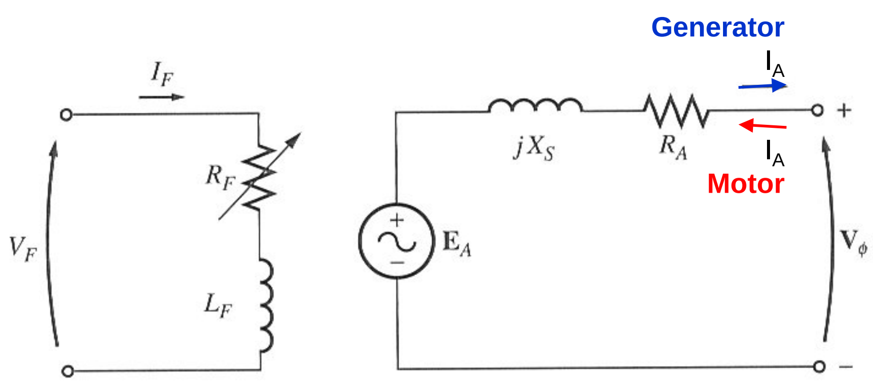
Electric Motors

- **Three basic types of motors**
  - Synchronous, SM
  - Induction (asynchronous), IM
  - DC motors
    - In the past: preferred for variable speed applications
    - Decreasing in popularity; replaced by combination of IM and power electronic variable speed drive (VSD)
- **Applications**
  - SM: largest power ratings, e.g. pumps for hydro power plant, electric ship propulsion, steel mills (with VSD)
  - IM: “workhorse” of the power industry, from fractional kW to MW ratings, e.g. air conditioner (compressor, fan), elevator, crane, electric vehicle (with VSD)
  - DC: low power, pure DC applications such as cars, also universal motor (for DC and AC),

Synchronous Motor (SM)

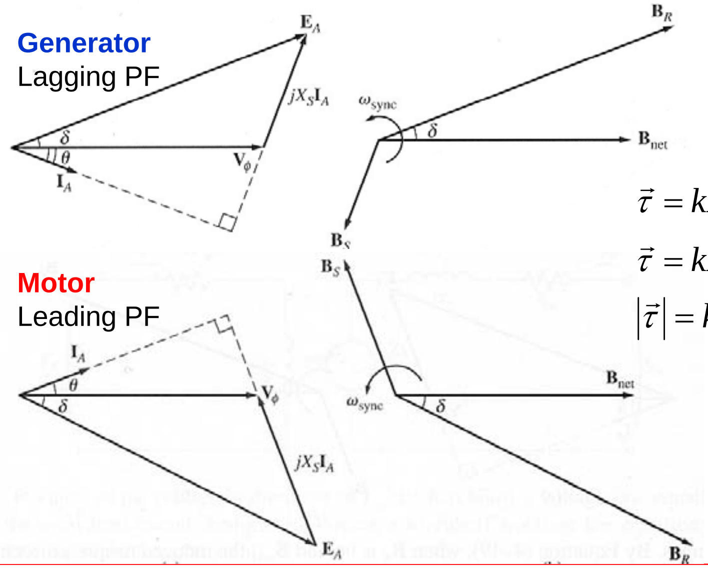


Generator: source convention, positive power **leaves** the machine
Motor: load convention, positive power **enters** the machine

Synchronous Motor (SM)

