Induction Machines

- Construction
- Principle of Operation
- Equivalent Circuit
- Power and Torque
- Torque-speed characteristic
- Loading & Stability
- Induction Machine Modes of Operation
- Starting of Induction motors
- Braking of Induction Motors
- Testing
- Practical Motors (Lab)

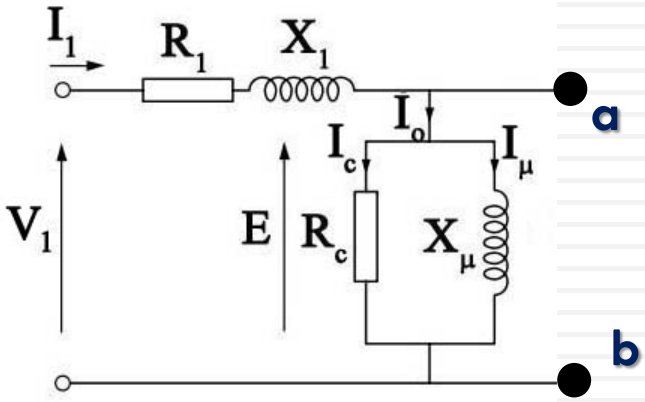
Induction Machines: Torque-Speed characteristic

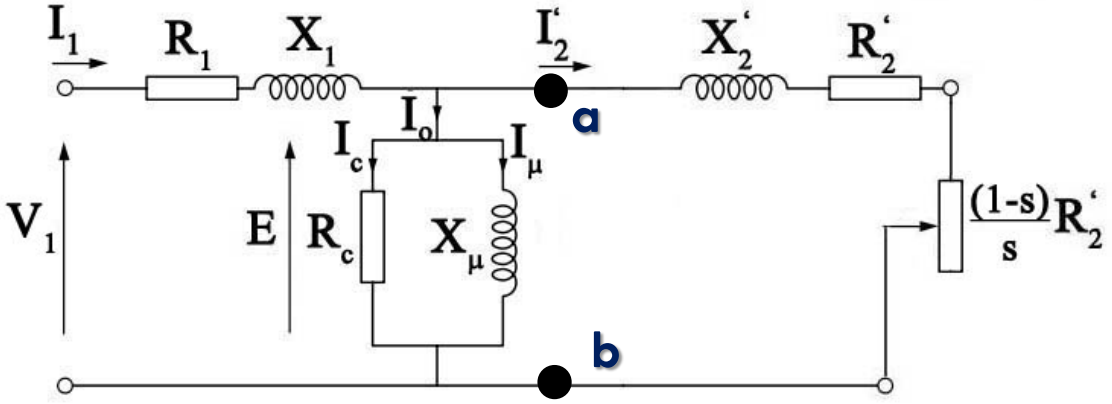
$$T_{out} = \frac{P_{out}}{\omega}$$

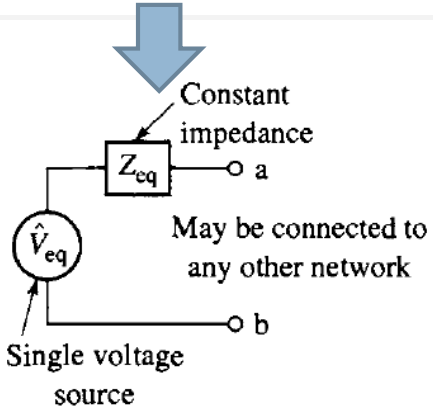
$$T_d = \frac{P_d}{\omega} = \frac{P_g}{\omega_s}$$

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

$$T_d = \frac{3I_2'^2 R_2'}{s\omega_s}$$







$$V_{1eq} = V_1\left(\frac{Z_m}{R_1 + jX_1 + Z_m}\right)$$

$$Z_{1eq} = \frac{Z_m(R_1 + jX_1)}{R_1 + jX_1 + Z_m}$$

$$Z_m = \frac{jX_m R_c}{R_c + jX_m}$$

Usually R_c is omitted and P_{iron} is lumped with mech. Losses

i.e ($Z_m = jX_m$)

Induction Machines: Torque-Speed characteristic

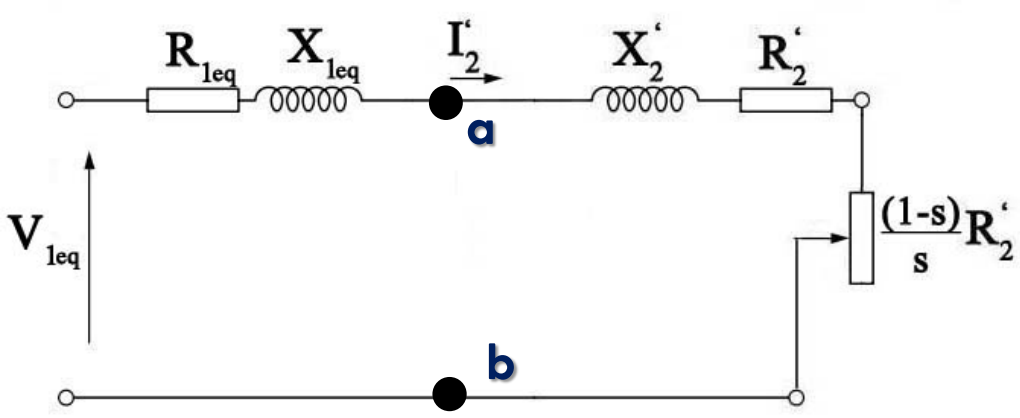
$$T_{out} = \frac{P_{out}}{\omega}$$

$$T_d = \frac{P_d}{\omega} = \frac{P_g}{\omega_s}$$

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

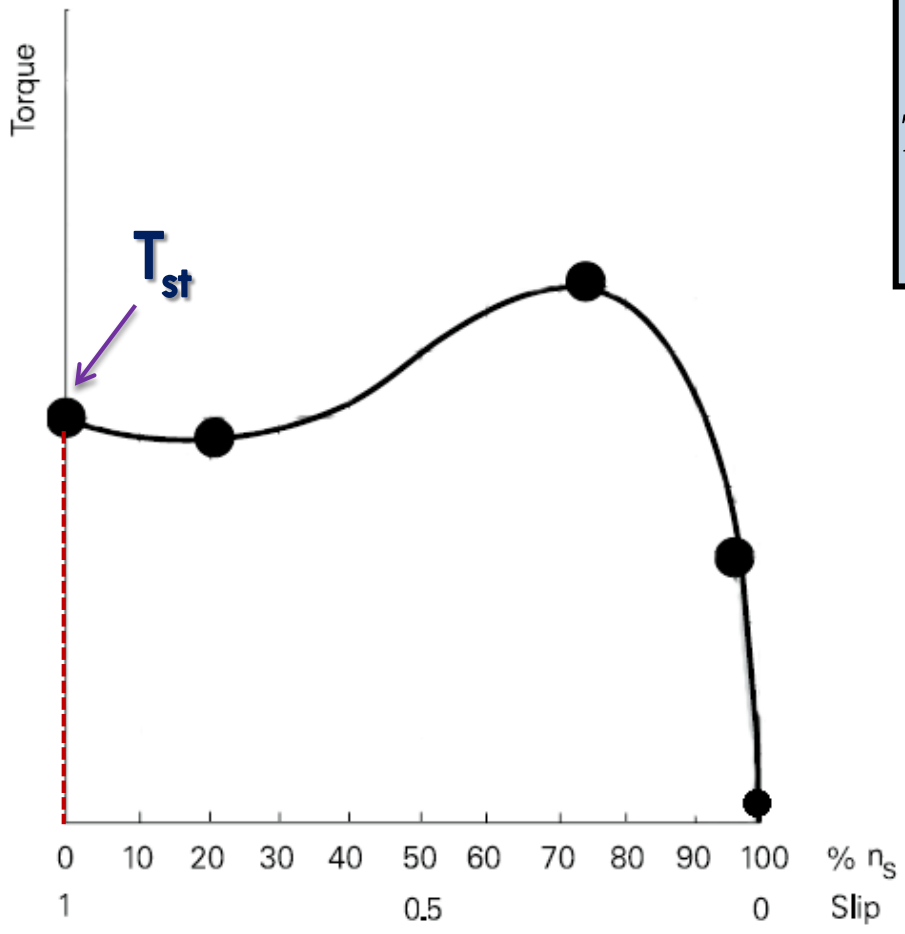
$$T_d = \frac{3I_2^{'2}R_2^{'}}{s\omega_s}$$

$$I_2^{'} = \frac{V_{1eq}}{R_{1eq} + jX_{1eq} + \frac{R_2^{'}}{s} + jX_2^{'}}$$



$$T_d = \frac{3V_{1eq}^2\frac{R_2^{'}}{s}}{\omega_s[(R_{1eq} + \frac{R_2^{'}}{s})^2 + (X_{1eq} + X_2^{'})^2]}$$

