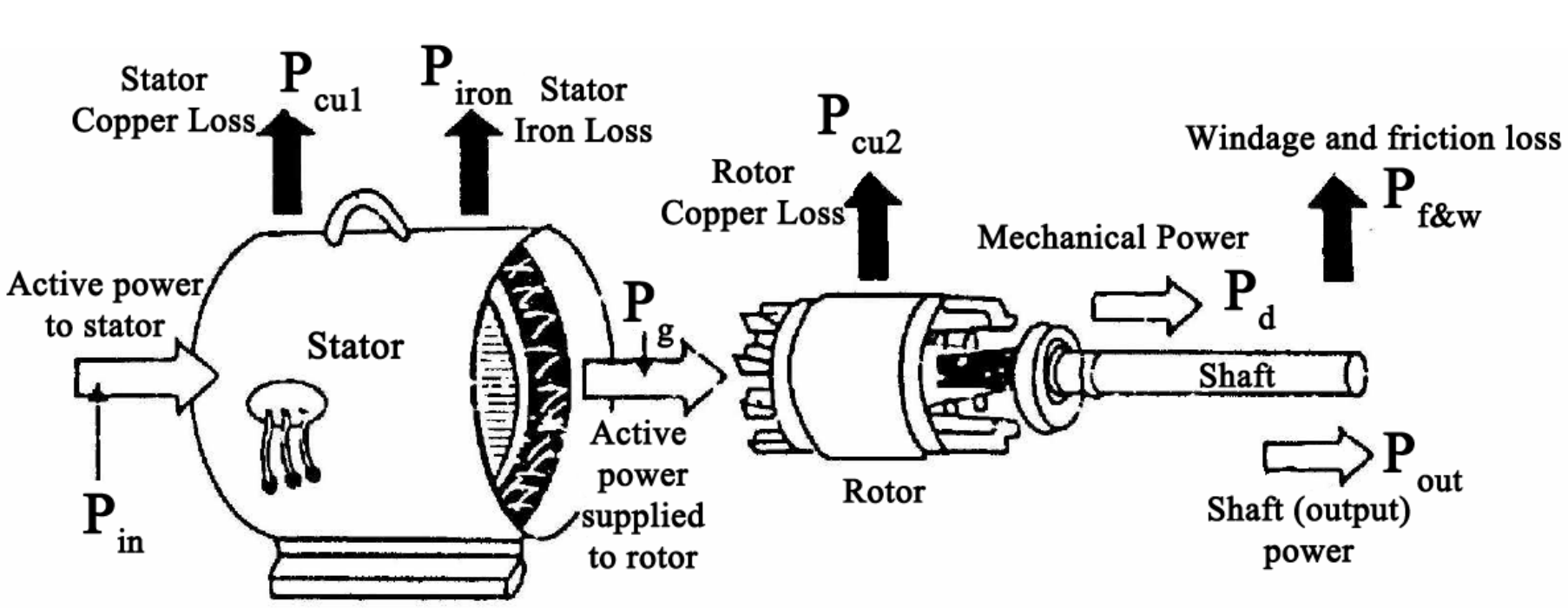
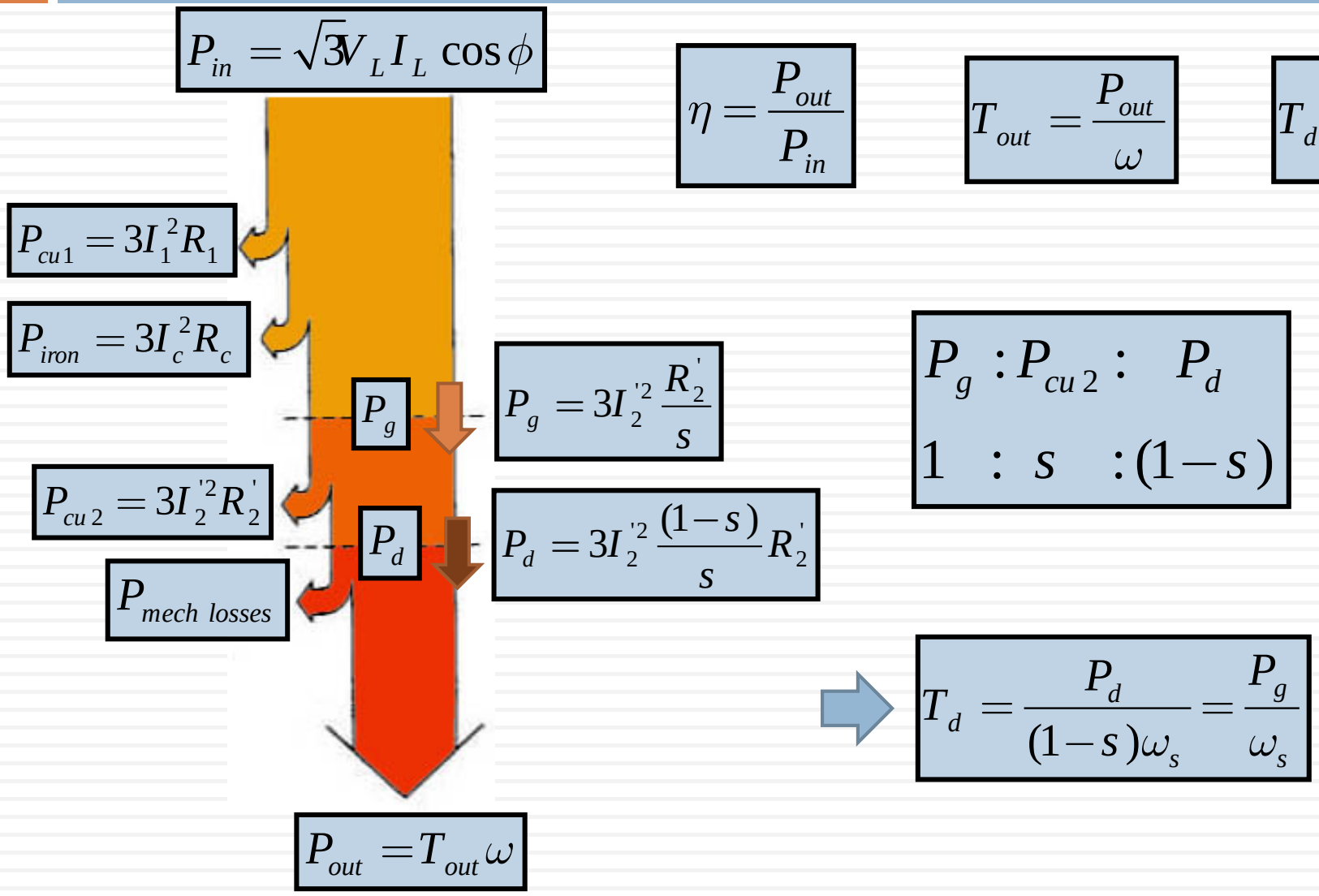
Induction Machines