Generator
Lagging PF

Motor
Leading PF

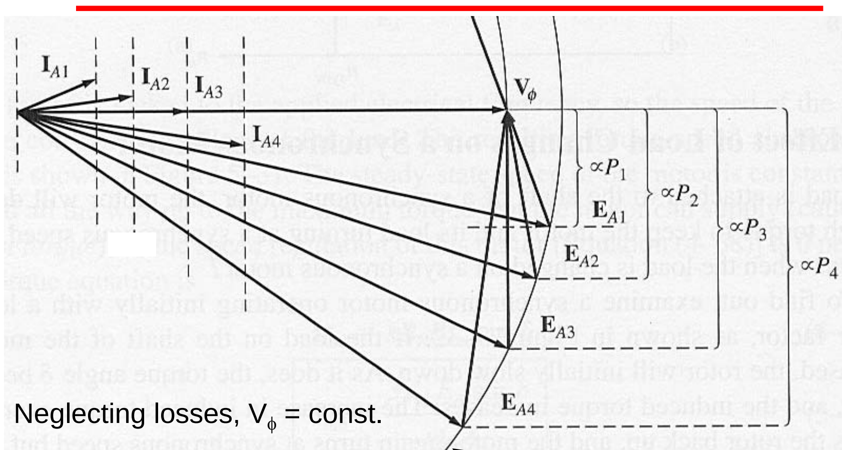


$$\vec{\tau} = k\vec{B}_R \times \vec{B}_S$$

$$\vec{\tau} = k\vec{B}_R \times \vec{B}_{Net}$$

$$\left|\vec{\tau}\right| = kB_R B_{Net} \sin\left(\delta\right)$$

SM Loading Characteristic, I_F = const

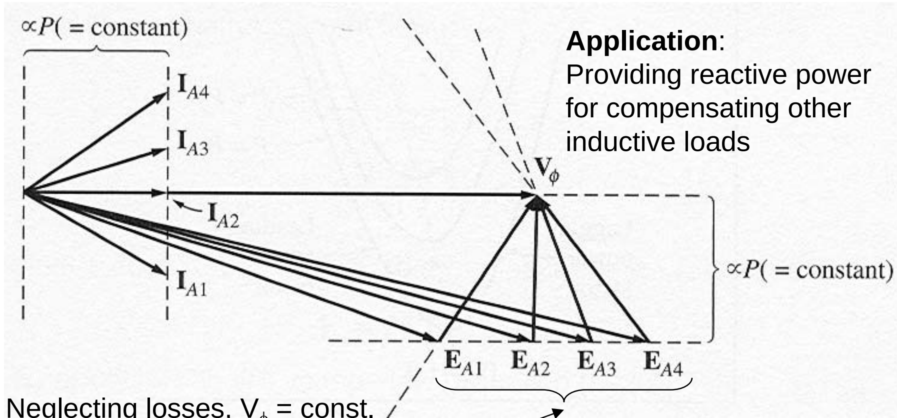


Neglecting losses, V_ϕ = const.

$$P_{in} = P_{out} = \frac{3V_\phi E_A \sin(\delta)}{X_S}$$

Constant field current: E_A = const.

SM Reactive Power Characteristic, P = const



Application:
Providing reactive power for compensating other inductive loads

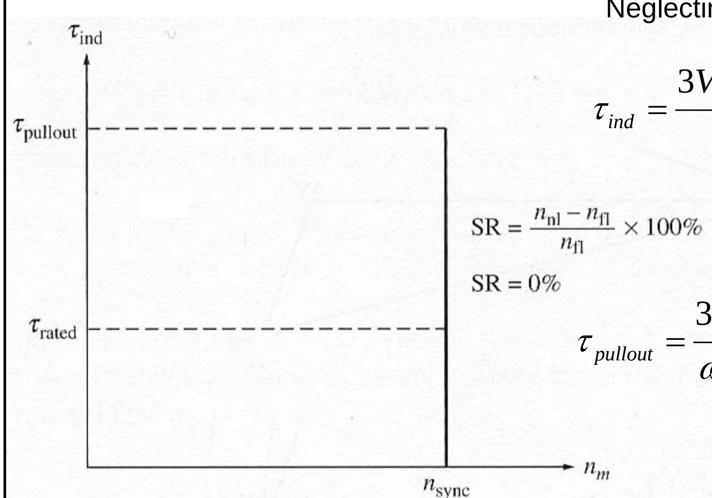
Neglecting losses, V_ϕ = const.

