduces the starting current.

Summary of Induction Motors

- The induction motor is the most popular type of ac motor. Basically it is a rotating transformer.

- Two types of induction motors:
  - Squirrel-cage rotors
  - Wound rotors

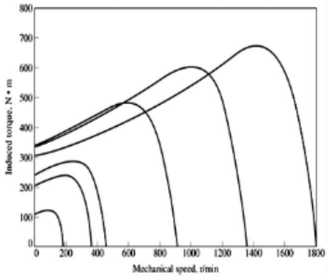
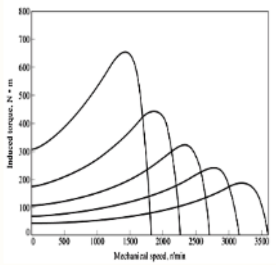
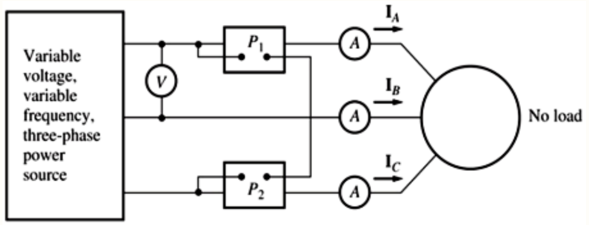
- An induction motor operates near synchronous speed, but it can never operate exactly at synchronous speed.

- The equivalent circuit of an induction motor is very similar to the equivalent circuit of a transformer.

Summary of Induction Motors

- The slip or speed at which the maximum torque occurs can be controlled by varying the rotor resistance.
- The value of the maximum torque is independent of the varying rotor resistance.
- Speed control of induction motors can be accomplished by changing the number of poles, the applied electrical frequency, the applied terminal voltage, or the rotor resistance in the case of wound-rotor type.
- Motor tests can be conducted to determine the circuit parameters of an induction motor.
- Starting circuits may be used to reduce the starting current to a safe level.

References

No.	Slide No.	Image	Reference
1	7		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 368), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
2	7		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 368), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
3	8		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 381), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.

References

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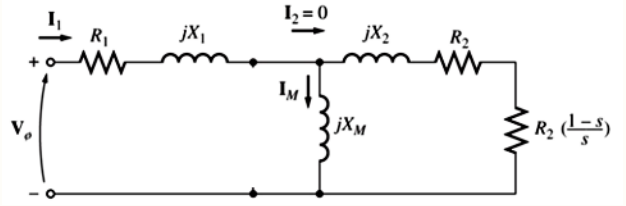
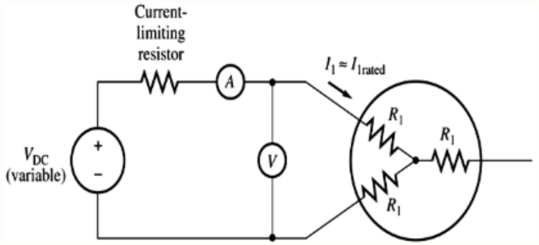
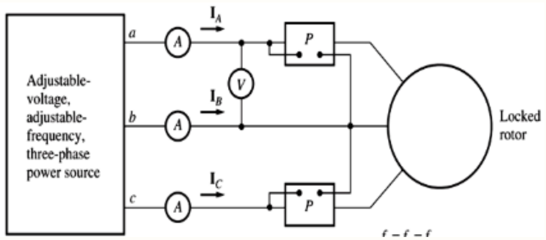
4	9		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 381), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Adapted with permission.
5	11		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 382), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
6	12		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 384), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.

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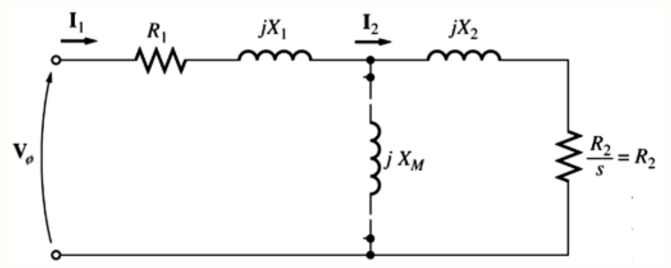
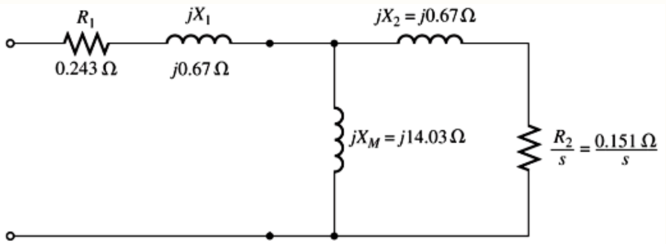
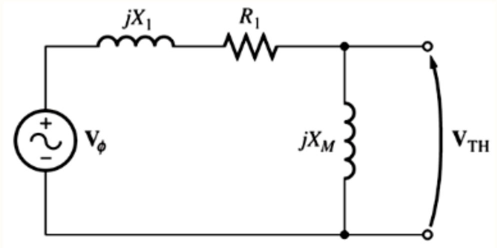
7	13		Adapted from *Electric Machinery Fundamentals, 5th ed.*, (p. 384), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Adapted with permission.
8	17		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 387), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
9	18		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 334), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.

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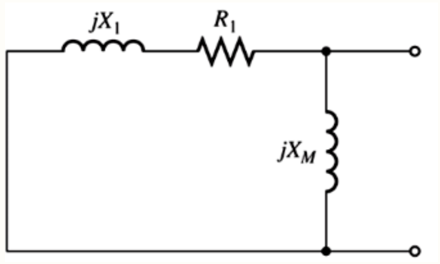
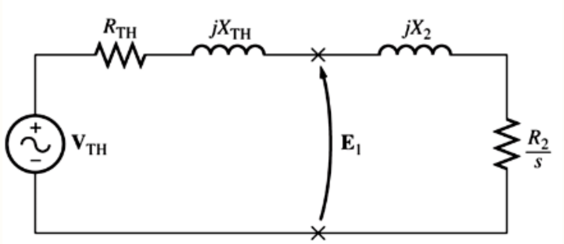
10	18		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 334), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.
11	19		Reprinted from *Electric Machinery Fundamentals, 5th ed.*, (p. 334), by S.J. Chapman, 2012, New York, NY: McGraw-Hill. Copyright 2012 by The McGraw-Hill Companies, Inc. Reprinted with permission.