Induction Machines: Torque-Speed characteristic



$$T_d = \frac{3V_{1eq}^2 \frac{R_2'}{s}}{\omega_s[(R_{1eq} + \frac{R_2'}{s})^2 + (X_{1eq} + X_2')^2]}$$

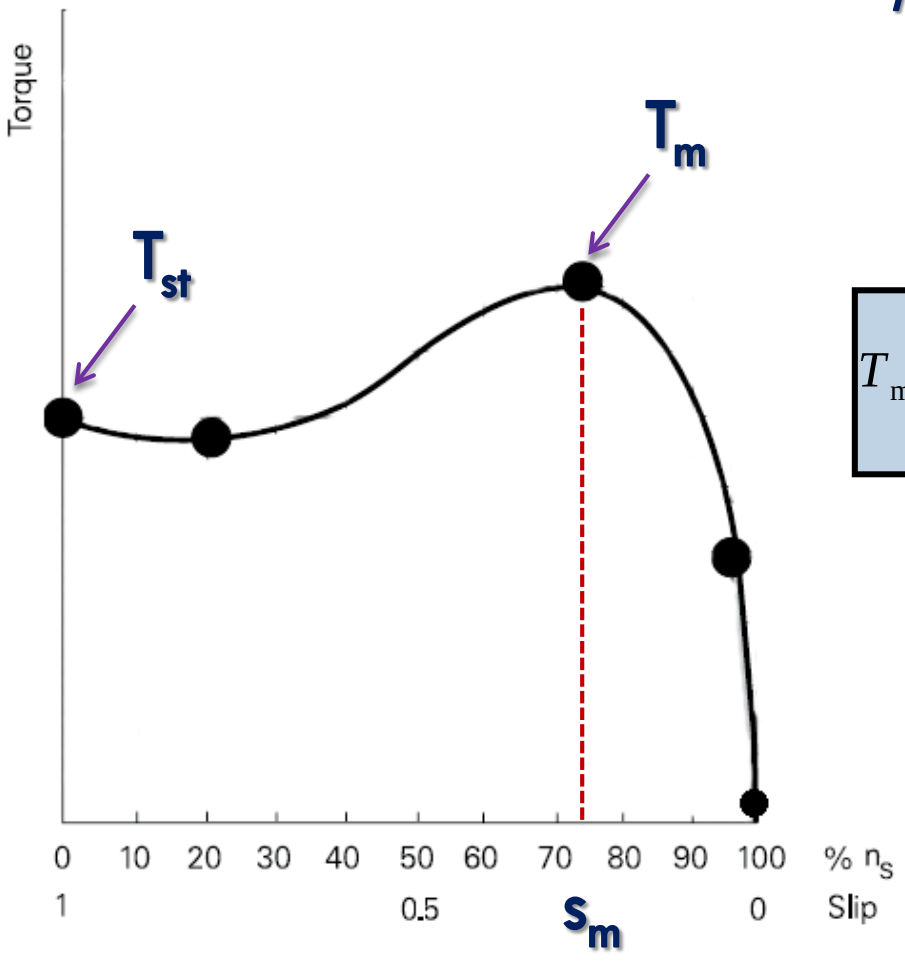
$$s = \frac{n_s - n}{n_s}$$

Starting (locked rotor) Torque

$n = 0$ $s = 1$

$$T_{st} = \frac{3V_{1eq}^2 R_2'}{\omega_s[(R_{1eq} + R_2')^2 + (X_{1eq} + X_2')^2]}$$

Induction Machines: Torque-Speed characteristic



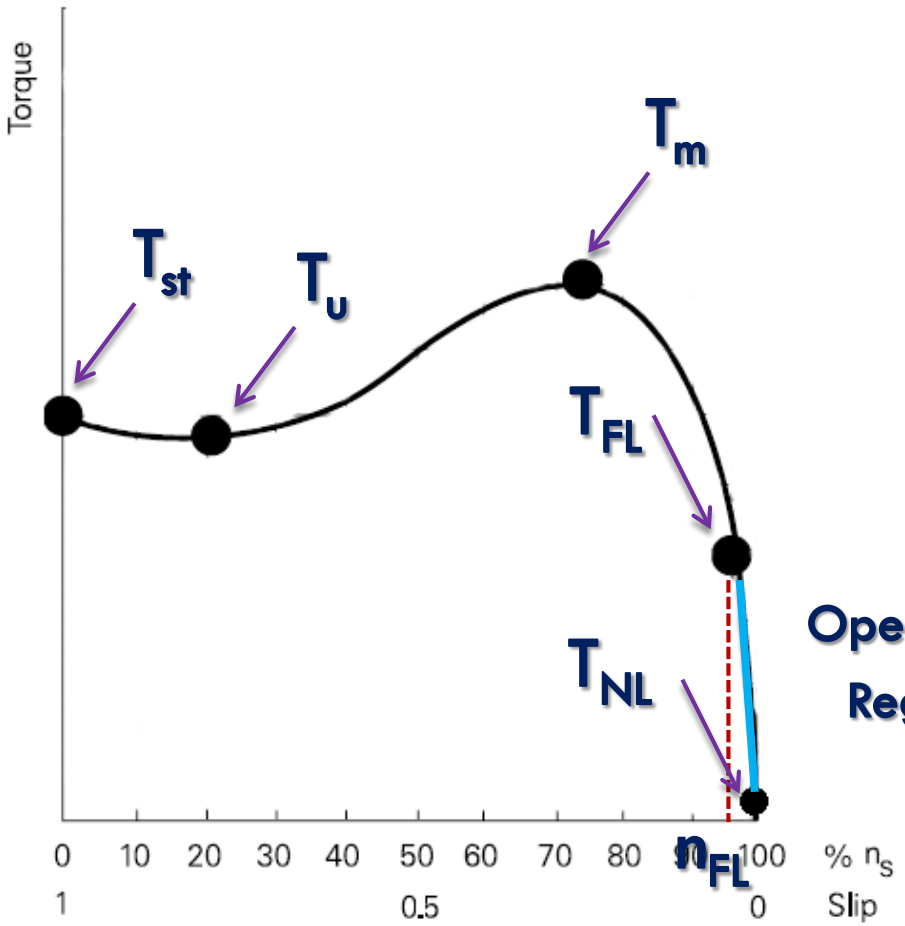
Maximum (breakdown/Pull-out) Torque

$$\frac{\partial T_d}{\partial s} = zero$$

$$T_m = \frac{3V_{1eq}^2}{2\omega_s[R_{1eq} + \sqrt{(R_{1eq})^2 + (X_{1eq} + X_2')^2}]}$$

$$s_{Tm} = \frac{R_2'}{\sqrt{(R_{1eq})^2 + (X_{1eq} + X_2')^2}]}$$

Induction Machines: Torque-Speed characteristic



Operating Region

Full Load Torque

$$\frac{T_m}{T_{FL}} \geq 1.6$$ Overload Capacity

No Load Torque

$$T_{NL} \simeq T_{mech\ losses}$$

$$n_{NL} \approx n_s \qquad s \approx 0$$

$$I_2^{'} \approx 0 \qquad I_1 \approx I_o$$

I_{NL} = 30-40% I_{FL}

Pull-up Torque

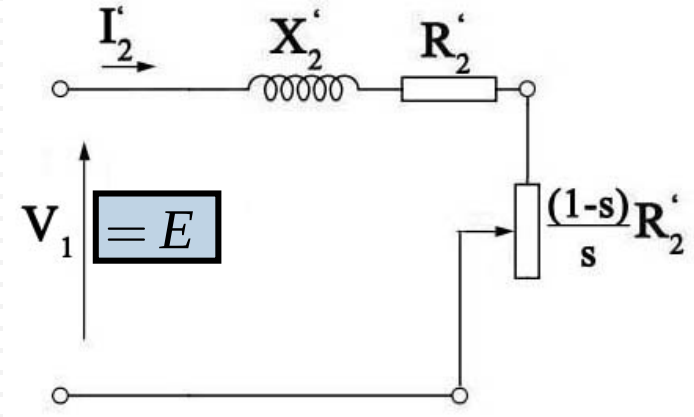
$$\frac{T_U}{T_{FL}} \geq 1$$

Induction Machines: Torque-Speed characteristic

Neglecting stator impedance (for large motors)