Varying field current: $E_A = k \cdot I_F$

$$P_{in} = P_{out} = \frac{3V_\phi E_A \sin(\delta)}{X_S}$$

SM Torque-Speed Characteristic

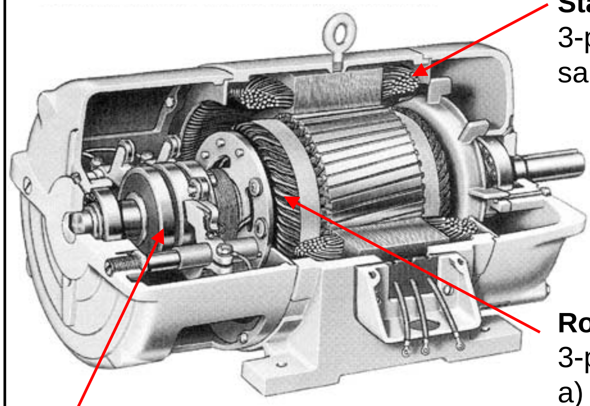
Neglecting losses:



$$\tau_{ind} = \frac{3V_\phi E_A \sin(\delta)}{\omega_m X_S}$$

$$\tau_{pullout} = \frac{3V_\phi E_A}{\omega_m X_S}, \delta = 90°$$

Induction (asynchronous) Motor (IM)



Stator (Armature)
3-phase winding, same as SM

Rotor
3-phase (or n-phase) winding,
a) terminated at slip rings
b) Short circuited, i.e. squirrel cage rotor

Slip rings
Allow electrical connection to rotor circuit

Induction (asynchronous) Motor (IM)

- Balanced 3-phase stator currents produce a magnetic field of constant magnitude B_S which rotates with the synchronous speed ω_{sync}
- If the rotor is not rotating (still stand, or locked rotor) a voltage E_{LR} of frequency

$$f_e = \frac{\omega_{sync}}{2\pi}$$

Provided: same number of poles in stator and rotor

is induced in the rotor winding

- If the rotor is rotating with a speed ω_m different from ω_{sync} a voltage

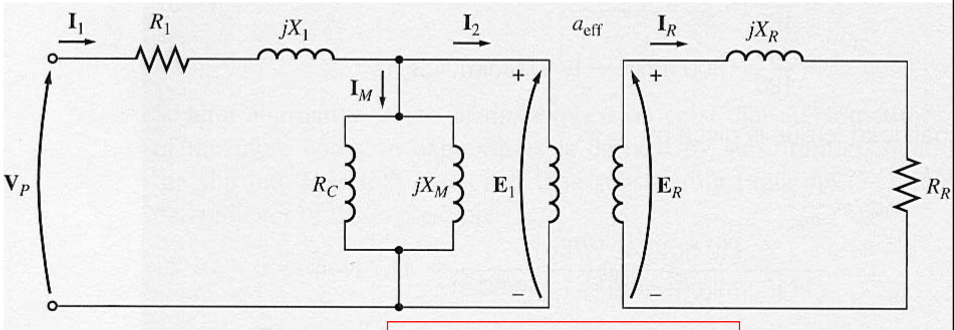
$$E_R = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} E_{LR}$$

is with frequency

$$f_R = \frac{\omega_{sync} - \omega_m}{2\pi} = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} f_{sync}$$

induced in the rotor winding

IM – Developing a Single-phase Equivalent Circuit Model



Stator circuit

a) Winding resistance and reactance

b) Magnetizing branch (magnetization provided by stator only!)

Stator ⇔ Rotor

a) Effective turns ratio $E_{LR}/E_1 = a_{eff}$

b) Ratio E_R/E_1 scales with rotor speed

c) Change of frequency!

Rotor circuit

Winding resistance and reactance

IM – The Concept of Slip

- The slip s is the relative (normalized) frequency in the rotor circuit

$$s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}}$$

  - **Locked rotor: s = 1**
  - **Rotor slower than synchronous speed: 1 > s > 0**
  - **Rotor at synchronous speed: s = 0**
  - **Rotor faster than synchronous speed s < 0**
  - **Rotor speed reversal: s > 1**
- The electrical frequency in the rotor becomes

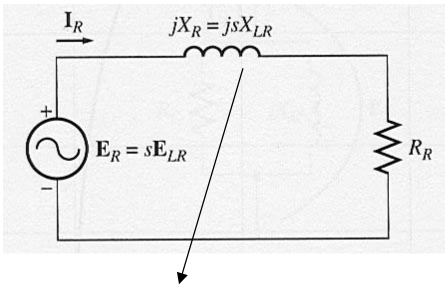
$$f_R = s \cdot f_e$$

- The mechanical speed of the rotor becomes

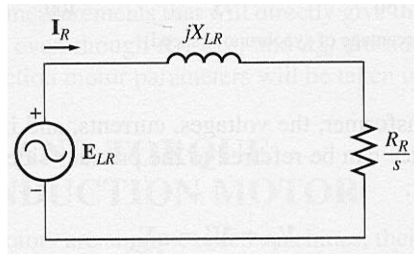
$$\omega_m = (1-s)\,\omega_{sync}, \quad n_m = (1-s)\,n_{sync}$$

