COLORADO SCHOOL OF MINES
ELECTRICAL ENGINEERING DEPARTMENT

EENG 577

ADVANCED ELECTRICAL MACHINE DYNAMICS FOR SMART-GRID SYSTEMS

M5-1 Induction Machines – An Overview

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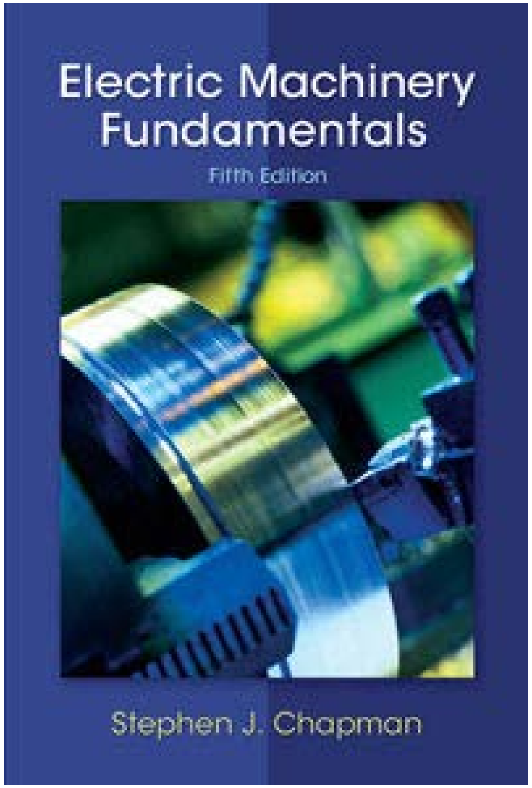
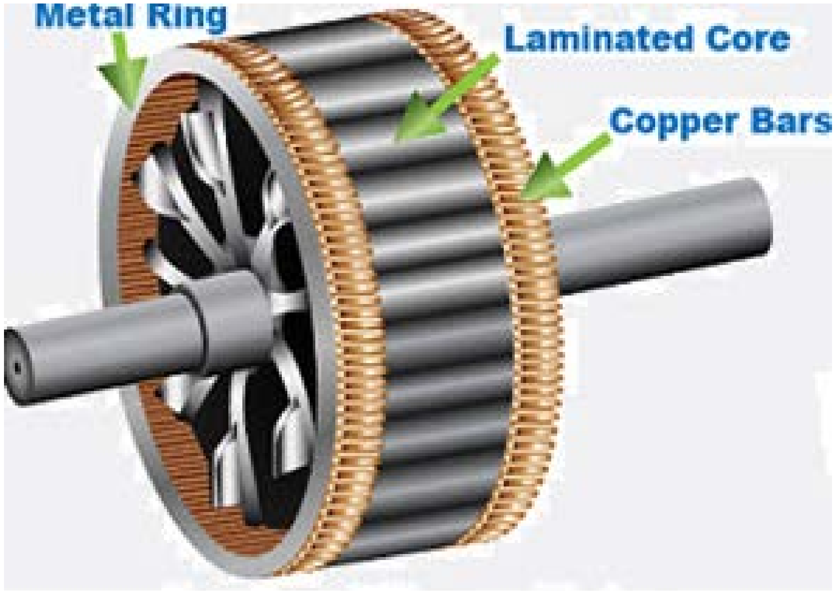


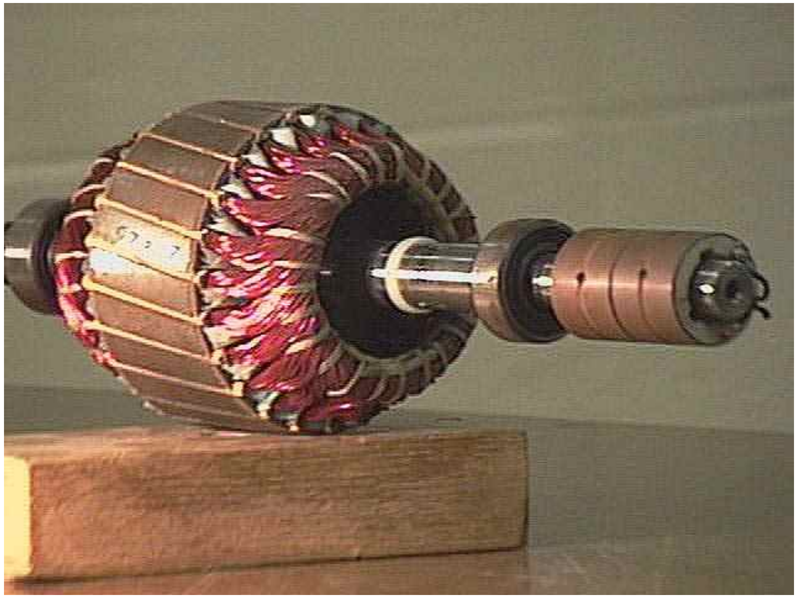
Source: Chapter 6 - Induction Motors

Overview Learning Objectives

- Explain principle of operation of an induction motor.
- Describe the concept of rotor slip and its relationship to rotor frequency.
- Draw and explain how to use the equivalent circuit of an induction motor.
- Explain the power flow diagram of an induction motor.
- Describe and use the equation for the torque–speed characteristic curve.
- Find information to measure induction motor circuit model parameters.
- Describe how the induction machine can be used as a generator.