- Magnetic Field Production and Distribution
- Generated Voltage and Torque Production
- Principle of Operation
- Equivalent Circuit
- Power Flow
- Torque-Speed Characteristics
- Loading & Stability
- Induction Machine Modes of Operation
- Testing

Induction Machines: Efficiency & Torque



Induction Machines: Efficiency & Torque



$$\eta = \frac{P_{out}}{P_{in}}$$

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

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

$$P_g : P_{cu2} : P_d$$
$$1 : s : (1-s)$$

$$T_d = \frac{P_d}{(1-s)\omega_s} = \frac{P_g}{\omega_s}$$

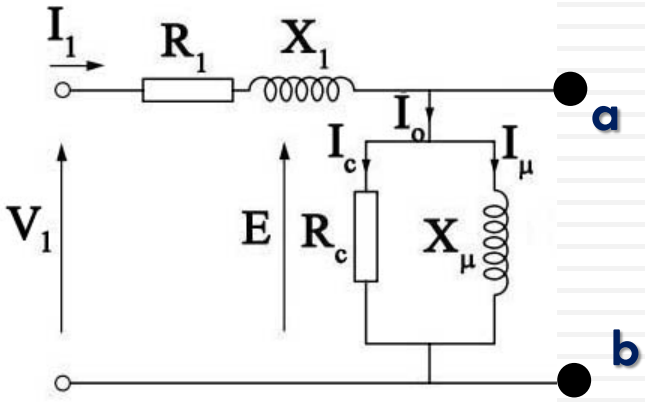
Induction Machines: Torque-Speed characteristic

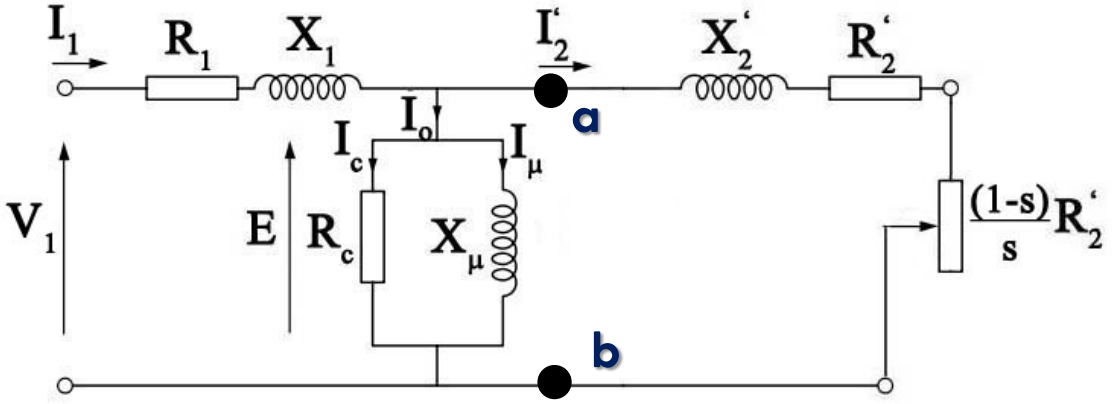
$$T_{out} = \frac{P_{out}}{\omega}$$

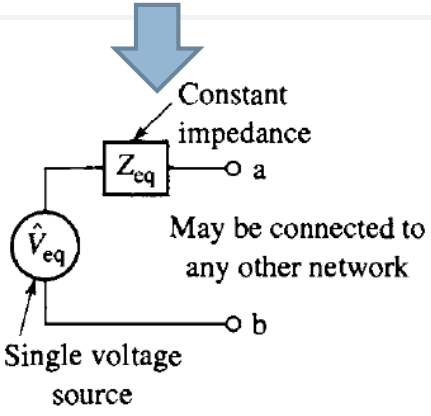
$$T_d = \frac{P_d}{\omega} = \frac{P_g}{\omega_s}$$

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

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







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

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

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

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

i.e ($Z_m = jX_m$)