IM – Equivalent rotor circuits (rotor short circuited)

Frequency of I_R: f_R, rotor

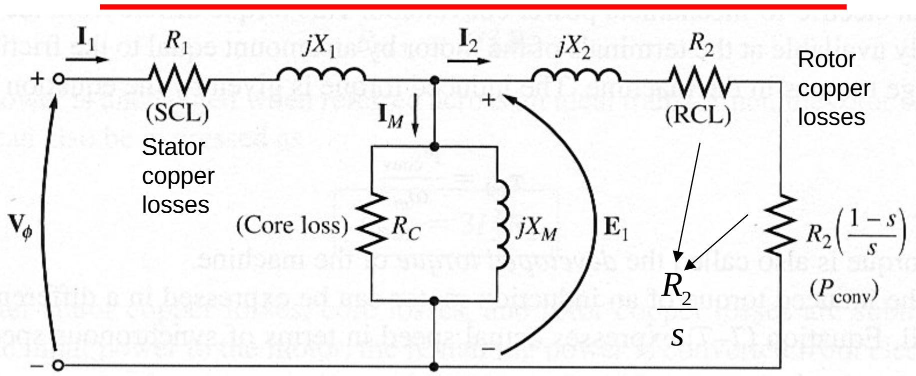


Frequency of I_R: f_e, stator



The **inductance** and **resistance** values are constant (independent of the rotor frequency, except for skin effects).
The rotor **reactance**, however, scales with the rotor frequency and thus with the slip!

IM – Equivalent Circuit Model



All rotor quantities are referred to the stator side

$$R_2 = a_{eff}^2 R_R$$

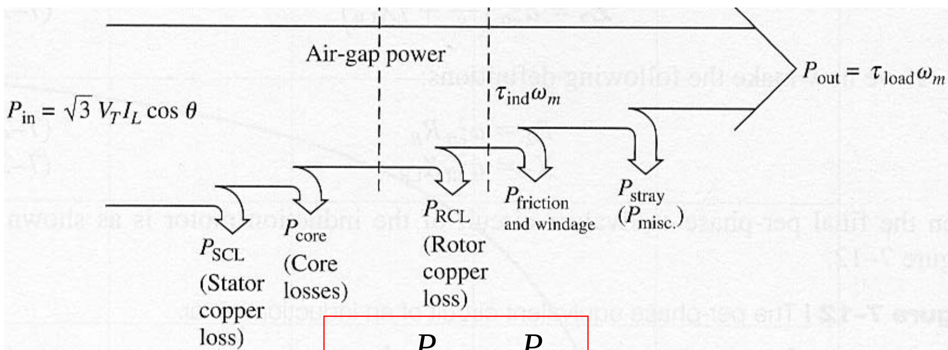
$$X_2 = a_{eff}^2 X_{LR}$$

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

represents converted mechanical power

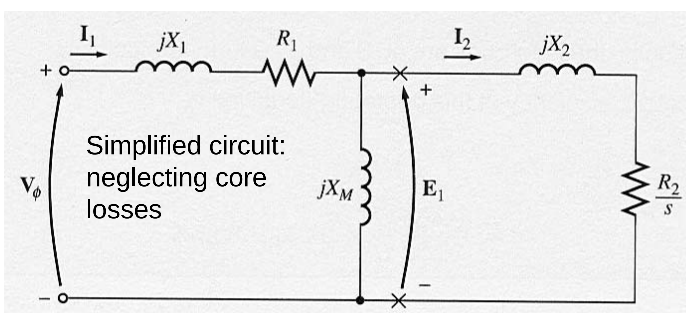
IM – Power Flow

$$P_{AG} = 3I_2^2 R_2 \frac{1}{s} \qquad P_{conv} = 3I_2^2 R_2 \left(\frac{1-s}{s}\right)$$