Squirrel Cage Rotor



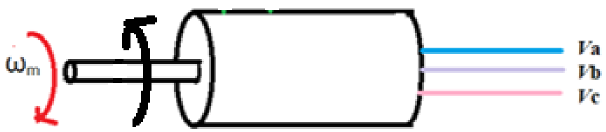
Wound Rotor

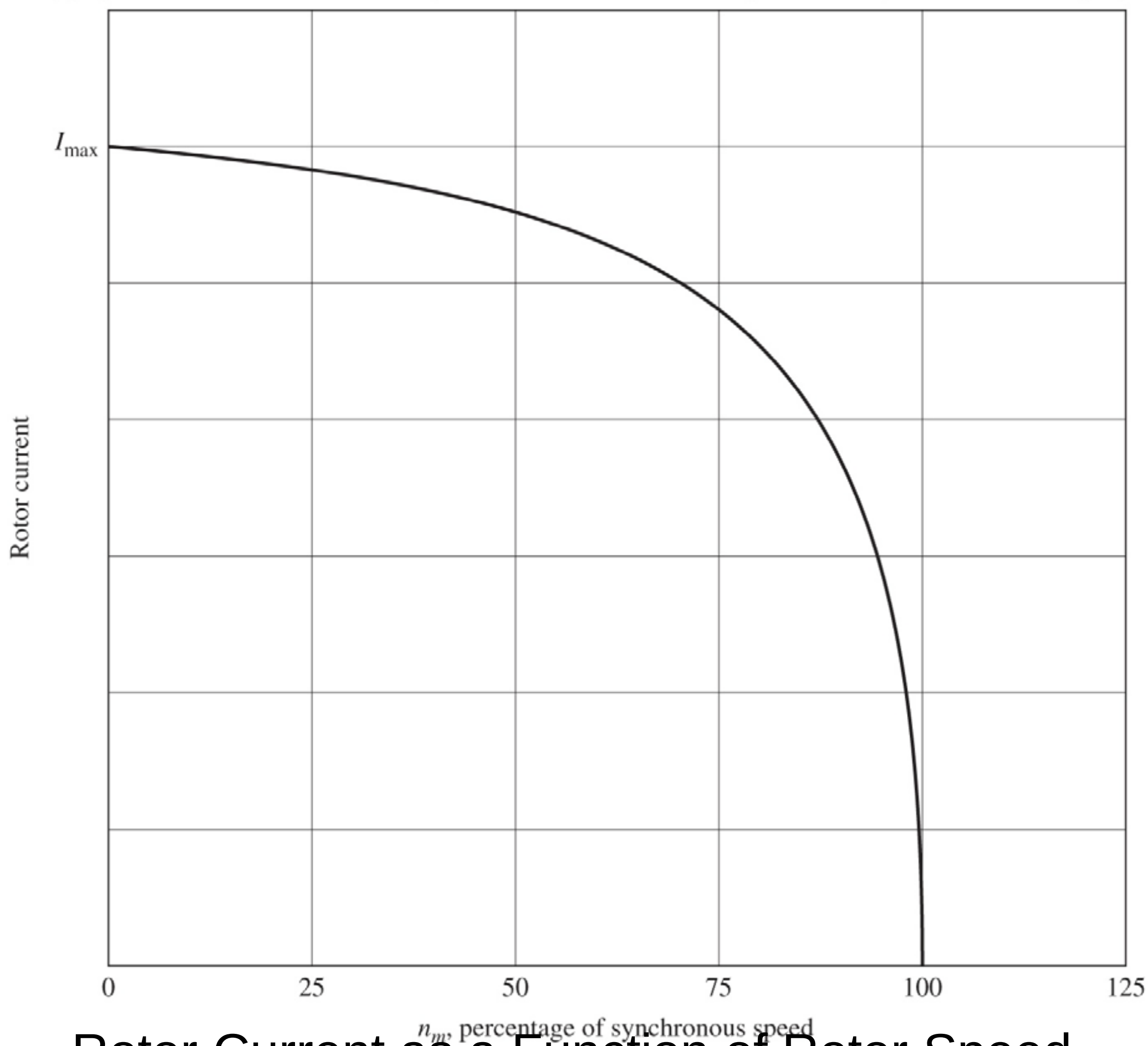
Source: Wikipedia

Consider a cage rotor induction motor. A three-phase set of voltages has been applied to the stator armature windings and resulted in a three-phase set of stator currents flowing. The stator currents produce a magnetic field $\mathbf{B_S}$, rotating at synchronous speed or n_{syn} in rev/min at the airgap. The speed of the magnetic field's rotation is given by

$$n_{sync} = 120\, f_{se}/P \qquad (6\text{–}1)$$

where f_{se} is the system frequency applied to the stator in Hertz and P is the number of poles in the machine. This rotating magnetic field $\mathbf{B_S}$ passes over the rotor bars and induces voltage in the rotor circuits. The 3-phase rotor currents in turn produce a rotating magnetic field $\mathbf{B_r}$. The interaction of the stator and rotor magnetic fields produces a torque that will result in a rotational speed, ω_m, or n_m in rev/min at the rotor shaft of an induction motor.





Rotor Current as a Function of Rotor Speed

The Concept of Rotor Slip

- Slip speed is defined as the difference between synchronous speed and rotor speed:

$$n_{slip} = n_{sync} - n_m$$

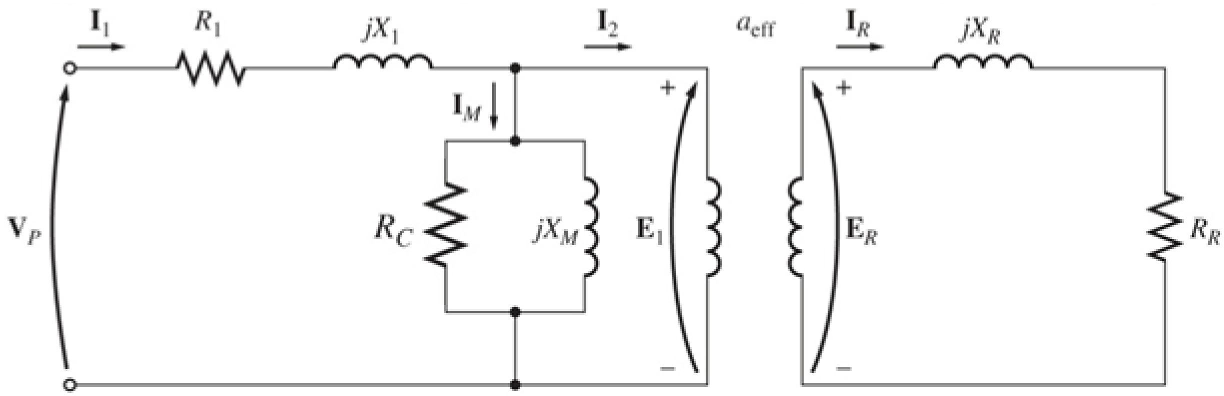
Where $n_{slip} =$ slip speed of the machine

$n_{sync} =$ speed of the magnetic field

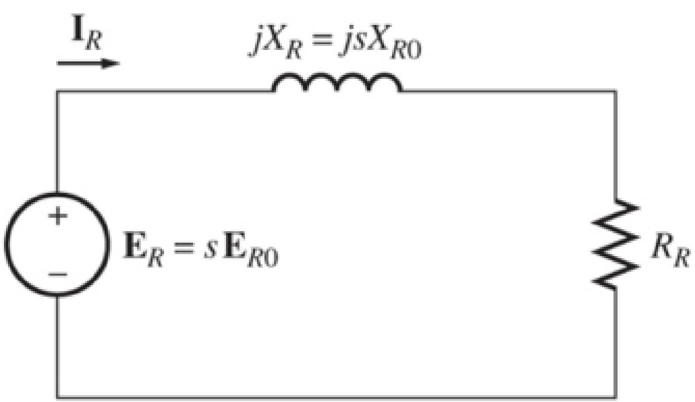
$n_m =$ rotor mechanical speed

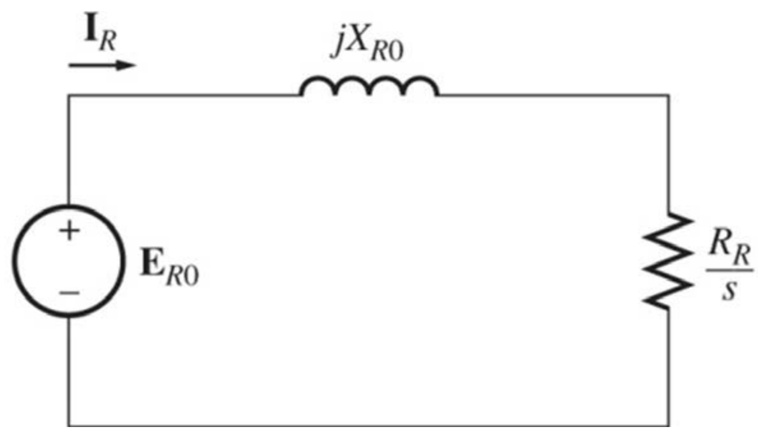
$$\text{slip} = s = \frac{n_{slip}}{n_{sync}} = \frac{n_{sync} - n_m}{n_{sync}}$$

Equivalent Circuit of Induction Motor

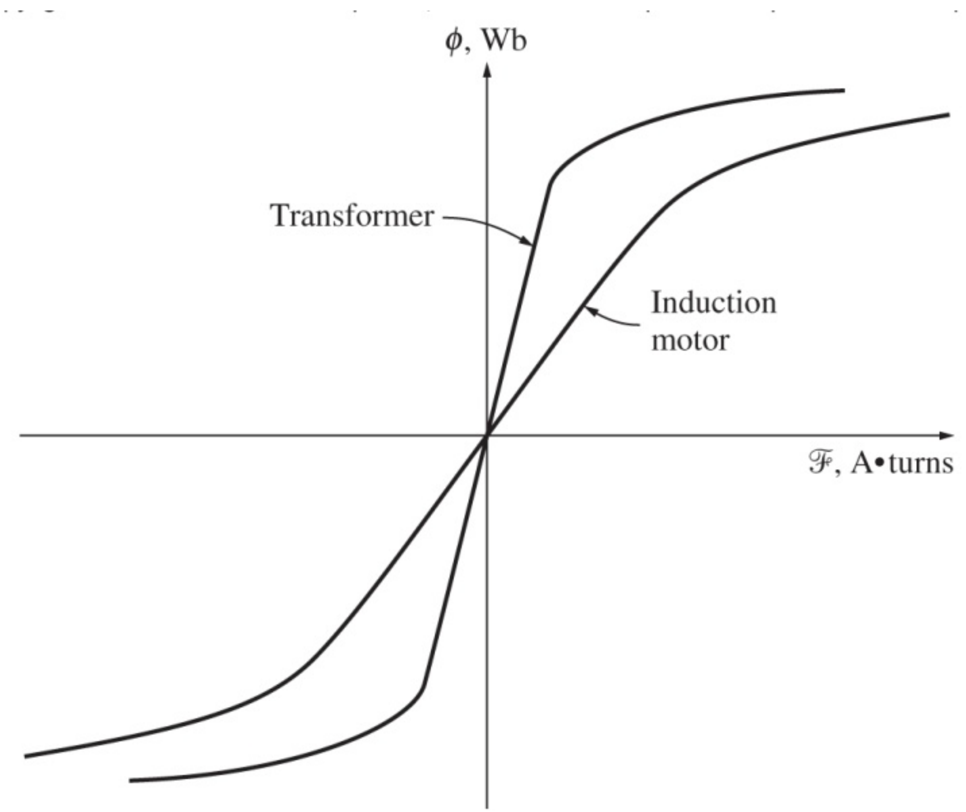


If E_{R0} is the induced rotor voltage at locked-rotor conditions and the magnitude of rotor voltage at any **slip "s"** is $E_R = sE_{R0}$ and $f_{re} = sf_{se}$





- Unlike a transformer, in an induction motor, due to the presence of an air gap, the magnetizing current is significant, and its effect may not be ignored. However, the core-loss resistance may be removed from the equivalent circuit and its effect accounted for by including core losses later in the calculations.