$$I_2' = \frac{V_1}{\frac{R_2'}{s} + jX_2'}$$

$$T_d = \frac{3V_1^2 \frac{R_2'}{s}}{\omega_s[(\frac{R_2'}{s})^2 + (X_2')^2]}$$



$$T_m = \frac{3V_1^2}{2\omega_s X_2'}$$

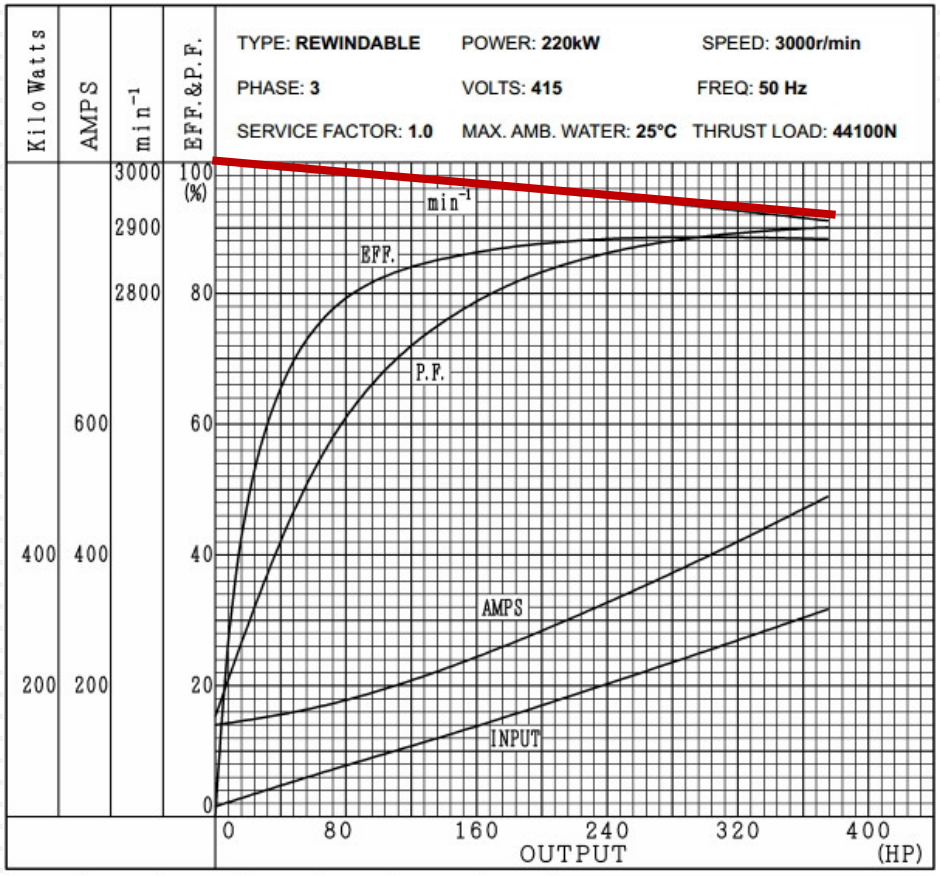
$$s_{Tm} = \frac{R_2'}{X_2'}$$

$$\frac{T_d}{T_m} = \frac{2\frac{R_2'}{s}X_2'}{[(\frac{R_2'}{s})^2 + (X_2')^2]}$$

$$\frac{T_d}{T_m} = \frac{2}{\frac{R_2'}{sX_2'} + \frac{sX_2'}{R_2'}}$$

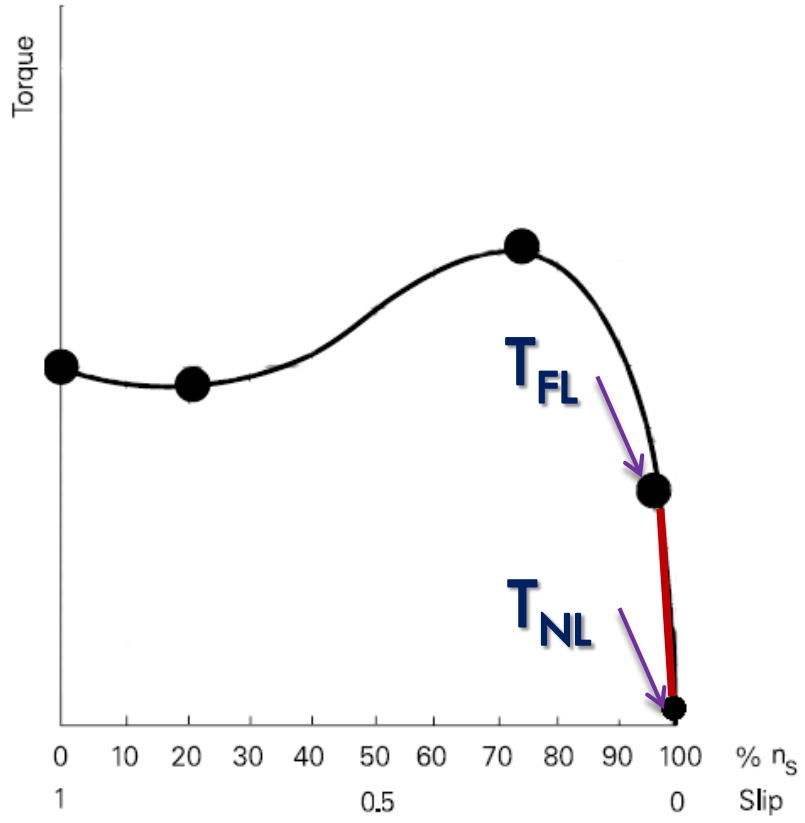
$$\frac{T_d}{T_m} = \frac{2}{\frac{s_m}{s} + \frac{s}{s_m}}$$

Induction Machines: Performance Characteristics



LOAD (HP)	No load (−)	25% (75)	50% (150)	75% (225)	100% (300)	125% (375)
AMPS	140.0	172.9	234.6	310.8	396.2	489.1
EFF.	0	77.6	85.8	88.1	88.6	88.3
P.F.	15.3	58.0	77.3	85.2	88.7	90.1
min⁻¹	3000	2984	2968	2951	2932	2911
WATTS	15400	72100	130420	190520	252600	316820

Full load Torque 730 N·m
Break Down Torque 2096 N·m
Locked Rotor Torque 1307 N·m
Locked Rotor Current 2950 Amperes
KVA Code H



Induction Machines: Motor Ratings

Rated Voltage (V_r)

Rated Frequency (f_r)

Rated Power (kW or HP)

Full Load Speed (rpm)

Full load Current (I_{FL})