Induction Machines: Torque-Speed characteristic

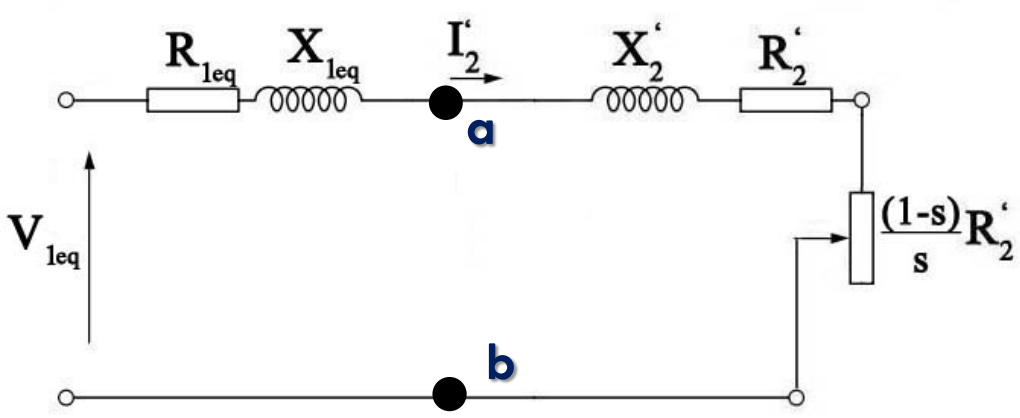
$$T_{out} = \frac{P_{out}}{\omega}$$

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

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

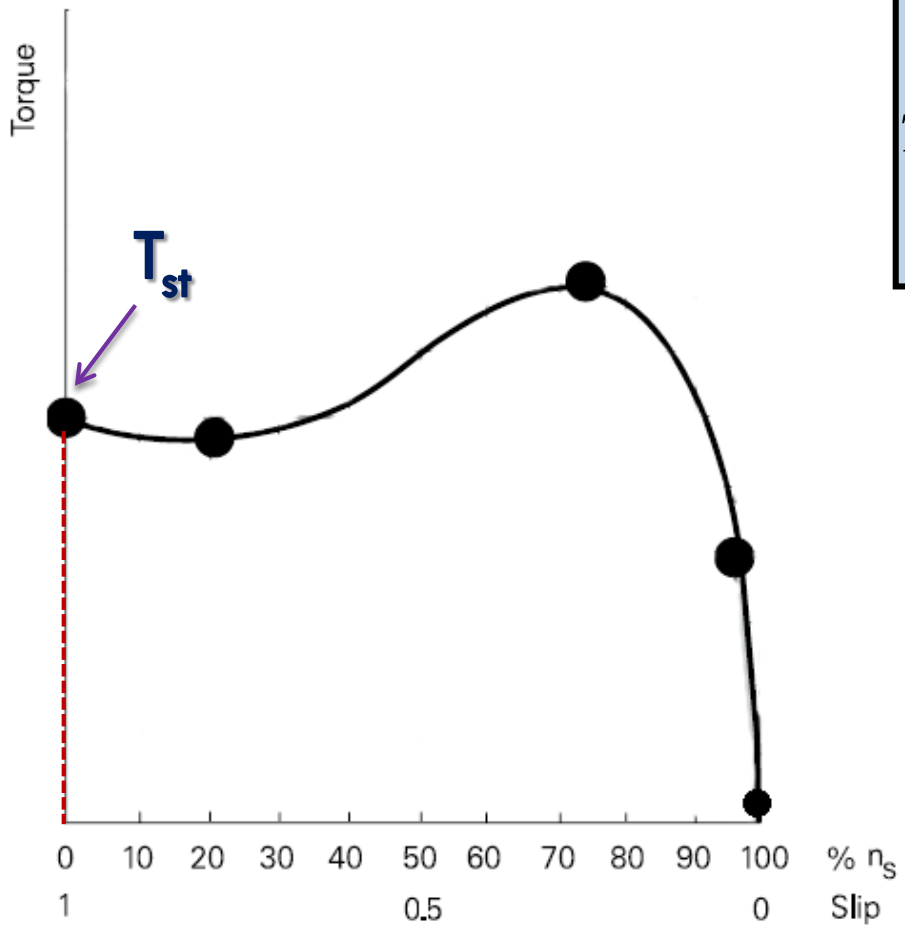
$$T_d = \frac{3I_2^{'2}R_2^{'}}{s\omega_s}$$