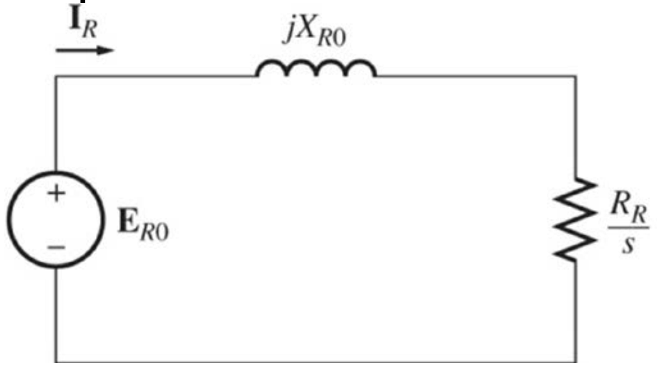


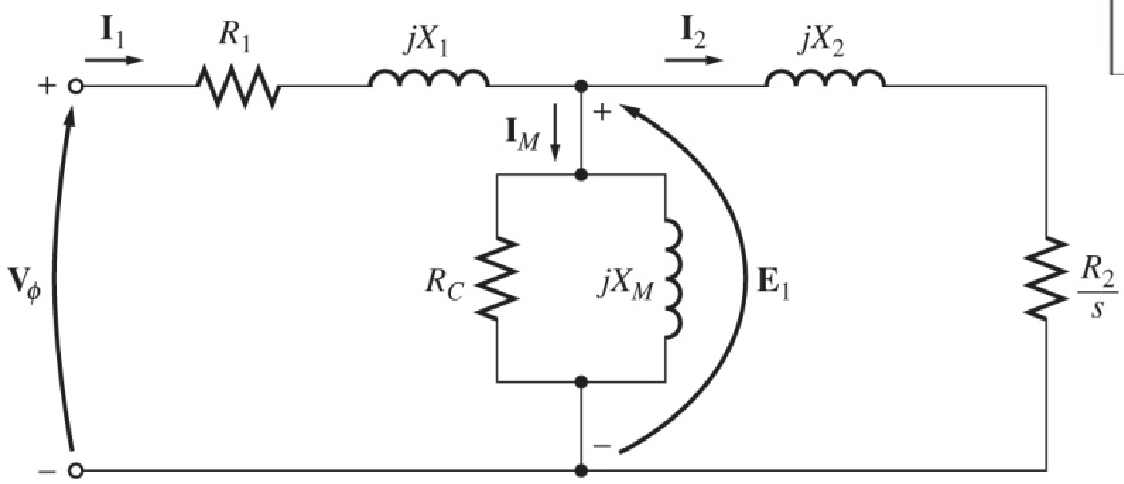
The magnetization curve of an induction motor compared to that of a transformer.

The Transformer Model of an Induction Motor

R_1 = Stator resistance/phase
X_1 = Stator leakage reactance/phase
R_2= Rotor resistance referred to stator/phase
X_2 = Rotor leakage reactance referred to stator/phase

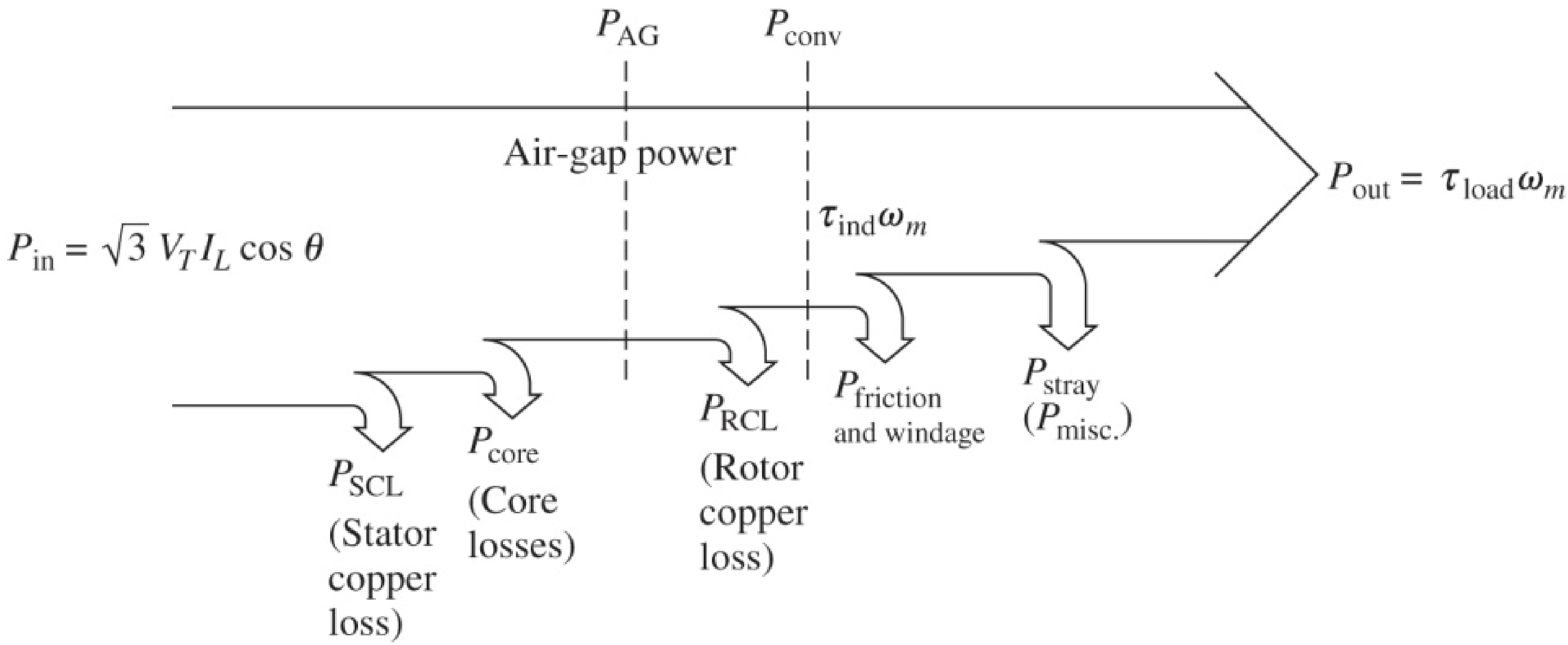
Recall



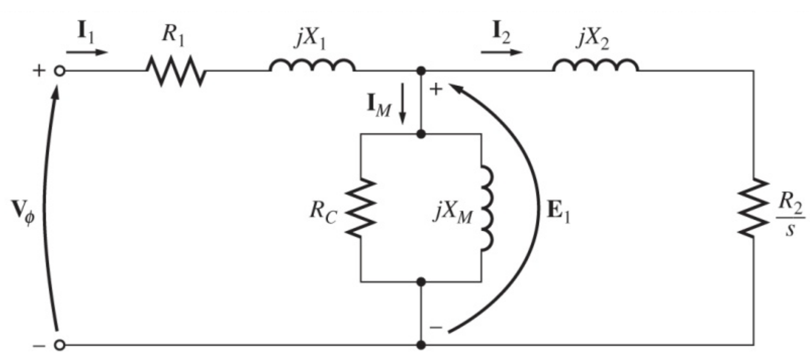


The per-phase equivalent circuit of an induction motor.

