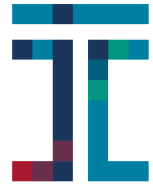

Cyprus University of Technology

EEN320 - Power Systems I (Συστήματα Ισχύος I)

Part 7: Induction machine

https://sps.cut.ac.cy/courses/een320/

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Today's learning objectives

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After this part of the lecture and additional reading, you should be able to . . .

1. . . . Understand the key differences between a synchronous motor and an induction motor;
2. . . . Understand the concept of rotor slip and its relationship to rotor frequency;
3. . . . Understand and know how to use the equivalent circuit of an induction motor; and,
4. . . . Be able to use the equation for the torque-speed characteristic curve.

Outline

1. Basic concepts of induction machine
2. Induction motor equivalent model
3. Induction machine characteristics

1 Outline

1. **Basic concepts of induction machine**
2. Induction motor equivalent model
3. Induction machine characteristics

1 Induced torque in induction machine

Supplying three-phase voltage to the stator creates a rotating magnetic field $\underline{B}_S$ with speed of rotation $n = (60 \ f_{se})/(P/2)$

The rotating magnetic field induces a voltage on the rotor (similar to a transformer). This is given by $e_{ind} = (\underline{v} \times \underline{B}) \cdot l$ where $\underline{v}$ is the velocity of the rotor relative to the magnetic field, $\underline{B}$ the magnetic flux density and l the length of the conductor.

The induced voltage creates a current in the rotor $\underline{I}_R$ (lagging the voltage due to the inductive nature of the rotor).

S. J. Chapman, Electric Machinery Fundamentals, 5th ed. McGraw-Hill, 2012.

2 Induction machine model

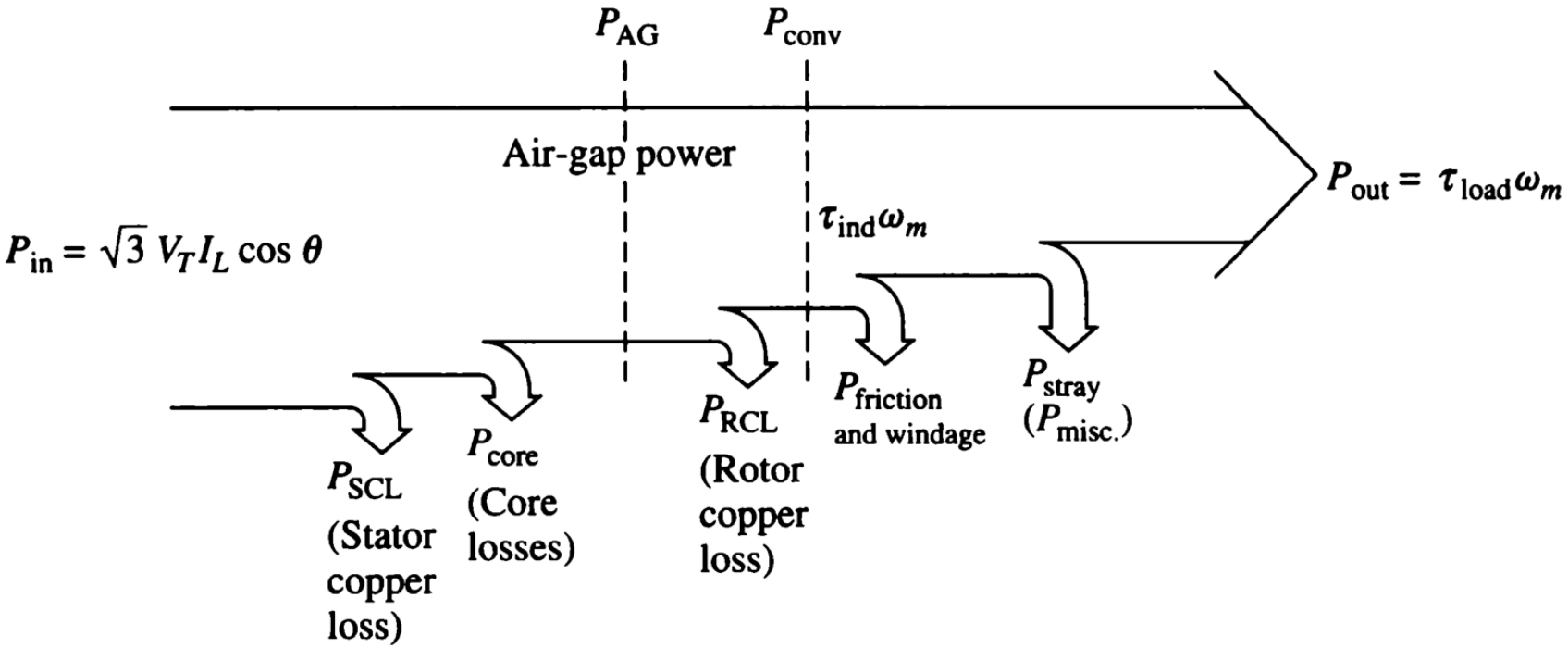
The induction machine is an electrical machine in which the stator windings are fed through a three- phase voltage source, while the rotor windings are short circuited and are circulated by currents induced by the stator.