Full load power factor

ABB

3 ~ Motor M3AA 160 L 4

IEC 160 M/L 42

No

Ins.cl. F IP 55

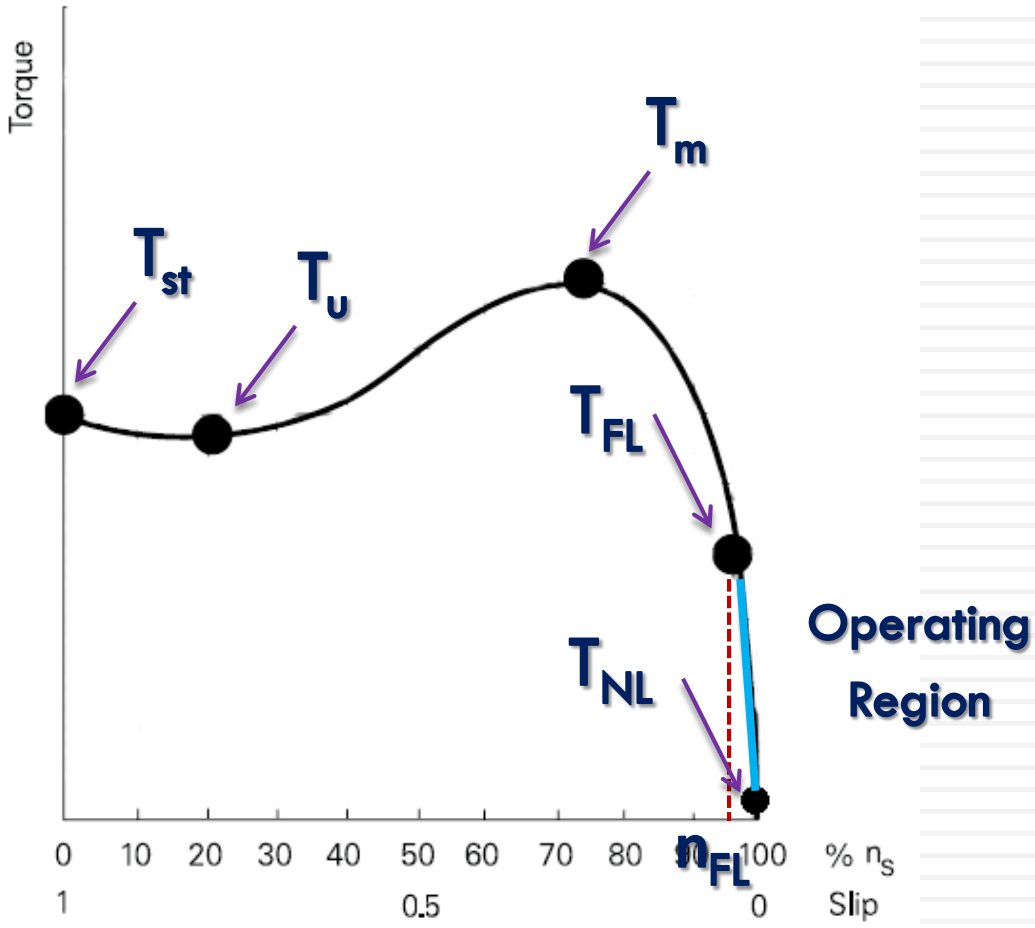
V	Hz	kW	r/min	A	cos φ	I_A/I_N	t_E/s
690 Y	50	15	1460	16.7	0.82		
400 Δ	50	15	1460	29	0.82		
660 Y	50	15	1455	17.3	0.84		
380 Δ	50	15	1455	30	0.84		
415 Δ	50	15	1465	28	0.81		
440 Δ	60	18	1750	30	0.84		