Power Flow and Losses of an Induction Motor



The power-flow diagram of an induction motor



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Power and Torque in an Induction Motor

- The input impedance of the motor is given by

$$Z_{eq} = (R_1 + jX_1) + (jX_m) \| (R_2/s + jX_2)$$

(R$_c$ Removed & lumped into losses)

$$I_1 = \frac{V_\phi}{Z_{eq}} = I_1 \angle \theta_1$$

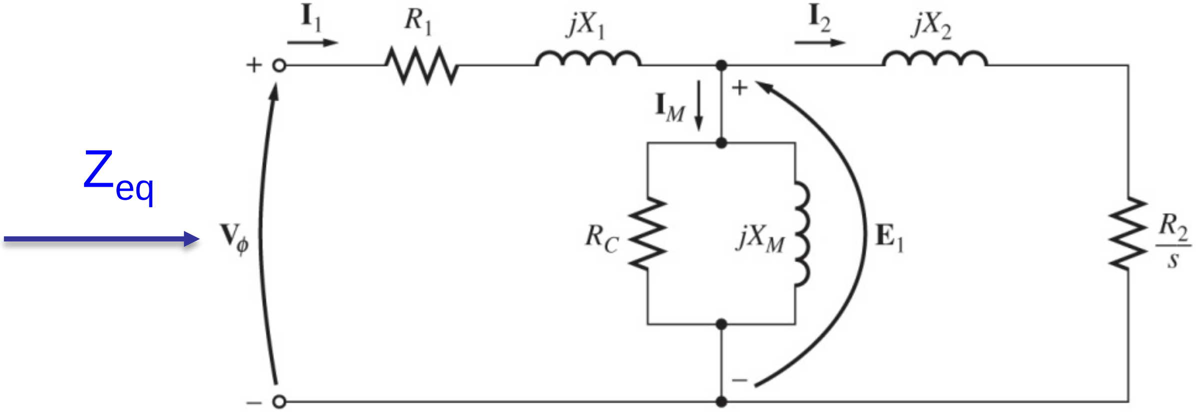
$$P_{in} = 3V_1 I_1 Cos(\theta_1)$$

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

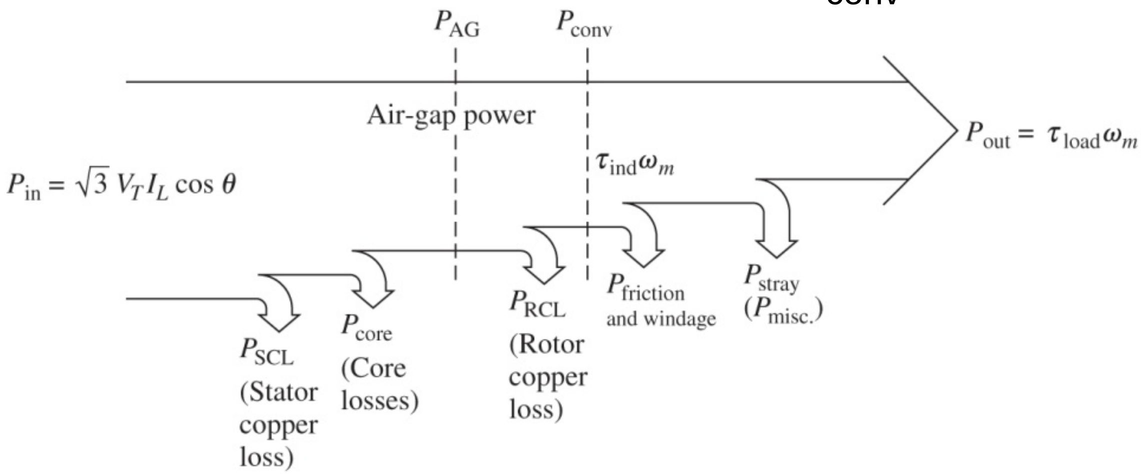
$$P_{SCL} = 3 I_1^2 R_1$$

Alternatively,

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



- The power converted from electrical to mechanical form, P_{conv}, is given by



$$P_{conv} = P_{AG} - P_{RCL}$$

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

$$P_{conv} = (1-s)P_{AG}$$

- The output power can be found as

$$P_{out} = P_{conv} - P_{F\&W} - P_{misc}$$

- The induced torque is given by the equation

$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s)P_{AG}}{(1-s)\omega_{sync}} = \frac{P_{AG}}{\omega_{sync}}$$

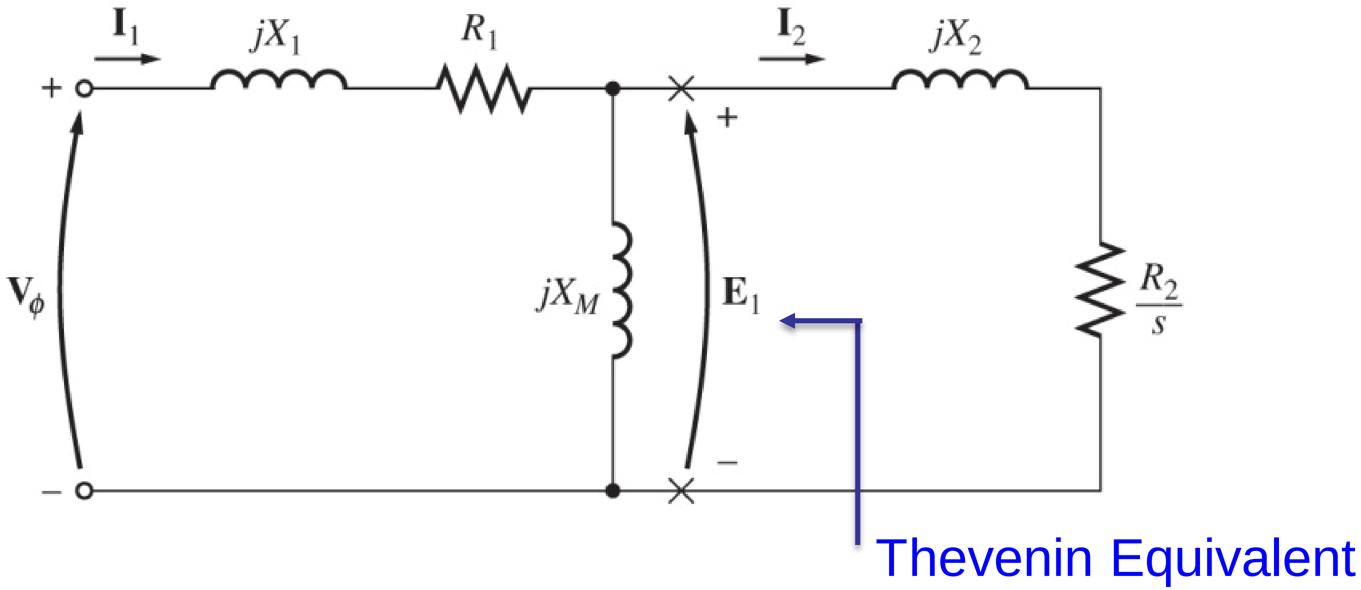
$$\tau_{ind} = \frac{3}{\omega_{sync}} I_2^2 \left(\frac{R_2}{s}\right)$$

Induced Torque in an Induction Motor

- The induced torque in an induction motor:

$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{AG}}{\omega_{sync}} = \frac{3}{\omega_{sync}} I_2^2 \left(\frac{R_2}{s}\right)$$

- ***To find rotor current I_2, the stator circuit is replaced with its Thevenin equivalent circuit.***



Per-phase equivalent circuit of an induction motor.