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



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

Induction Machines: Torque-Speed characteristic



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

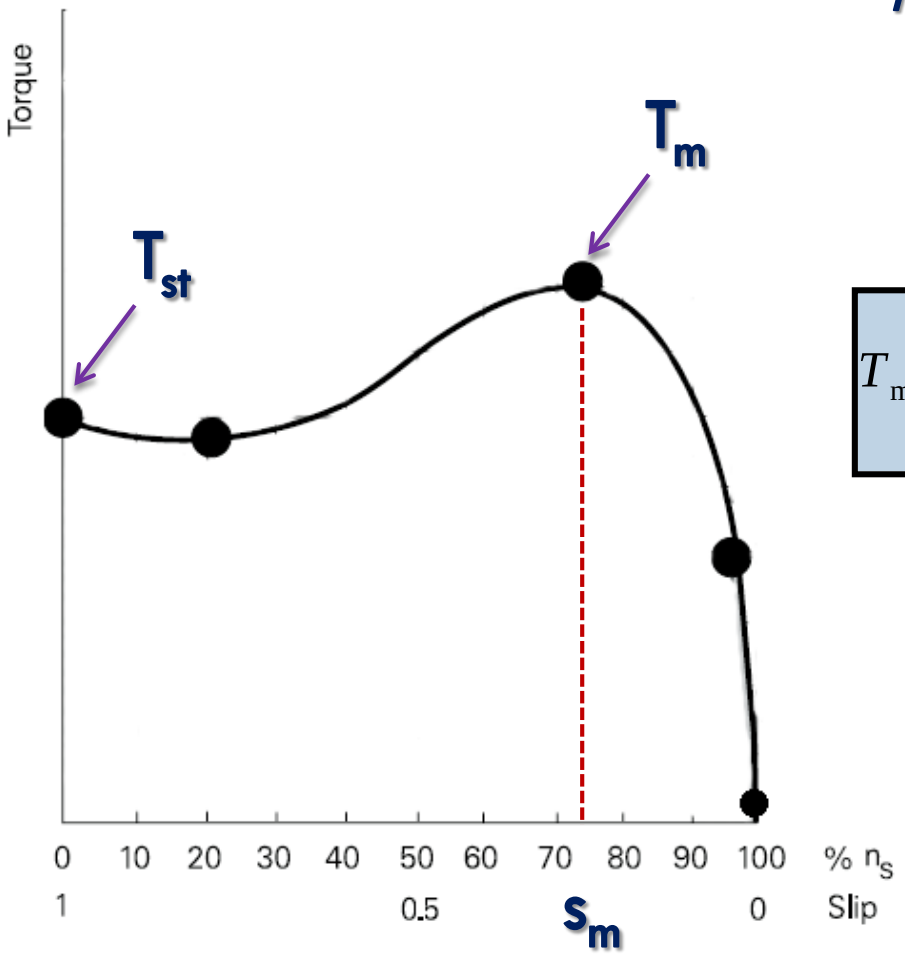
$$s = \frac{n_s - n}{n_s}$$

Starting (locked rotor) Torque

$n = 0$ $\quad$ $s = 1$

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

Induction Machines: Torque-Speed characteristic



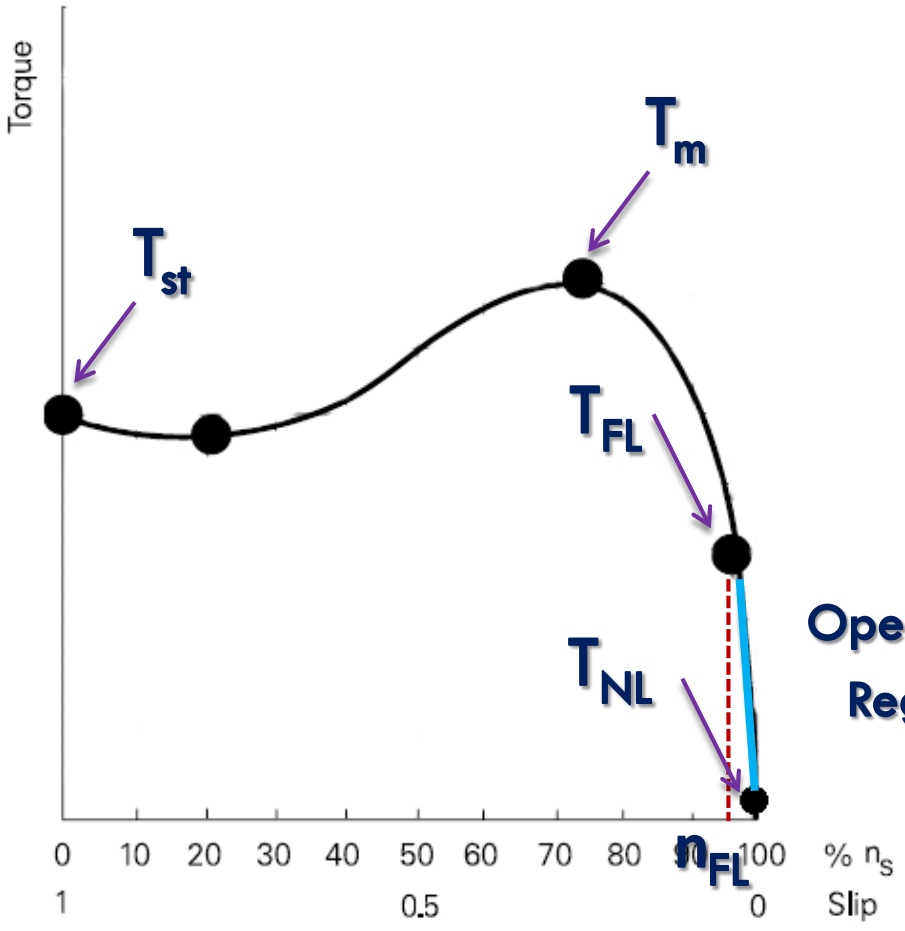
Maximum (breakdown/Pull-out) Torque

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

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

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

Induction Machines: Torque-Speed characteristic



Operating Region

Full Load Torque

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

No Load Torque

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

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

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

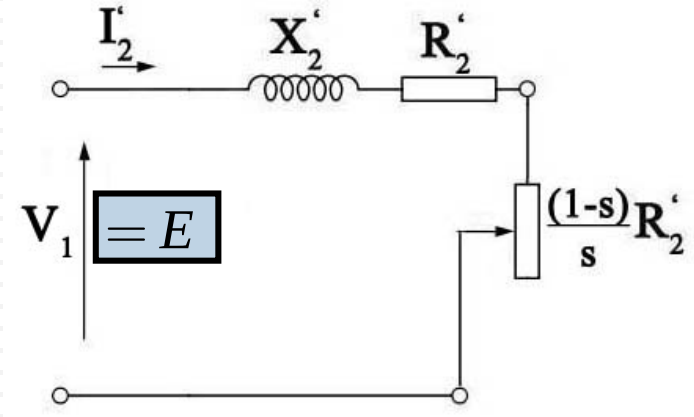
I_{NL} = 30-40% I_{FL}

Induction Machines: Torque-Speed characteristic

Neglecting stator impedance (for large motors)

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

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



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

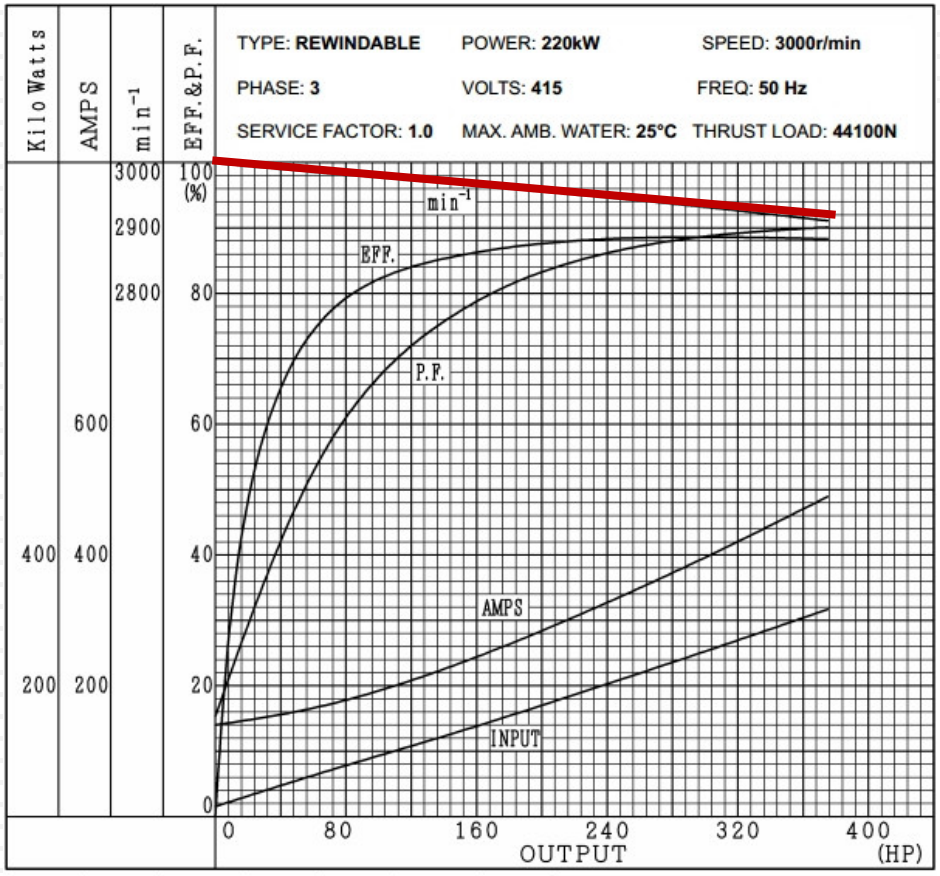
$$s_{Tm} = \frac{R_2'}{X_2'}$$

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

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

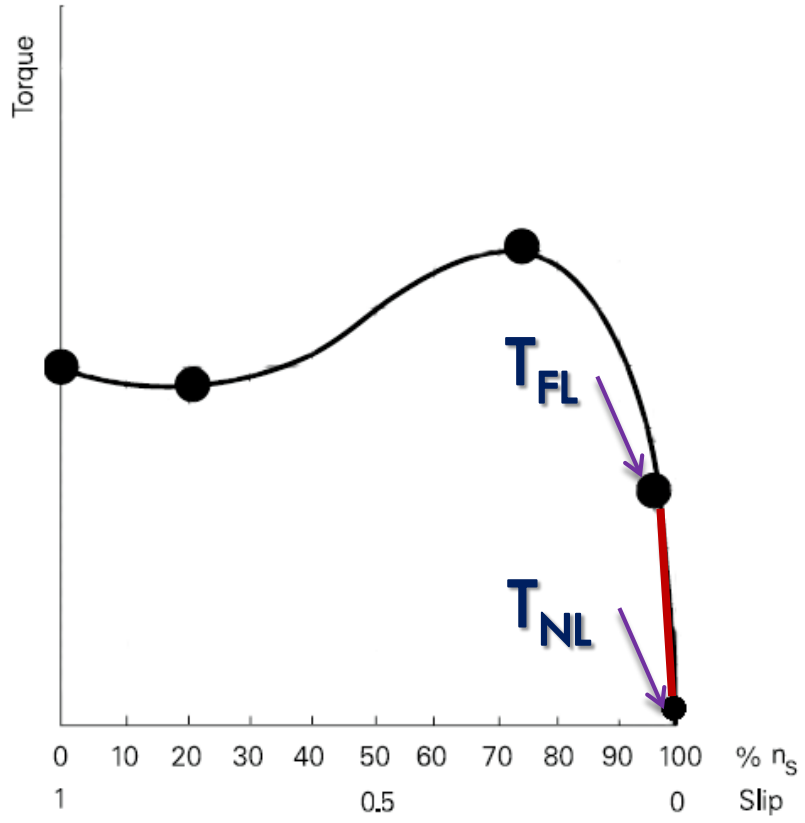
$$\frac{T_d}{T_m} = \frac{2}{\frac{s_m}{s} + \frac{s}{s_m}}$$