In balanced steady-state conditions, the induction machine has an analog behavior to that of a transformer and hence a transformer model can be used to represent this machine.

It should be noted that the frequency on the secondary is different than the primary (unlike transformers).

S. J. Chapman, Electric Machinery Fundamentals, 5th ed. McGraw-Hill, 2012.

2 Losses and the power-flow diagram



S. J. Chapman, Electric Machinery Fundamentals, 5th ed. McGraw-Hill, 2012.

2 Losses and the power-flow diagram

Based on the digram of the induction motor:

- Stator coper losses
$$P_{SCL} = 3I_1^2 R_1$$
- Core losses
$$P_{core} = 3E_1^2 G_C$$
- Air-gap power
$$P_{AG} = P_{in} - P_{SCL} - P_{core} = 3I_2^2 \frac{R_2}{s}$$
- Rotor coper losses
$$P_{RCL} = 3I_2^2 R_2$$
- Developed mechanical power
$$P_{conv} = 3I_2^2 R_2 \left(\frac{1-s}{s}\right) = (1-s)P_{AG}$$
- Developed torque
$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s)P_{AG}}{(1-s)\omega_{sync}} = \frac{P_{AG}}{\omega_{sync}}$$

3 Outline

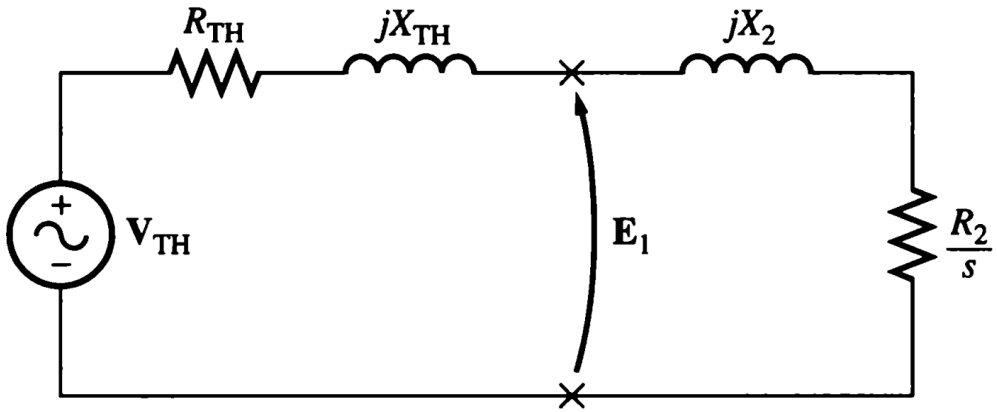
1 Basic concepts of induction machine

2 Induction motor equivalent model

3 **Induction machine characteristics**

3 Thevenin equivalent

We can use the Thevenin equivalent for the primary side of the induction motor model (ignoring R_C):



where

$$V_{TH} = V_\phi \frac{X_M}{X_1 + X_M} \qquad \textit{and} \qquad Z_{TH} = R_{TH} + jX_{TH} = \frac{Z_1 Z_M}{Z_1 + Z_M}$$