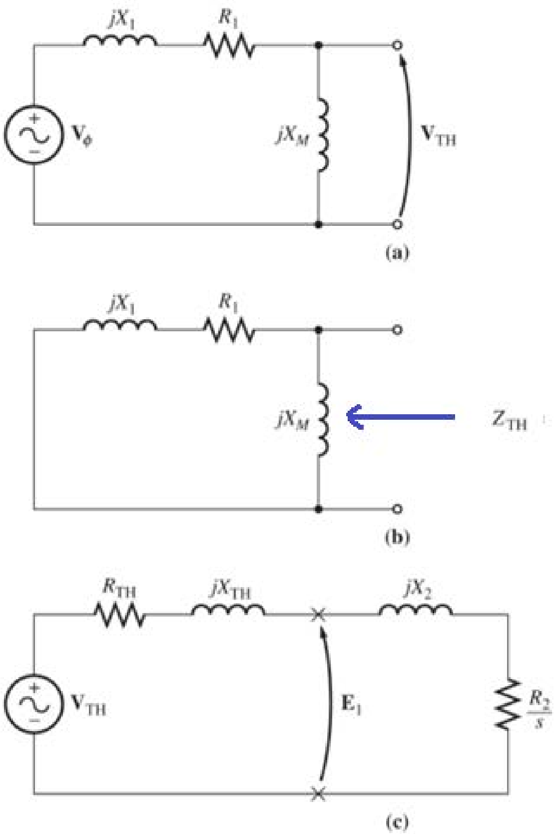
$$\mathbf{V}_{TH} = \mathbf{V}_{\phi} \frac{jX_M}{R_1 + j(X_1 + X_M)}$$

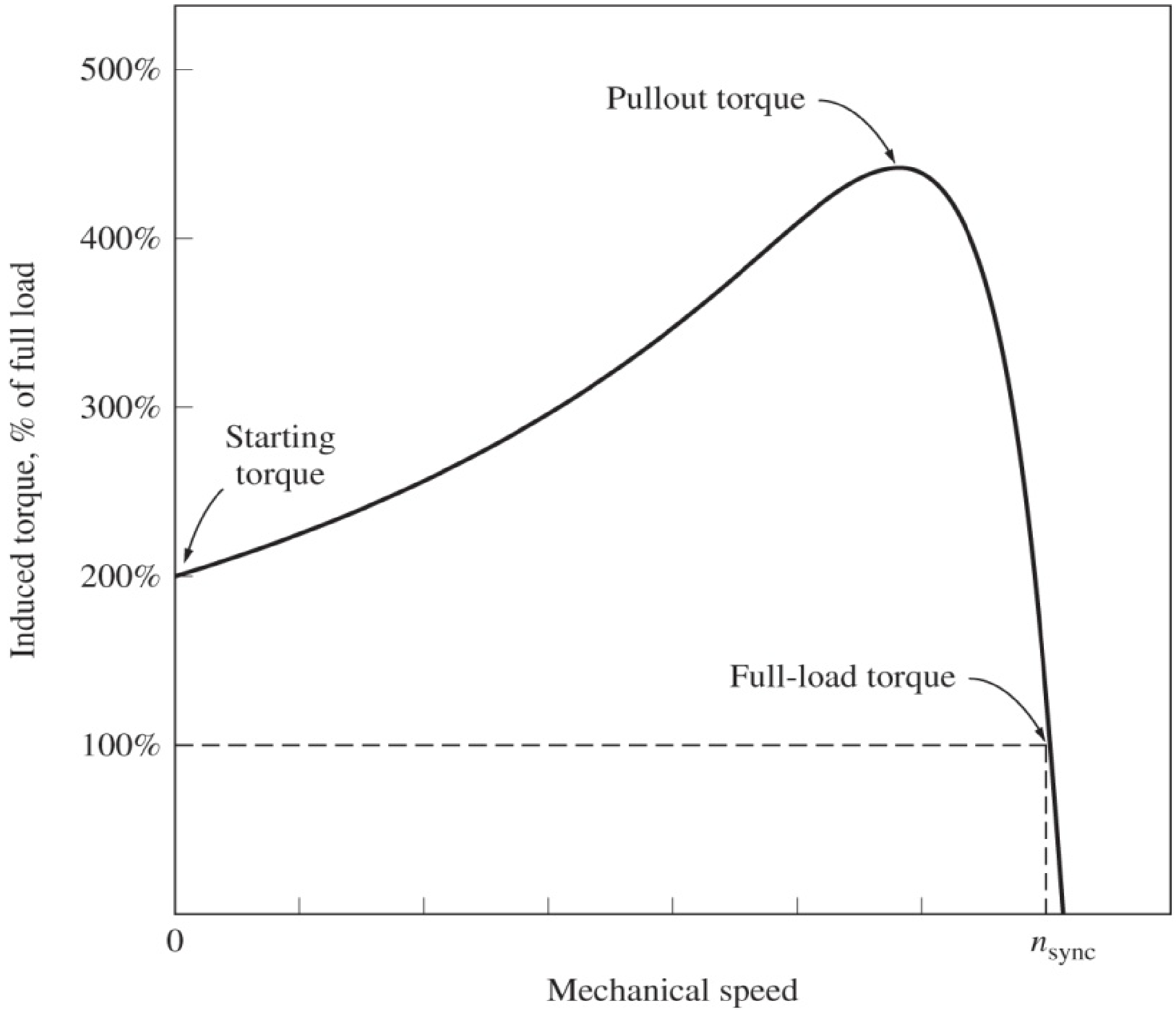
$$Z_{TH} = R_{TH} + jX_{TH} = \frac{jX_M(R_1 + jX_1)}{R_1 + j(X_1 + X_M)}$$

$$\mathbf{I}_2 = \frac{\mathbf{V}_{TH}}{R_{TH} + (R_2/s) + j(X_{TH} + X_2)}$$

$$I_2 = \frac{V_{TH}}{\sqrt{(R_{TH} + R_2/s)^2 + (X_{TH} + X_2)^2}}$$

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





A typical induction motor torque-speed characteristic curve

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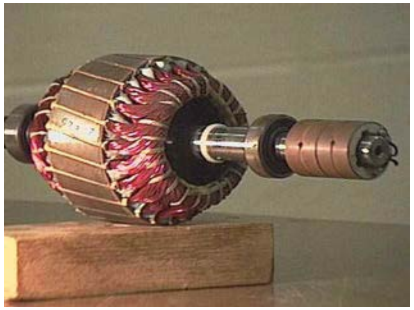
Maximum (Pullout) Torque in an Induction Motor