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)

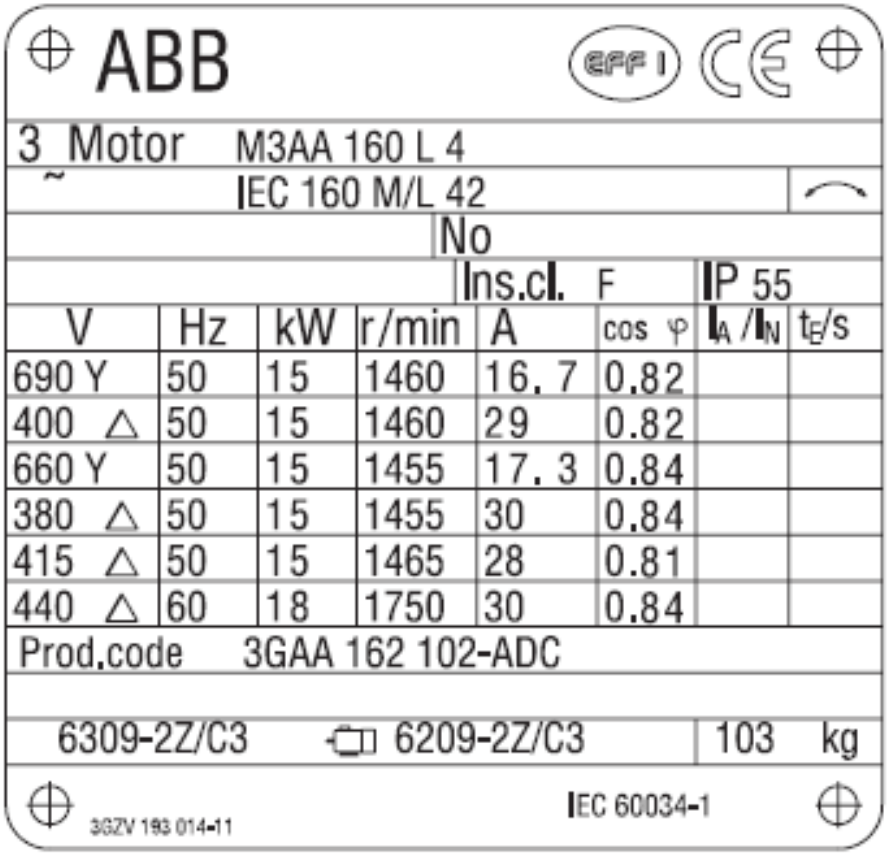
Rated Frequency (f_r)

Rated Power (kW or HP)

Full Load Speed (rpm)

Full load Current (I_{FL})

Full load power factor



ABB

EFF 1

3 Motor M3AA 160 L 4

~ IEC 160 M/L 42

No

Ins.cl. F IP 55

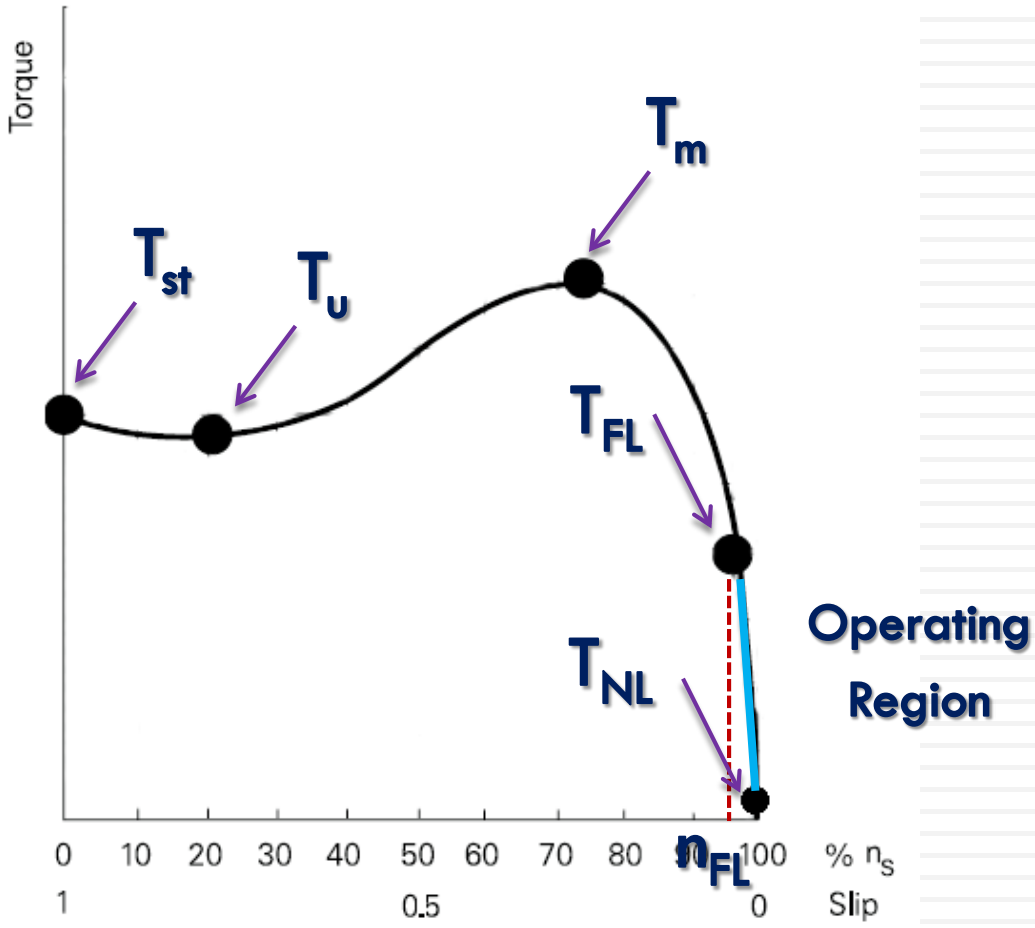
V	Hz	kW	r/min	A	cos φ	I_A/I_N	t_E/s
690 Y	50	15	1460	16. 7	0.82		
400 △	50	15	1460	29	0.82		
660 Y	50	15	1455	17. 3	0.84		
380 △	50	15	1455	30	0.84		
415 △	50	15	1465	28	0.81		
440 △	60	18	1750	30	0.84		