Prod.code 3GAA 162 102-ADC

6309-2Z/C3 6209-2Z/C3 103 kg

3GZV 193 014-11 IEC 60034-1

Induction Machines: Torque-Speed characteristic



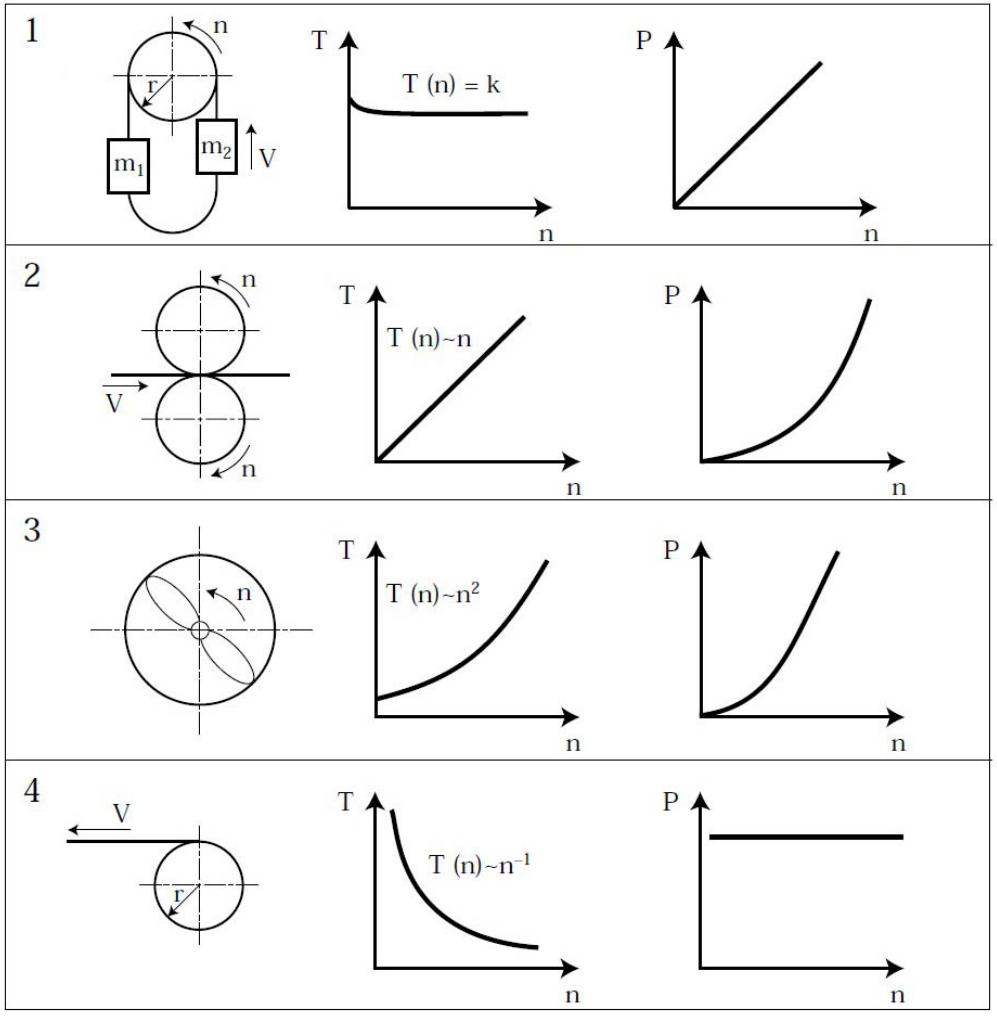
Induction Machines: Loading & Stability

Constant Torque

Linear Load

Squared Load

Constant Power



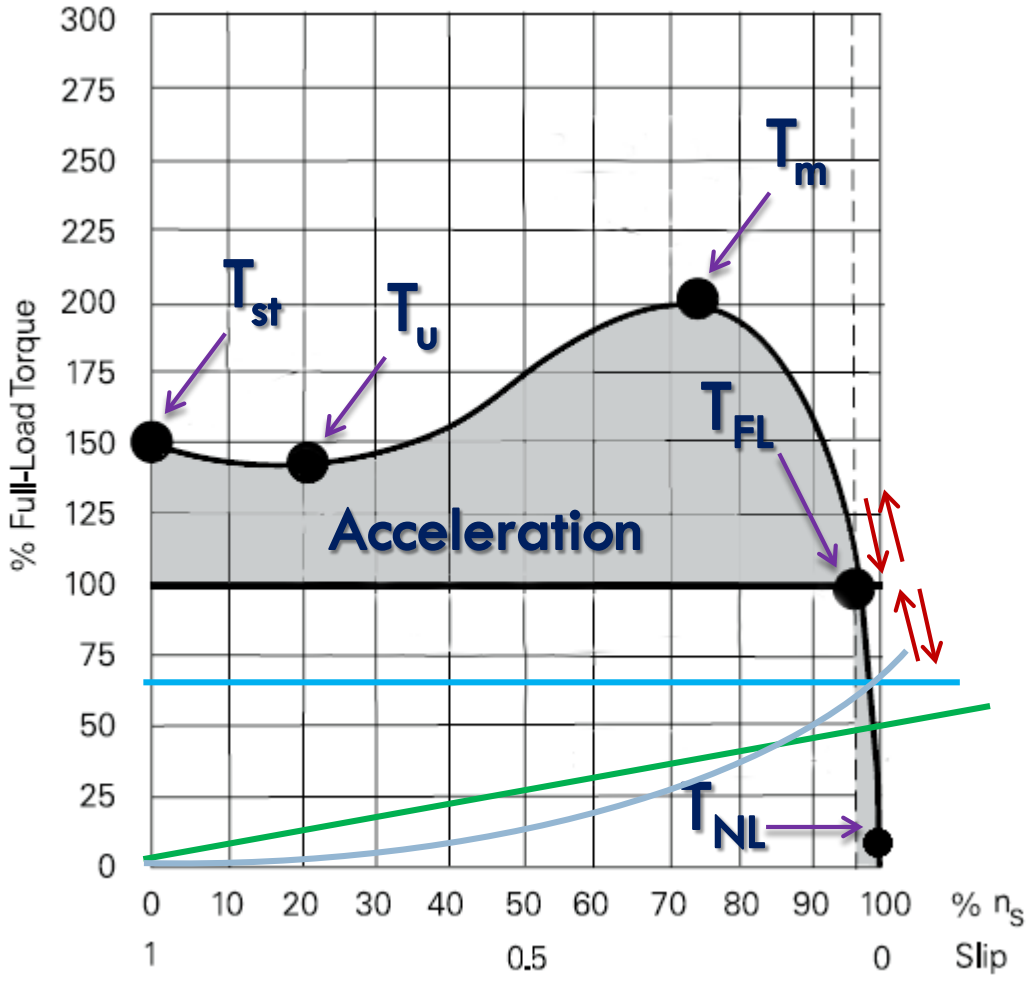
Conveyors
Hoists
Crushers

Centrifuges
Mixers

Centrifugal pump
Fans
Blowers

Winders, unwinders
Extruding machine

Induction Machines: Loading & Stability



$$T_m - T_L = J \frac{d\omega}{dt}$$

$T_m > T_L$ **Acceleration**

$T_m < T_L$ **Deceleration**

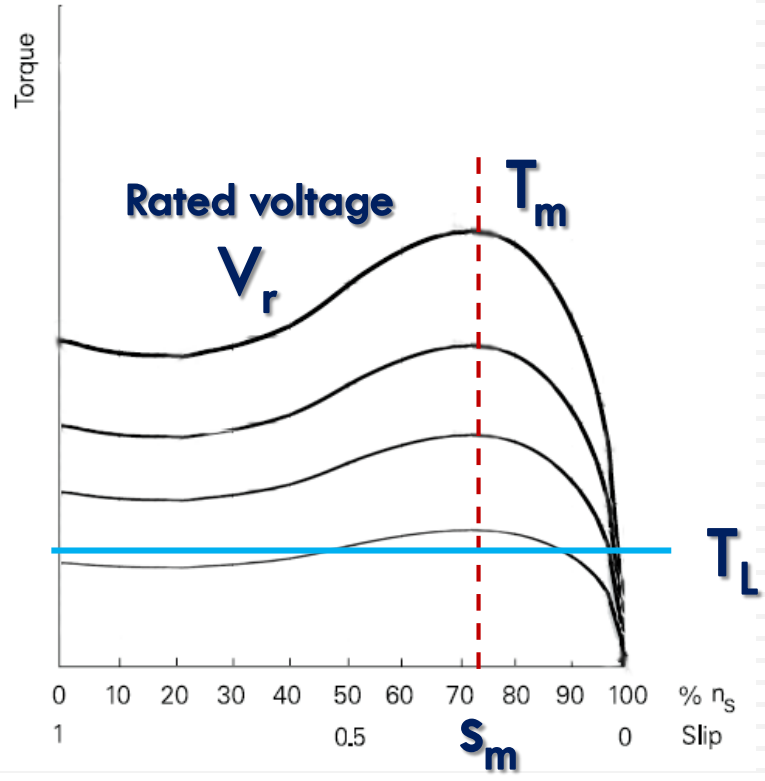
At Operating Point

$T_m = T_L \Rightarrow n = const.$

Induction Machines: Loading & Stability

Effects of changes in the supply voltage and frequency

1. Changing the supply voltage (V_1)



$$T_d = \frac{3V_{1eq}^2 \frac{R_2'}{s}}{\omega_s[(R_{1eq} + \frac{R_2'}{s})^2 + (X_{1eq} + X_2')^2]}$$

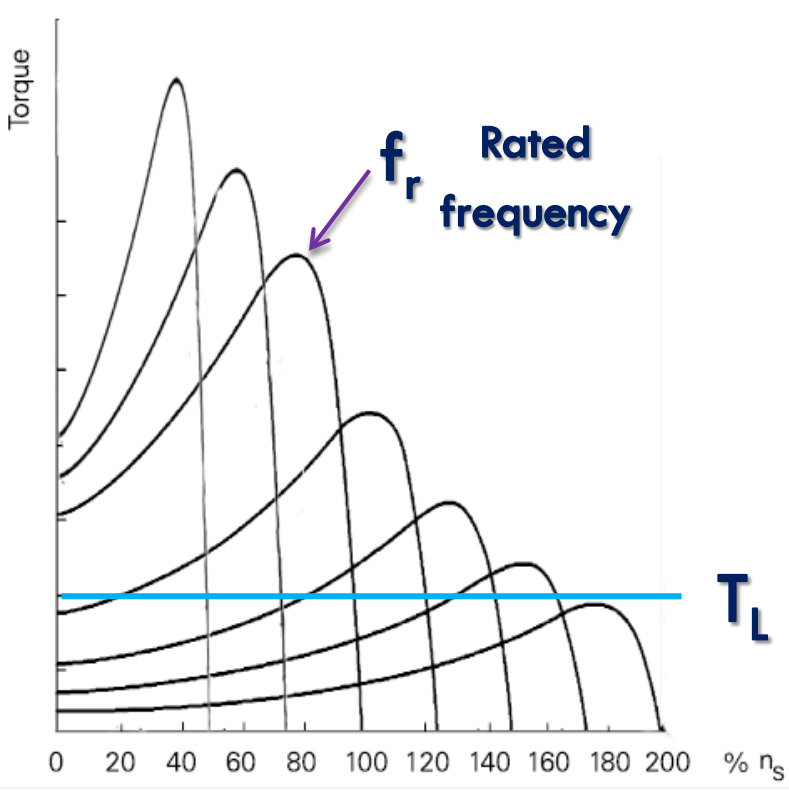
$$T_d \propto V^2$$

$$s_{Tm} = \frac{R_2'}{\sqrt{(R_{1eq})^2 + (X_{1eq} + X_2')^2]}}$$

Induction Machines: Loading & Stability

Effects of changes in the supply voltage and frequency

2. Changing the supply frequency (f_1)



$$T_d = \frac{3V_{1eq}^2 \frac{R_2'}{s}}{\frac{2\pi f_1}{p}\left[\left(R_{1eq} + \frac{R_2'}{s}\right)^2 + \left(2\pi f_1 L_{1eq} + 2\pi f_1 L_2'\right)^2\right]}$$

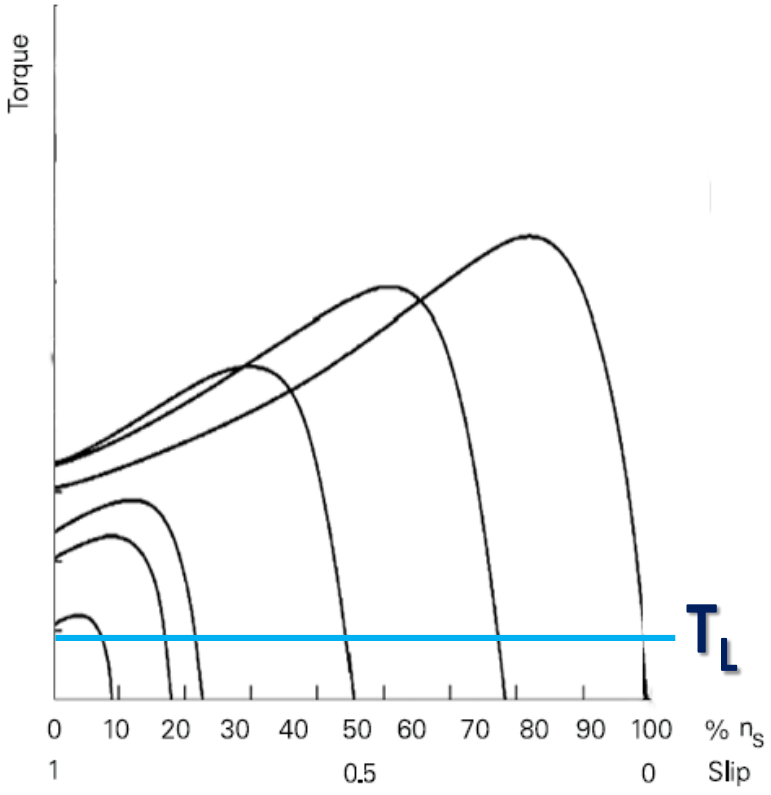
$$s_{Tm} = \frac{R_2'}{\sqrt{\left(R_{1eq}\right)^2 + \left(2\pi f_1 L_{1eq} + 2\pi f_1 L_2'\right)^2}}$$