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

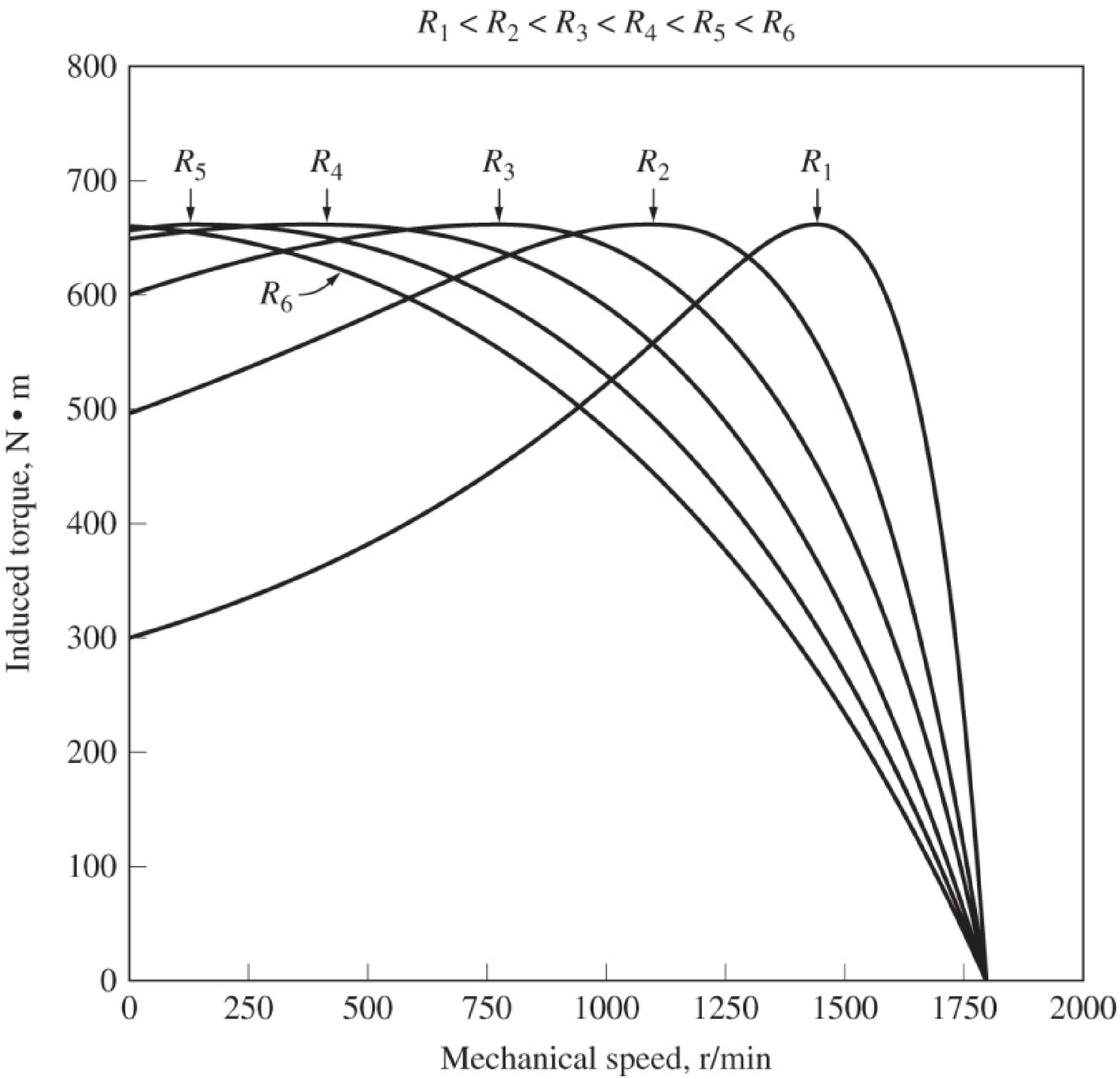
$$\frac{d\tau_{ind}}{ds} = 0$$

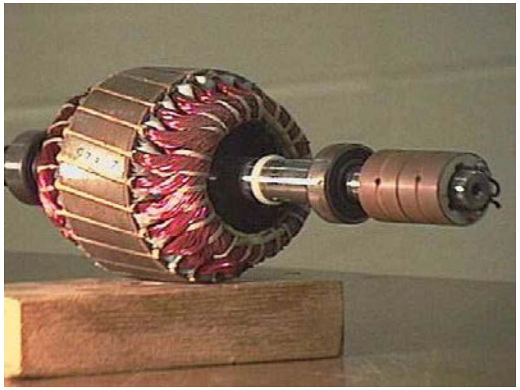
$$s_{max} = \frac{R_2}{\sqrt{R_{TH}^2 + \left(X_{TH}+X_2\right)^2}}$$

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



- *Slip at maximum torque can be varied by changing rotor resistance while the corresponding maximum torque is independent of* R_2





Effect of **varying rotor resistance** on the torque-speed characteristic of a wound-rotor induction motor.

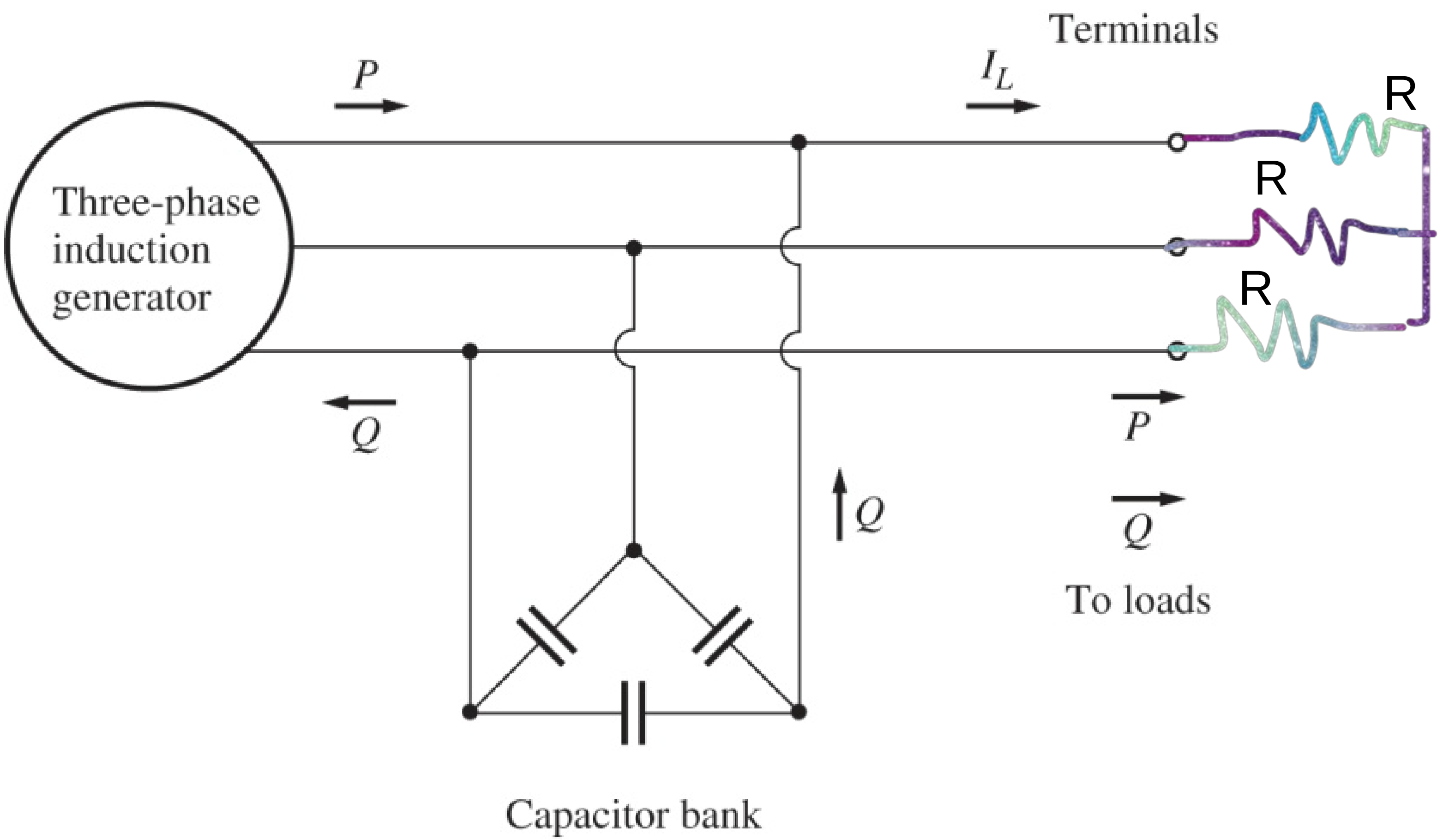
Induction Motor Testing

(IEEE Standard 112)