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



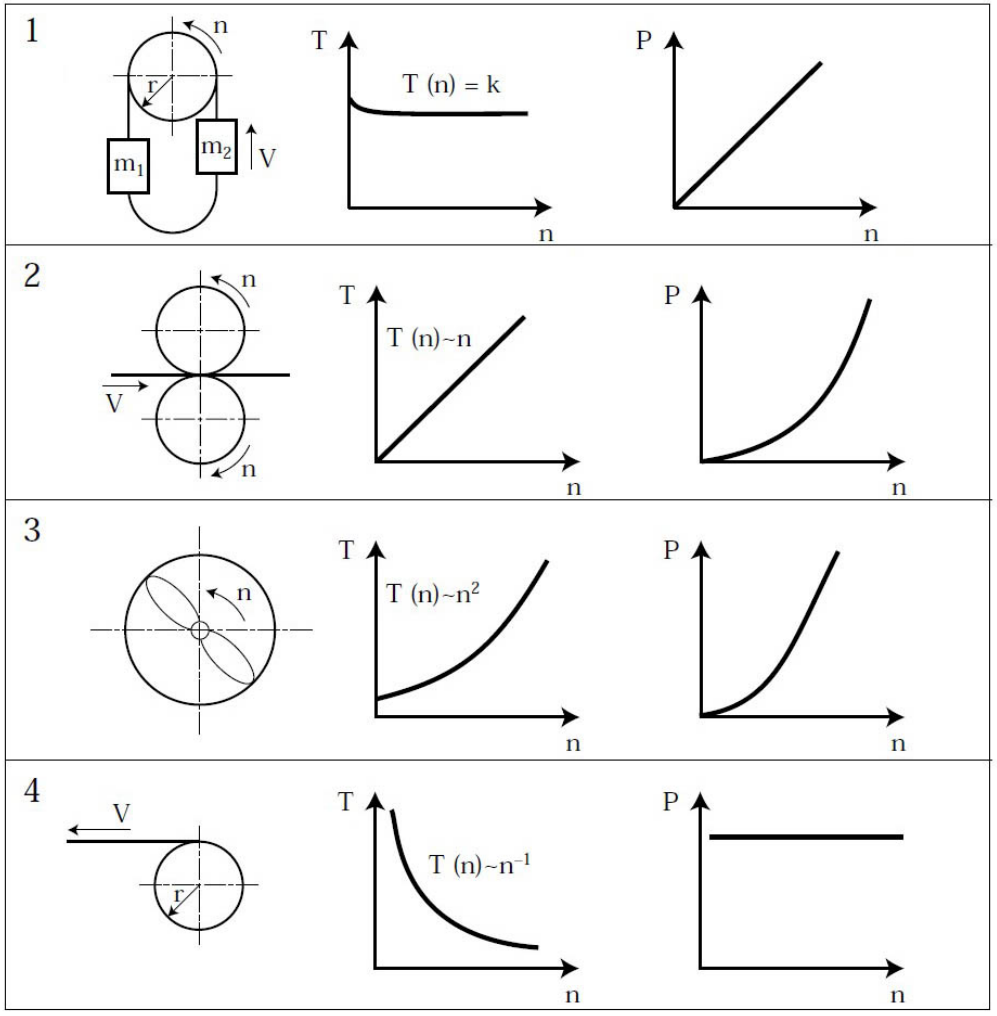
Induction Machines: Loading & Stability

Constant Torque

Linear Load

Squared Load

Constant Power



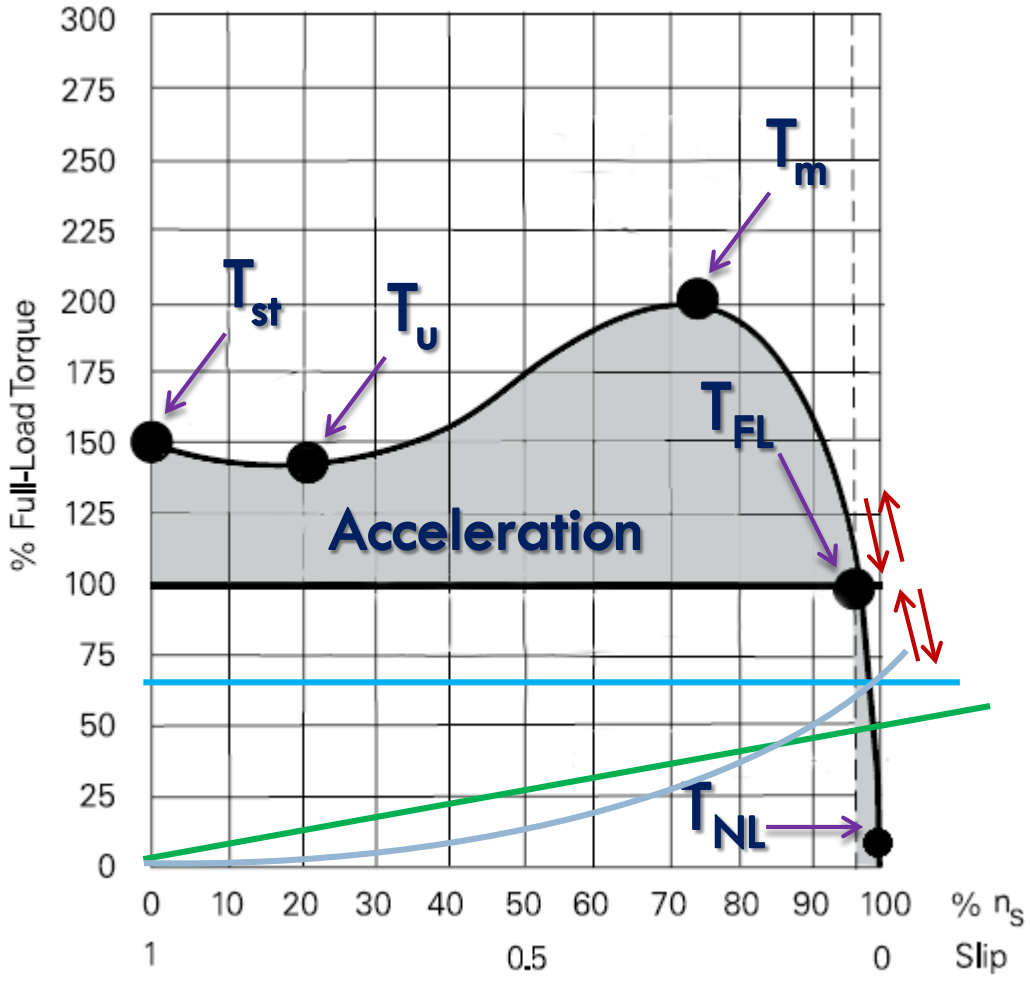
Conveyors
Hoists
Crushers

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**