and

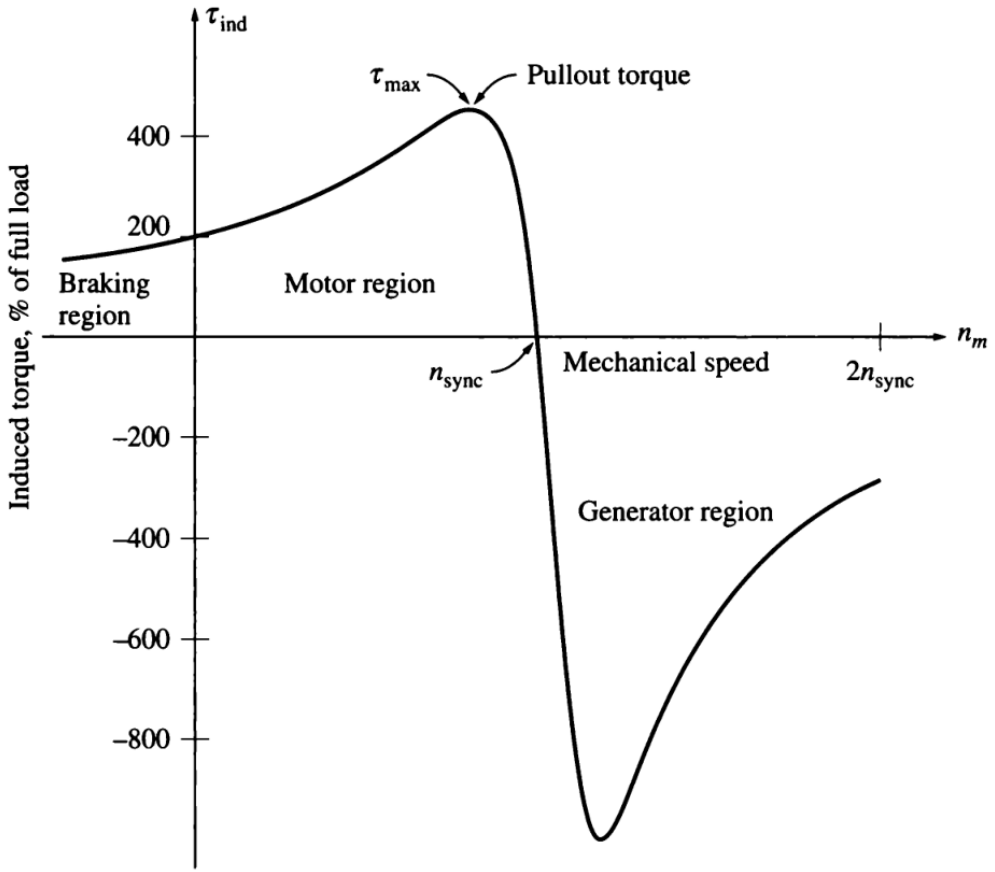
$$I_2 = \frac{V_{TH}}{Z_{TH} + Z_2}$$

S. J. Chapman, Electric Machinery Fundamentals, 5th ed. McGraw-Hill, 2012.

3 Torque-speed characteristic

Using the Thevenin equivalent, we get:

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{3V_{TH}^2 R_2/s}{\omega_{\text{sync}}\left[(R_{TH} + R_2/s)^2 + (X_{TH} + X_2)^2\right]}$$