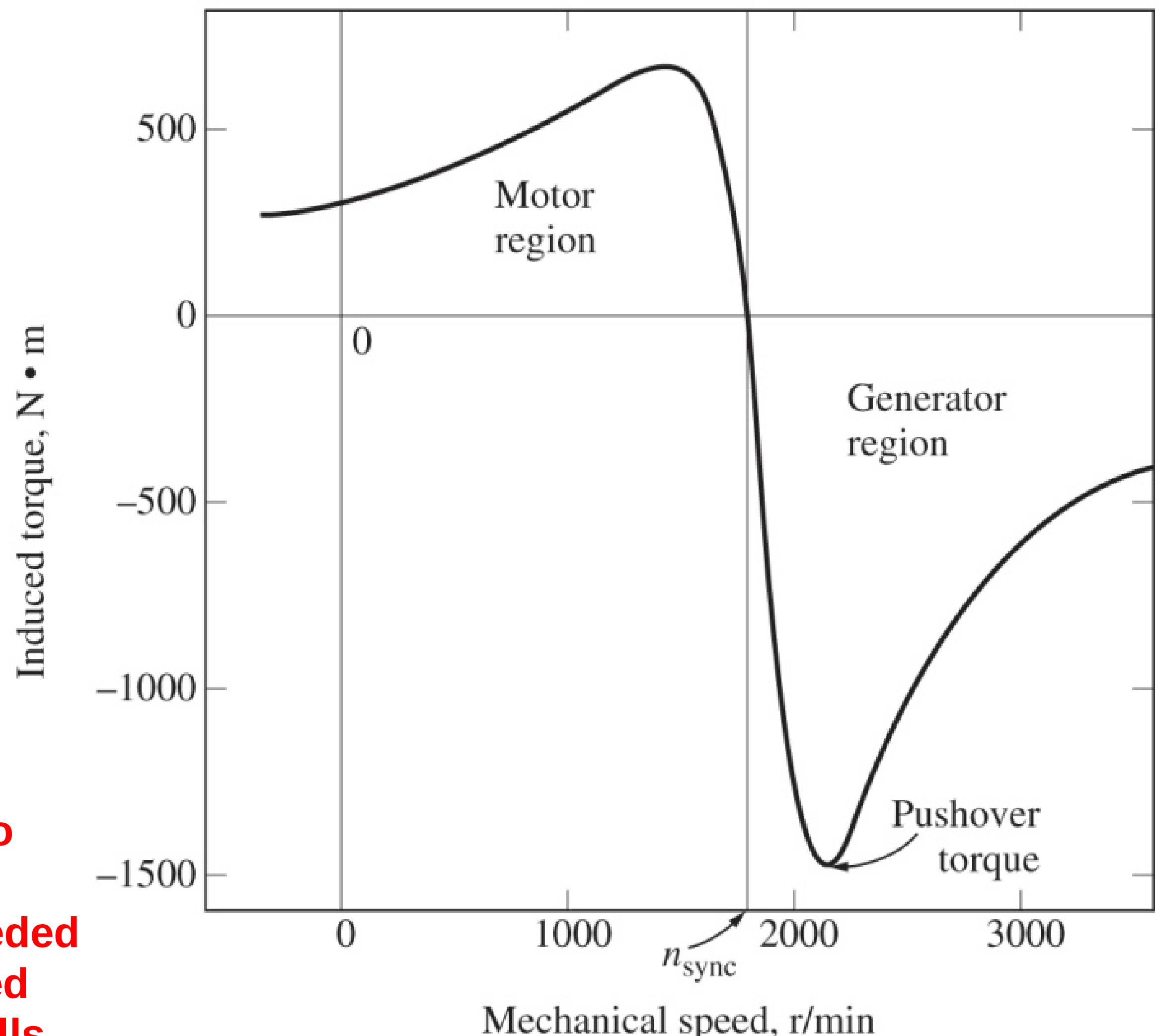
- The **No-Load Test**: to obtain the rotational losses and information leading to magnetizing reactance.
- The **DC Test**: to obtain stator resistance, R_1.
- The **Locked-Rotor** (or **Blocked-Rotor**) Test: to obtain R_2, X_1+X_2, and X_M (using the no-load test results).

For full details, IEEE Standard 112 should be consulted.

The Induction Generator

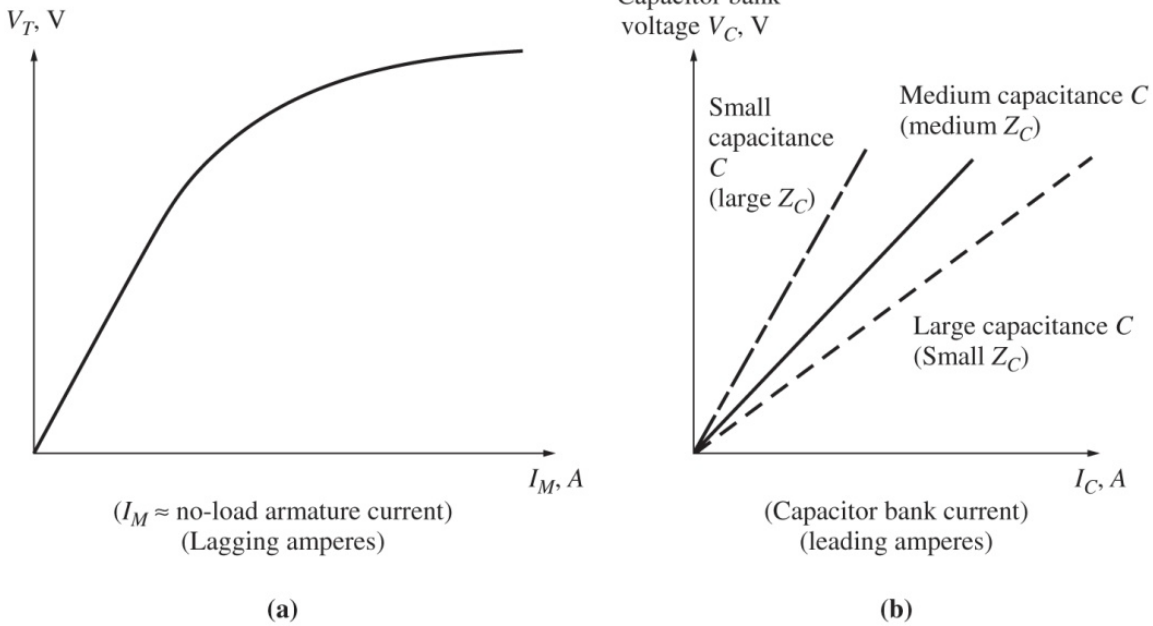


The Induction Generator



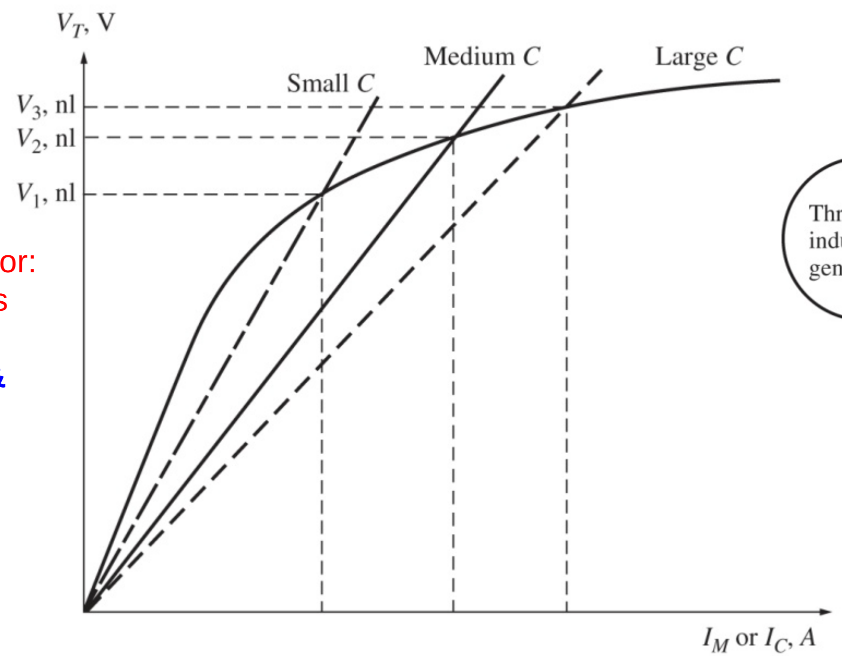
- We use a prime mover to drive the rotor
- If pushover speed exceeded generator will overspreed
- Good choice for windmills

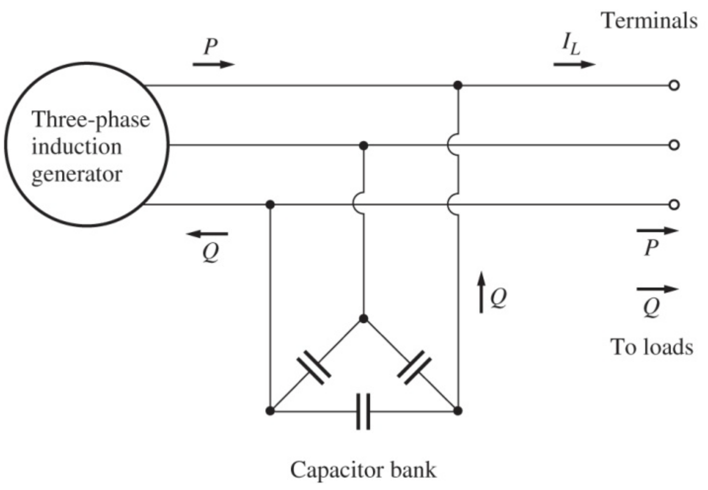
IM Terminal Voltage vs. Magnetization Current