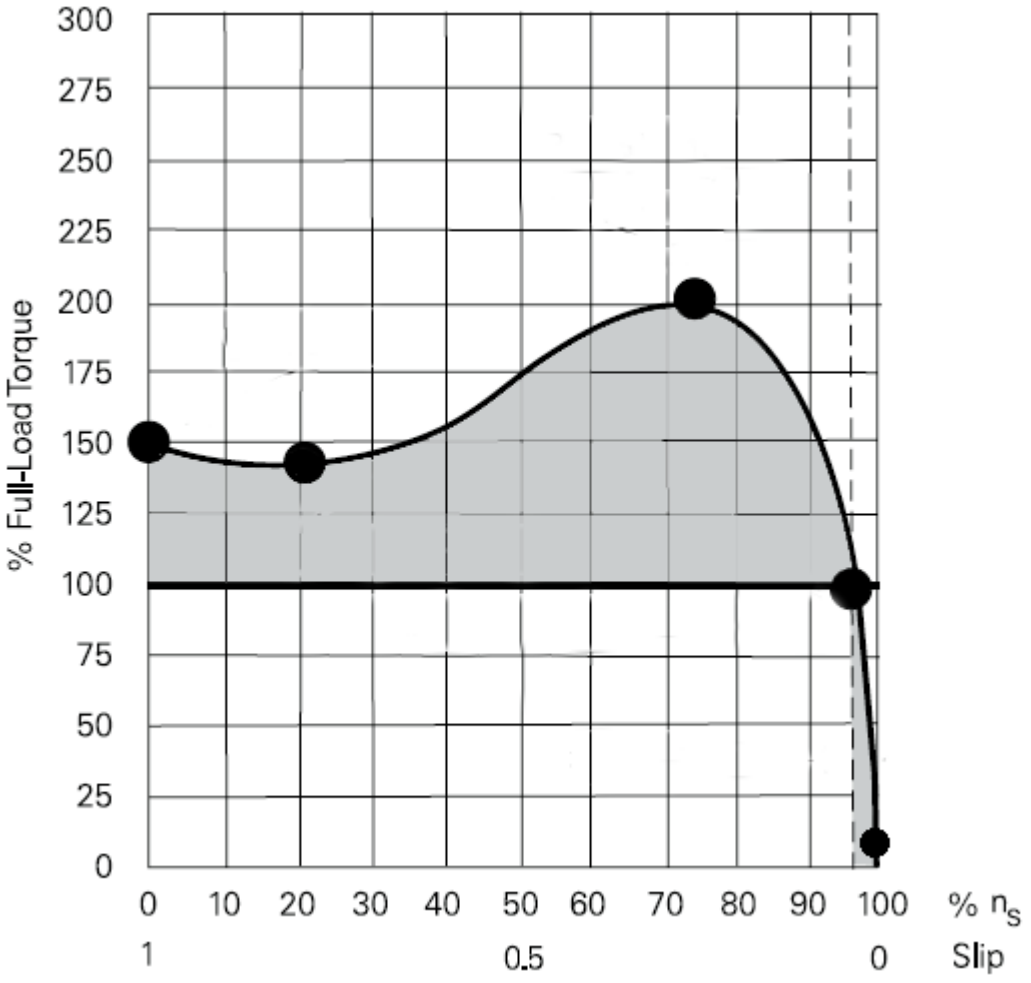
$T_m < T_L$ **Deceleration**

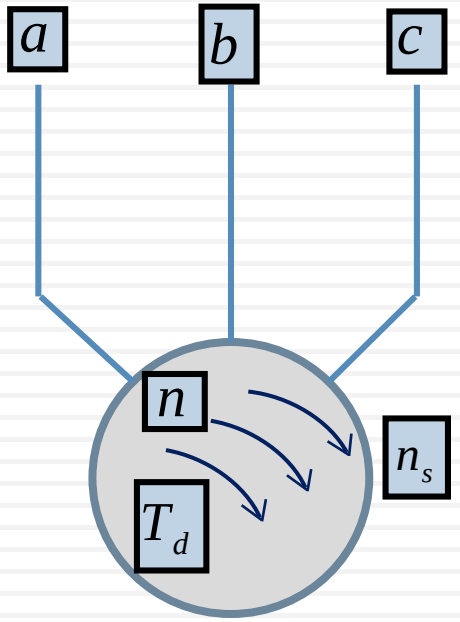
At Operating Point

$T_m = T_L \Rightarrow n = const.$

Induction Machines: Operating Modes

1. Motoring

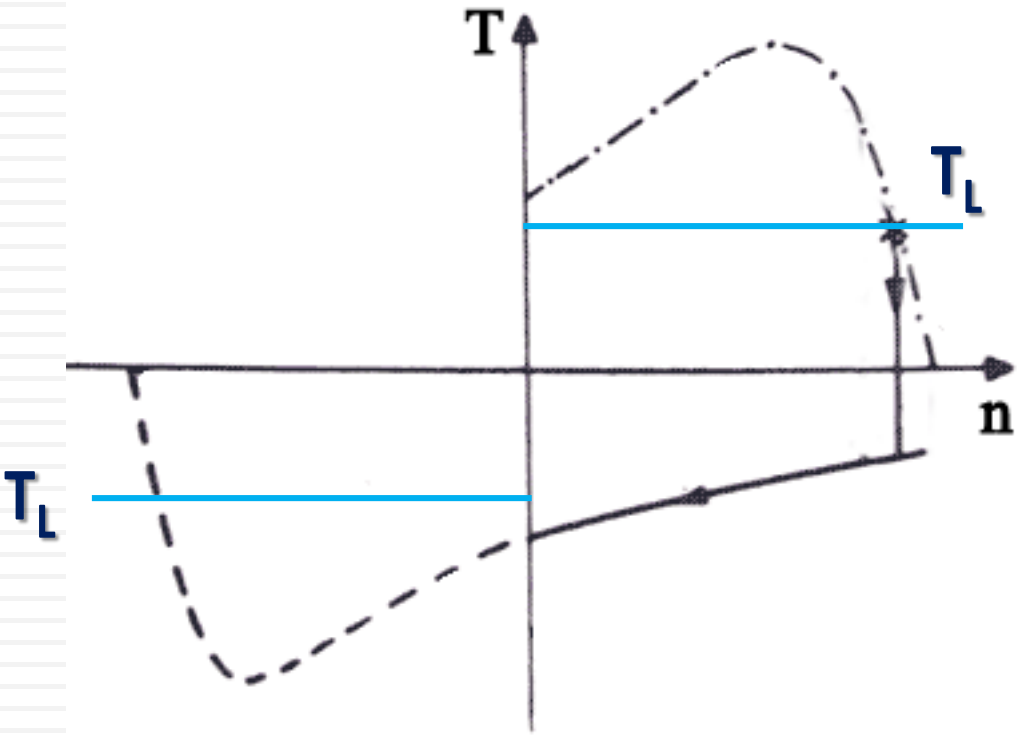




Induction Machines: Operating Modes

2. Braking

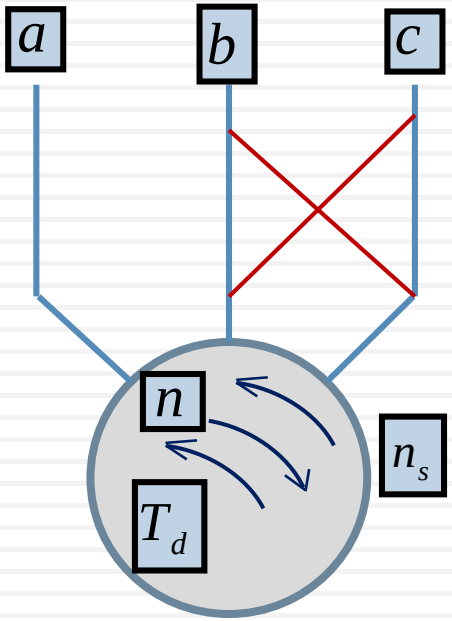