$$n_s = \frac{60 f_1}{p}$$

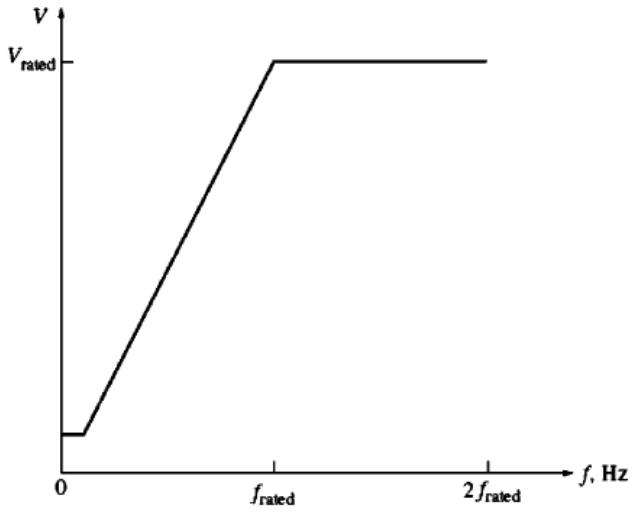
Induction Machines: Loading & Stability

Effects of changes in the supply voltage and frequency

3. Changing the supply voltage & frequency (V/f)



$$T_d = \frac{3V_{1eq}^2 \frac{R_2'}{s}}{\frac{2\pi f_1}{p}\left[\left(R_{1eq} + \frac{R_2'}{s}\right)^2 + \left(2\pi f_1 L_{1eq} + 2\pi f_1 L_2'\right)^2\right]}$$



Induction Machines: Loading & Stability

Effects of changes in the supply voltage and frequency

4. Constant flux operation (E/f)

$$\frac{E}{f_1} = 4.44\phi N_1 \frac{k_{w_1}}{m}$$

$$I_2^{'} = \frac{E}{\frac{R_2^{'}}{s} + j\,2\pi f_1 L_2^{'}}$$

$$s = \frac{f_2}{f_1}$$

$$T_d = \frac{3I_2^{'2}\frac{R_2^{'}}{s}}{\omega_s} = \frac{3E^2\frac{R_2^{'}}{f_2}f_1}{\frac{2\pi f_1}{p}[(\frac{R_2^{'}}{f_2}f_1)^2 + (2\pi f_1 L_2^{'})^2]}$$

$$\Rightarrow \quad T_d = 3p\left(\frac{E}{f_1}\right)^2 \frac{f_2}{2\pi R_2^{'}[1+(2\pi f_2 \frac{L_2^{'}}{R_2^{'}})^2]}$$

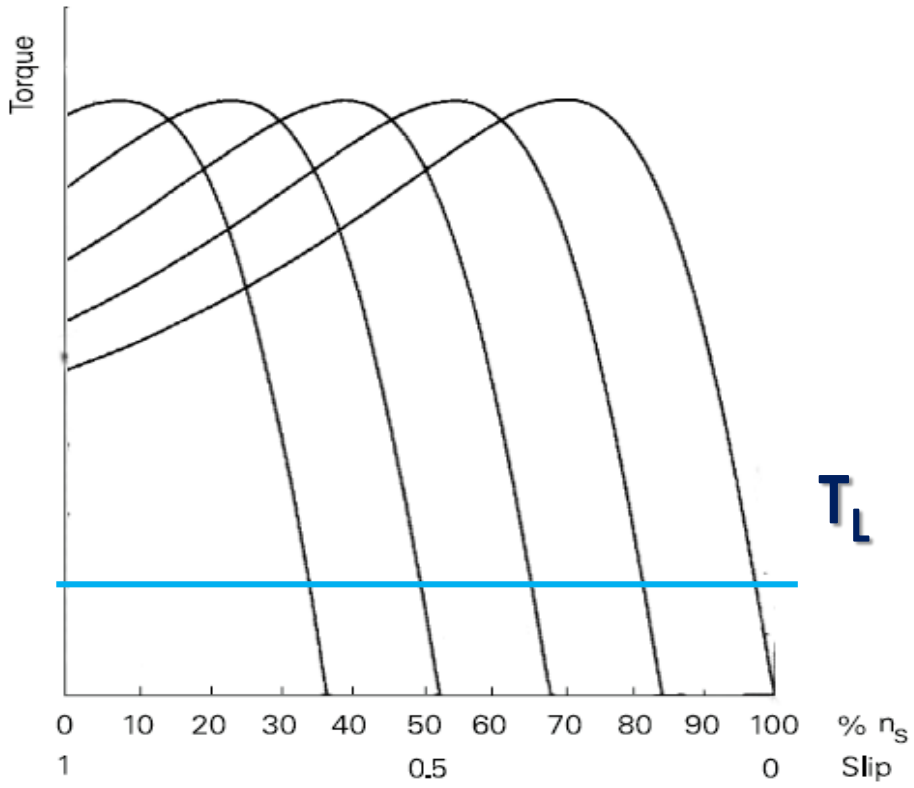
$$T_m = \frac{3E^2}{2\omega_s[X_2^{'}]} = \frac{3E^2}{2\frac{2\pi f_1}{p}[2\pi f_1 L_2^{'}]}$$

$$\Rightarrow \quad T_m = \frac{3p}{4\pi}\left(\frac{E}{f_1}\right)^2 \frac{1}{2\pi L_2^{'}}$$

Induction Machines: Loading & Stability

Effects of changes in the supply voltage and frequency

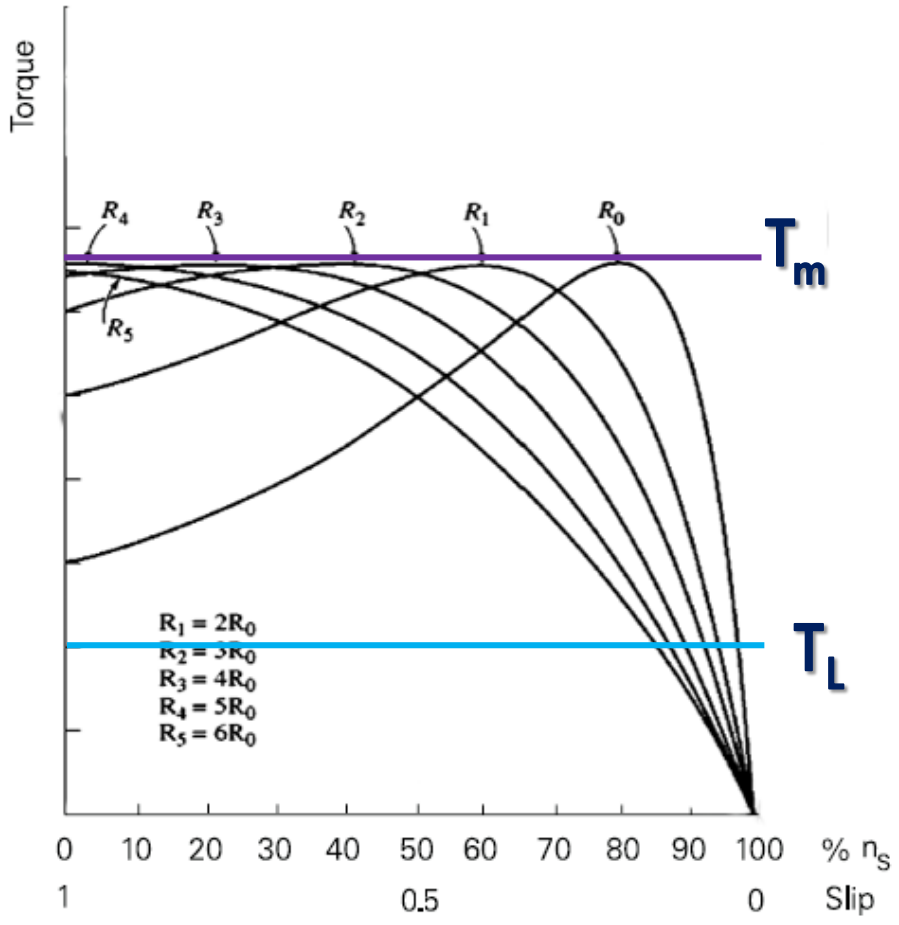
4. Constant flux operation (E/f)



$$T_d = \frac{3E^2 \frac{R_2^{'}}{s}}{\frac{2\pi f_1}{p}[(\frac{R_2^{'}}{s})^2 + (2\pi f_1 L_2^{'})^2]}$$