$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{P_{AG}}{\omega_{sync}}$$

IM – Characteristics



IM – Characteristics

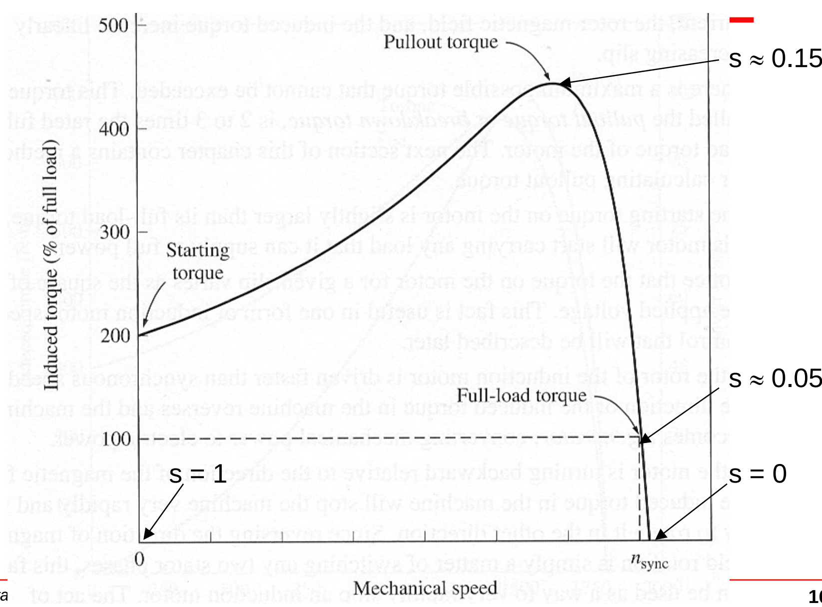
$$\tau_{ind} = \frac{3V_{TH}^2}{\omega_{sync}} \frac{R_2/s}{\left(R_{TH} + R_2/s\right)^2 + \left(X_{TH} + X_2\right)^2}$$

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

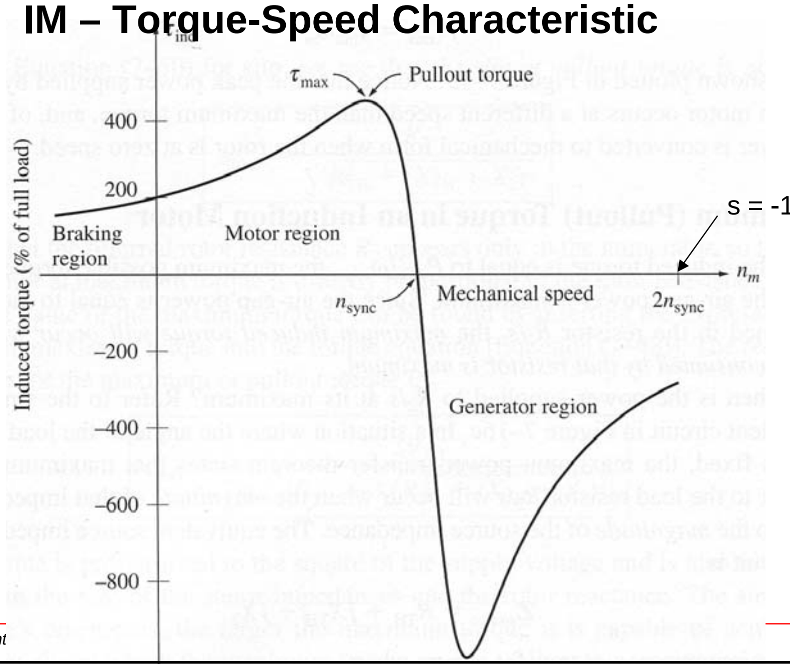
$$s_{\max} = \frac{R_2}{\sqrt{R_{TH}^2 + \left(X_{TH} + X_2\right)^2}}$$

$$\tau_{\max} = \frac{3V_{TH}^2}{2\omega_{sync}} \frac{1}{R_{TH} + \sqrt{R_{TH}^2 + \left(X_{TH} + X_2\right)^2}}$$

IM – Torque-Speed Characteristic



IM – Torque-Speed Characteristic



HW 10

Problem 5-29 in book