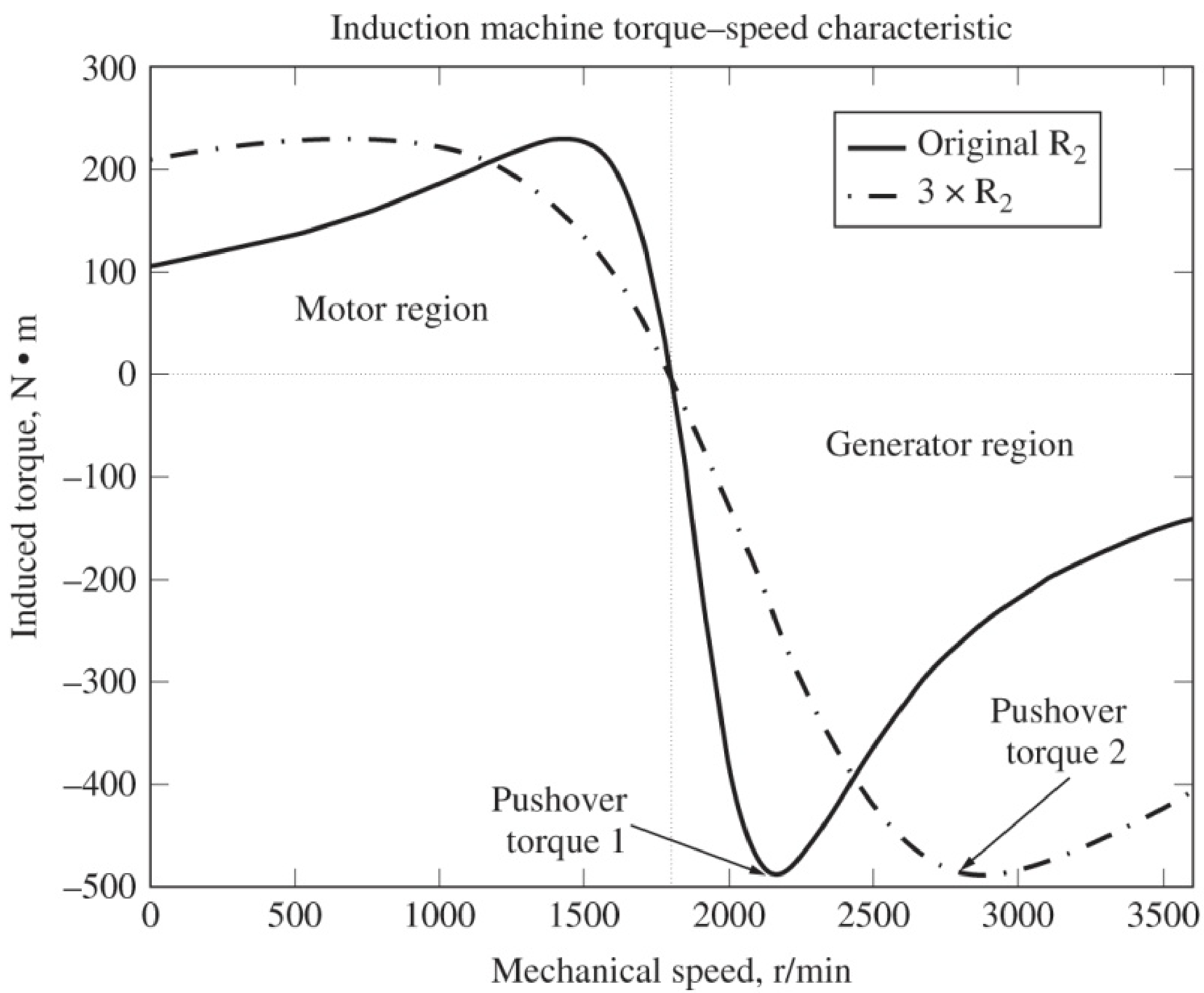


Capacitor Bank Voltage Current Characteristics

Isolated Induction Generator: **Terminal Voltage** found as **the Intersection** of **Gen. Terminal** Characteristics **& Cap. Voltage-Current** Characteristics

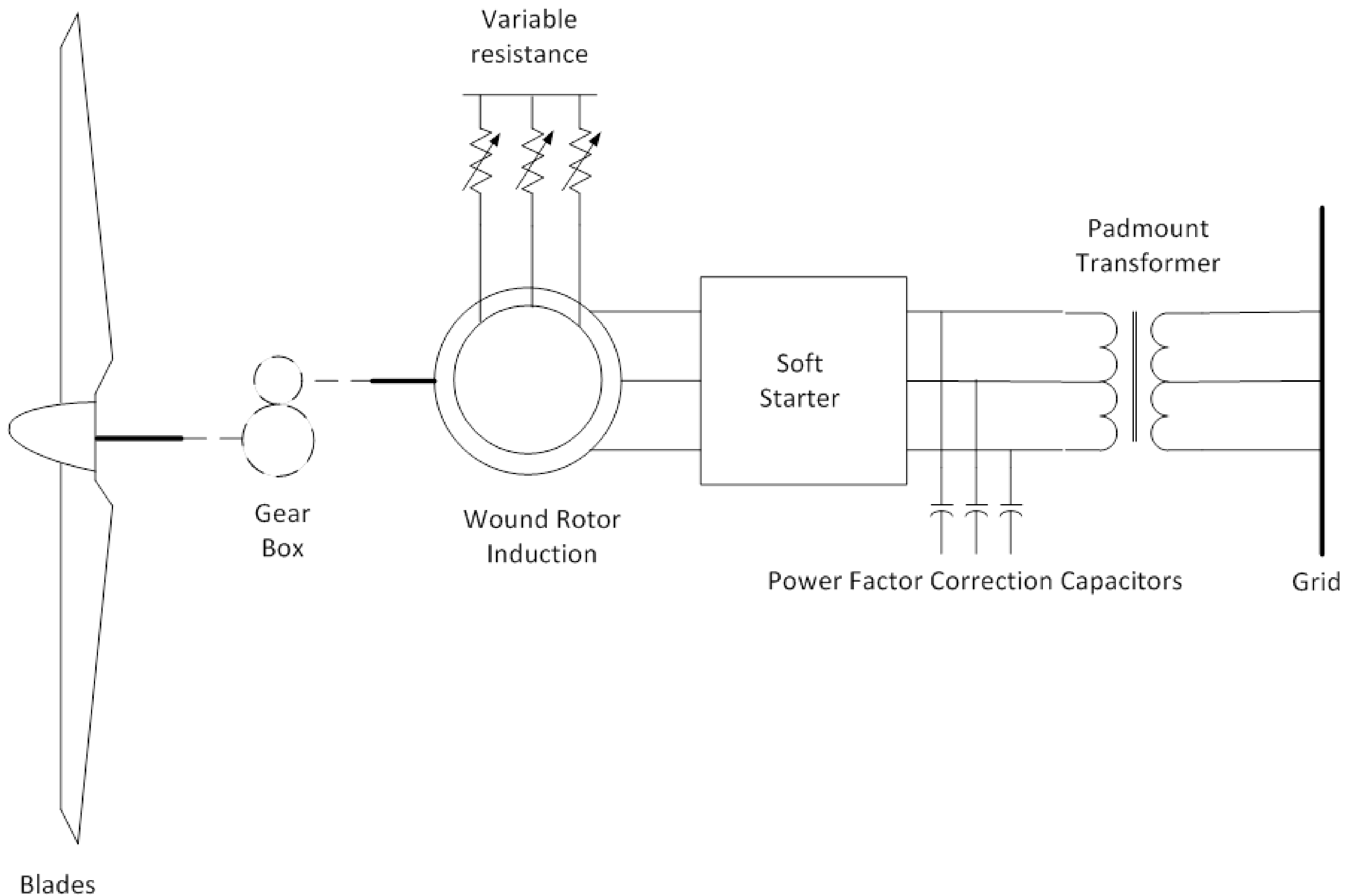






Torque-Speed Characteristics of Wound Rotor IM with Original R_2 and triple R_2 Values ⇒ **Increase** in Generator Operating **Speed Range**

Wound-Rotor Induction Generator with External Resistance Control



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