Induction Machines: Loading & Stability

Effects of changes in the rotor resistance



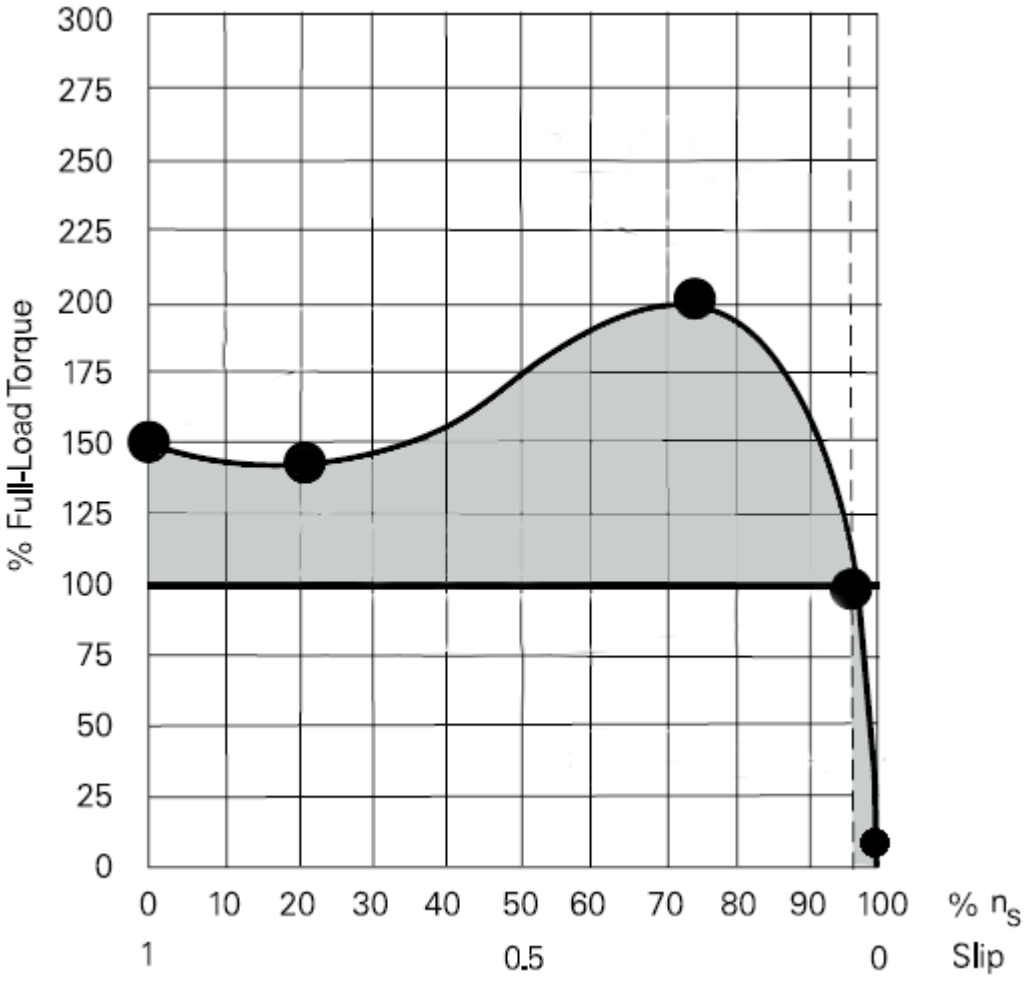
$$T_d = \frac{3V_{1eq}^2 \frac{R_2'}{s}}{\omega_s[(R_{1eq} + \frac{R_2'}{s})^2 + (X_{1eq} + X_2')^2]}$$

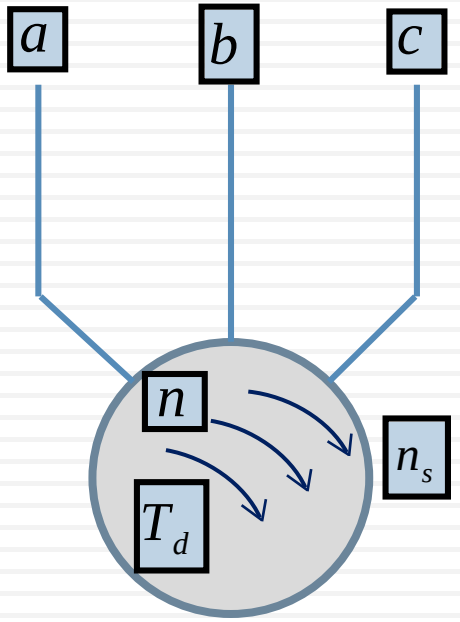
$$T_m = \frac{3V_{1eq}^2}{2\omega_s[R_{1eq} + \sqrt{(R_{1eq})^2 + (X_{1eq} + X_2')^2}]}$$