S. J. Chapman, Electric Machinery Fundamentals, 5th ed. McGraw-Hill, 2012.

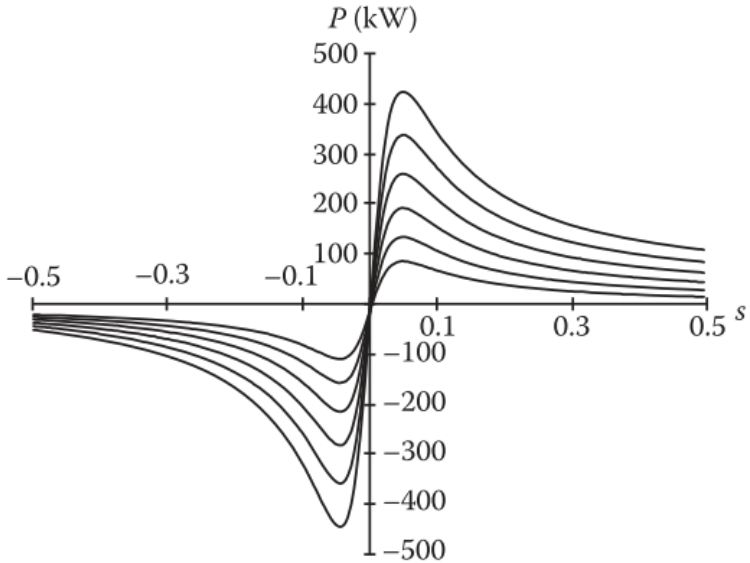
Using the *maximum power transfer theorem*, the slip at maximum power is given by:

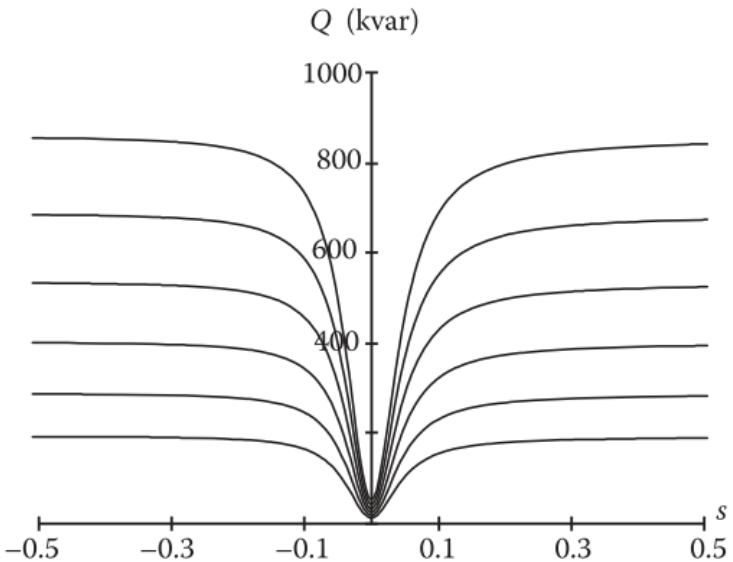
$$\frac{R_2}{s} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2} \rightarrow s_{max} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}}$$

Leading to:

$$\tau_{ind-max} = \frac{3V_{\mathrm{TH}}^2}{2\omega_{\mathrm{sync}}\left[R_{\mathrm{TH}} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}\right]}$$

3 P-s and Q-s characteristics





- Special cases: $s = 1 \rightarrow$ locked-rotor, $s = 0 \rightarrow$ no-load
- Operating limits:
  - Stator thermal limit I_{max}
  - Dielectric insulation or maximum feeding voltage limit $V_{s,max}$
  - Stability or magnetizing limit (from curve)

A. Gomez-Exposito, A. J. Conejo, and C. A. Cañizares, Electric Energy Systems Analysis and Operation, 2018.

- Induction motors do not present the types of starting problems that synchronous motors do (check torque curve).
- However, the starting current required may cause an unacceptable dip in the power system voltage
- Starting apparent power is given

$$S_{start} = \frac{\text{rated power}}{\text{code letter factor}} \longrightarrow I_{start} = \frac{S_{start}}{\sqrt{3}V_T}$$

- To limit the starting current, different methods are used:
  - Autotransformer starter
  - Three-step resistive starter
  - Star-Delta method

Nominal code letter	Locked rotor, kVA/hp	Nominal code letter	Locked rotor, kVA/hp
A	0 – 3.15	L	9.00 – 10.00
B	3.15 – 3.55	M	10.00 – 11.00
C	3.55 – 4.00	N	11.20 – 12.50
D	4.00 – 4.50	P	12.50 – 14.00
E	4.50 – 5.00	R	14.00 – 16.00
F	5.00 – 5.60	S	16.00 – 18.00
G	5.60 – 6.30	T	18.00 – 20.00
H	6.30 – 7.10	U	20.00 – 22.40
J	7.10 – 8.00	V	22.40 and up
K	8.00 – 9.00		