$$s_{Tm} = \frac{R_2'}{\sqrt{(R_{1eq})^2 + (X_{1eq} + X_2')^2}}$$

Induction Machines: Operating Modes

1. Motoring

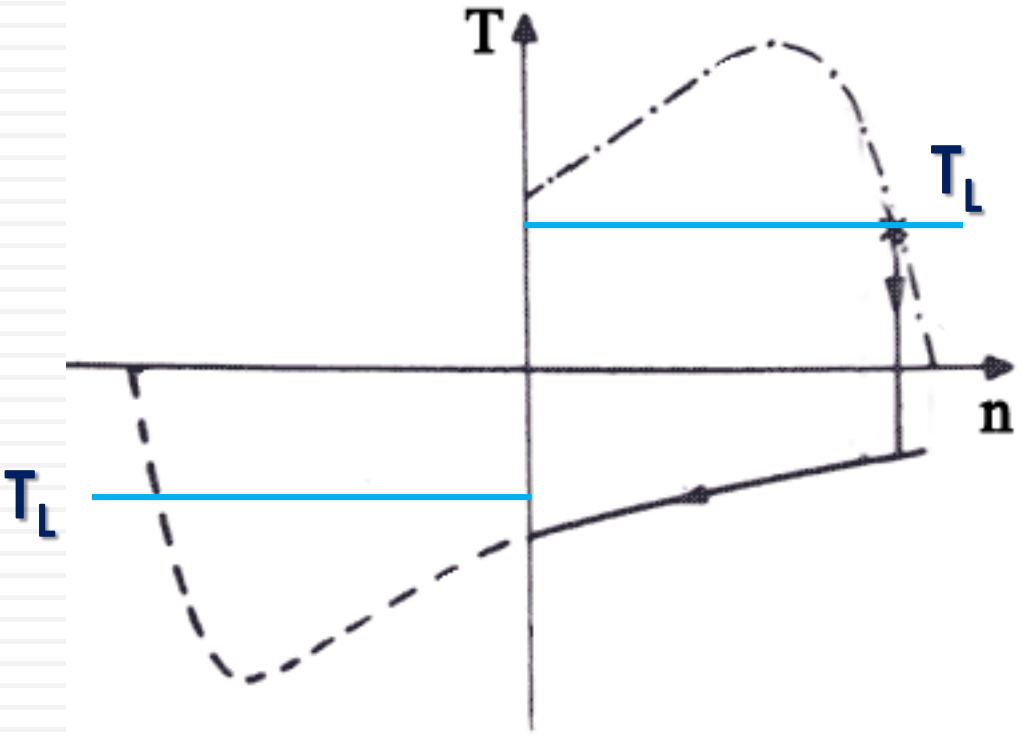




Induction Machines: Operating Modes

2. Braking

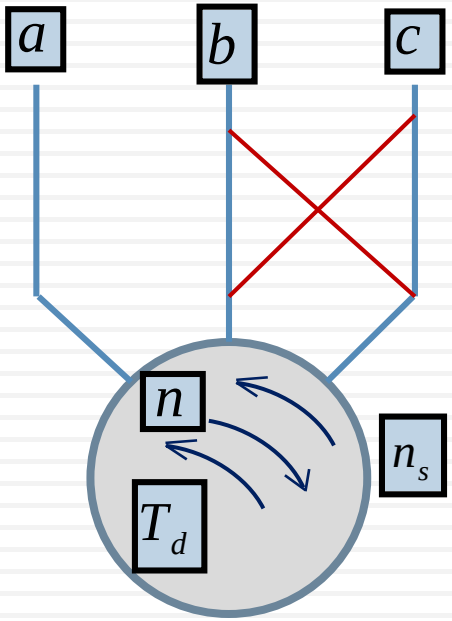
Plugging



$$T_m - T_L = J\frac{d\omega}{dt}$$

$$-T_m - T_L = J\frac{d\omega}{dt}$$

Deceleration



Induction Machines: Operating Modes

2. Braking

Plugging

$$P_{in} = \sqrt{3} V_L I_L \cos\phi$$

$$P_{cu1} = 3 I_1^2 R_1$$

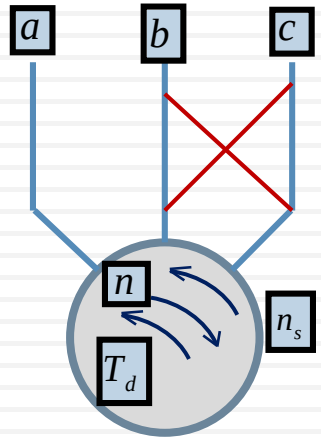
$$P_{iron} = 3 I_c^2 R_c$$

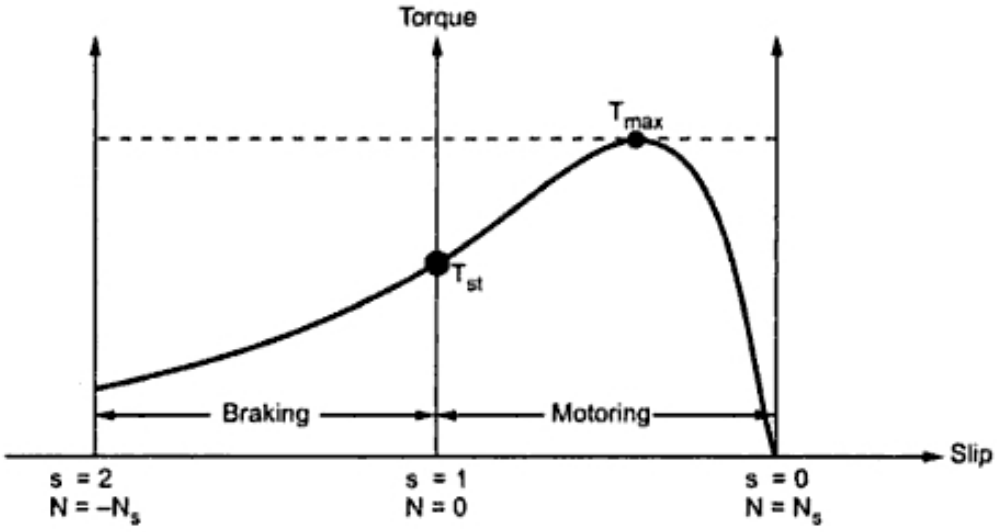
P_g

$$P_{cu2} = 3 I_2'^2 R_2'$$

$$P_{mech\ losses}$$

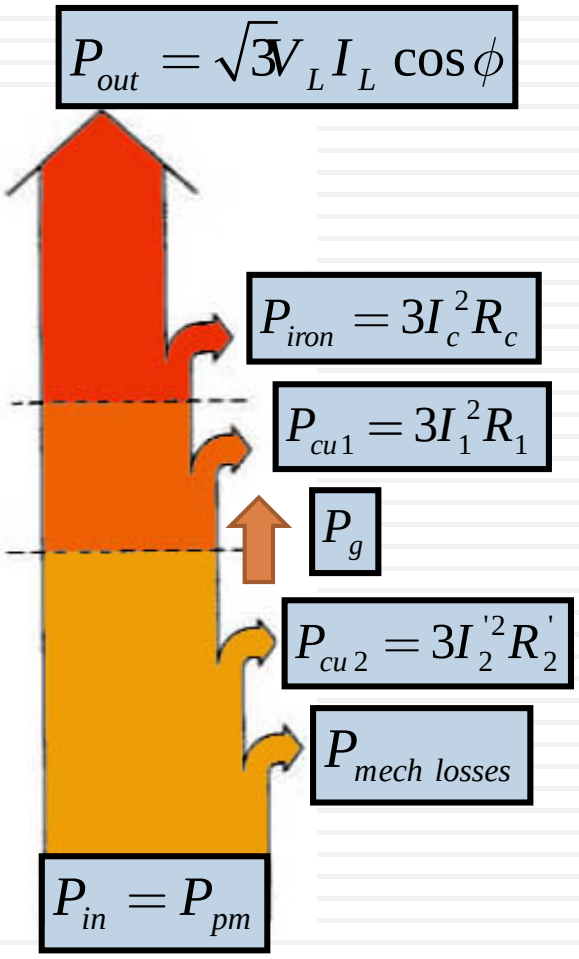
$$P_{mech} = T_m \omega$$

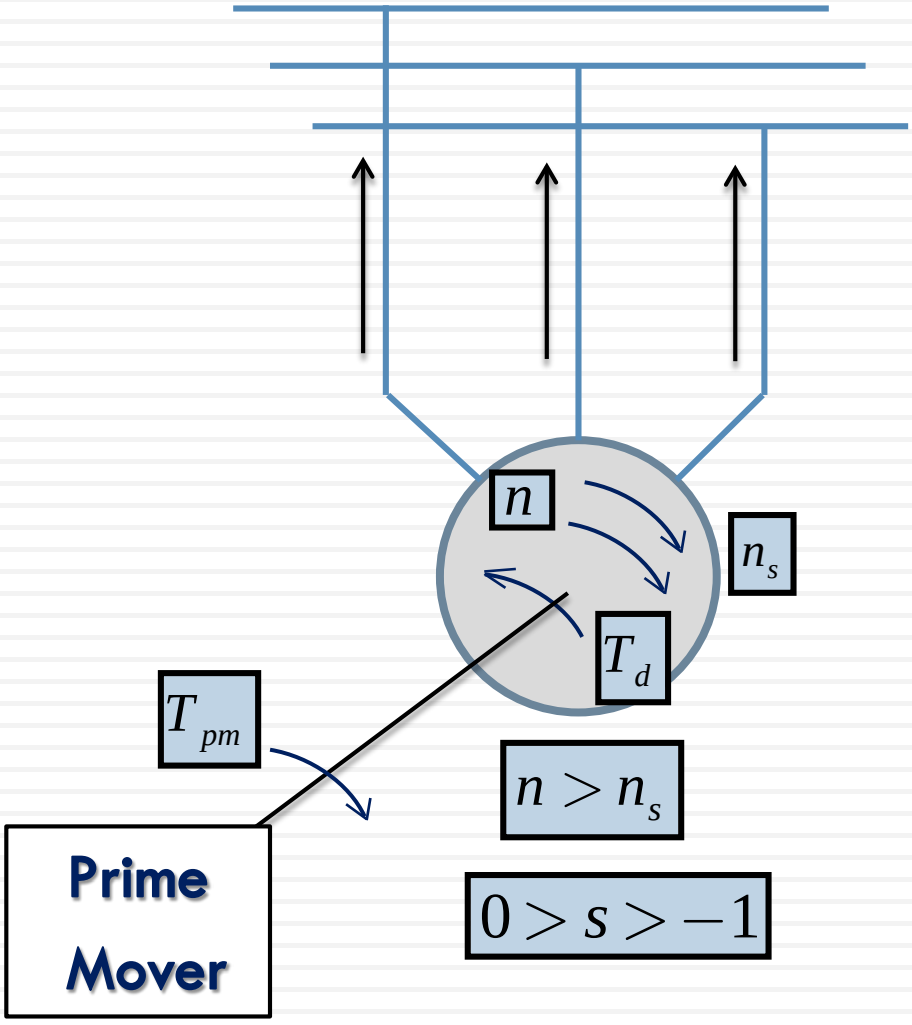




Induction Machines: Operating Modes

3. Generating





Induction Machines: Operating Modes