Plugging



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

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

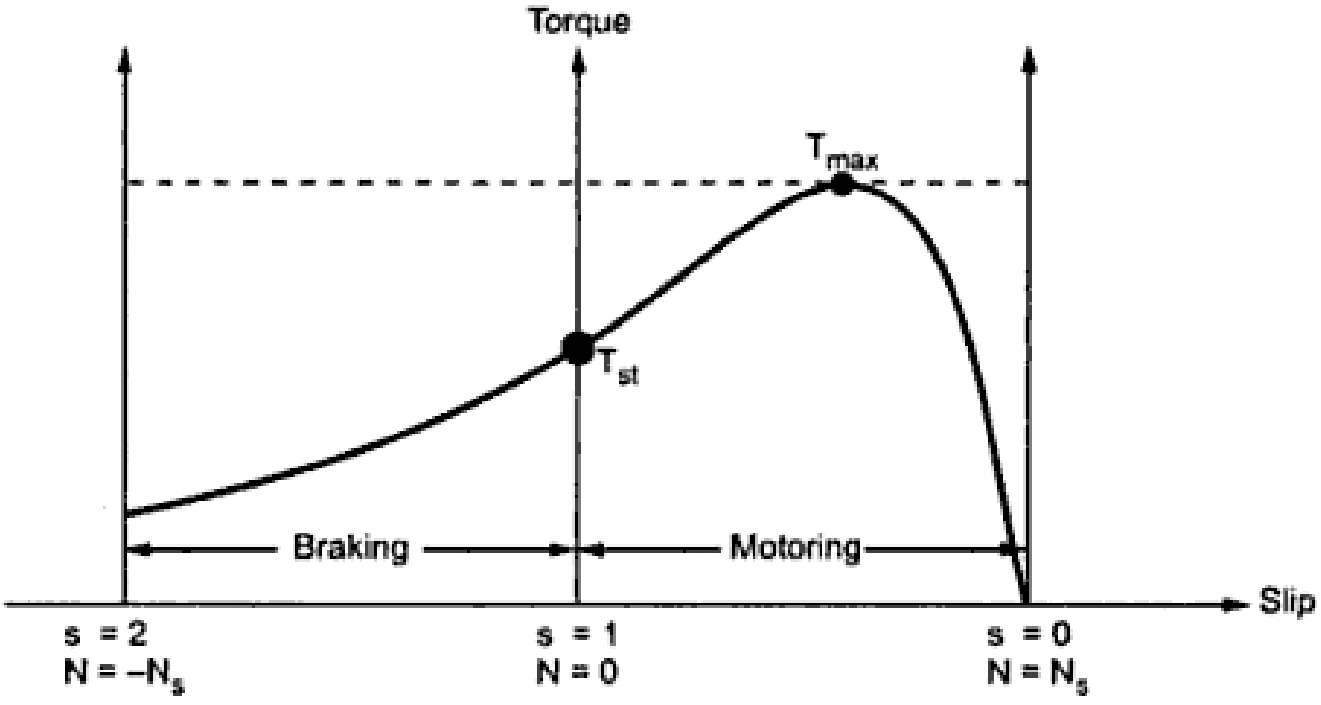
Deceleration

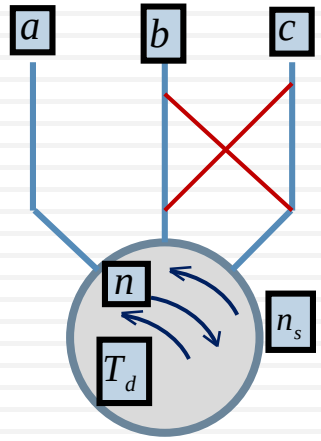


Induction Machines: Operating Modes

2. Braking

Plugging

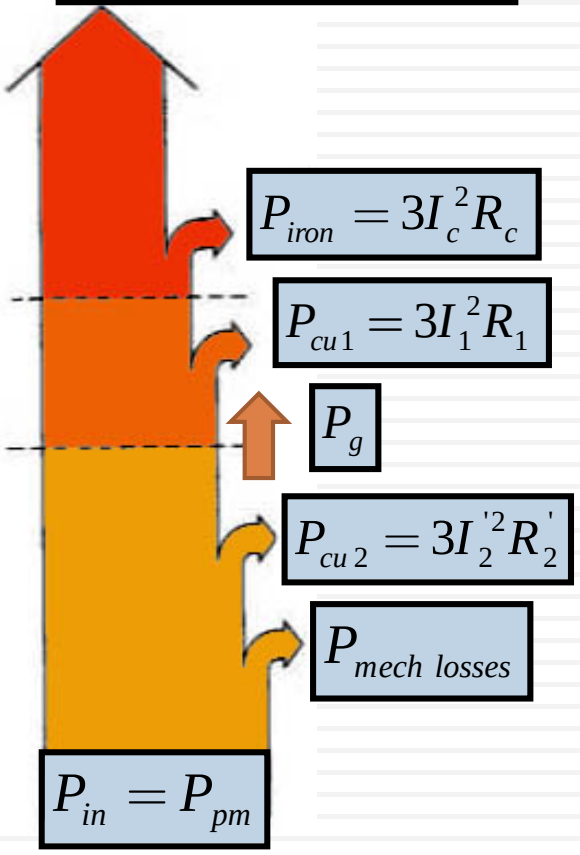


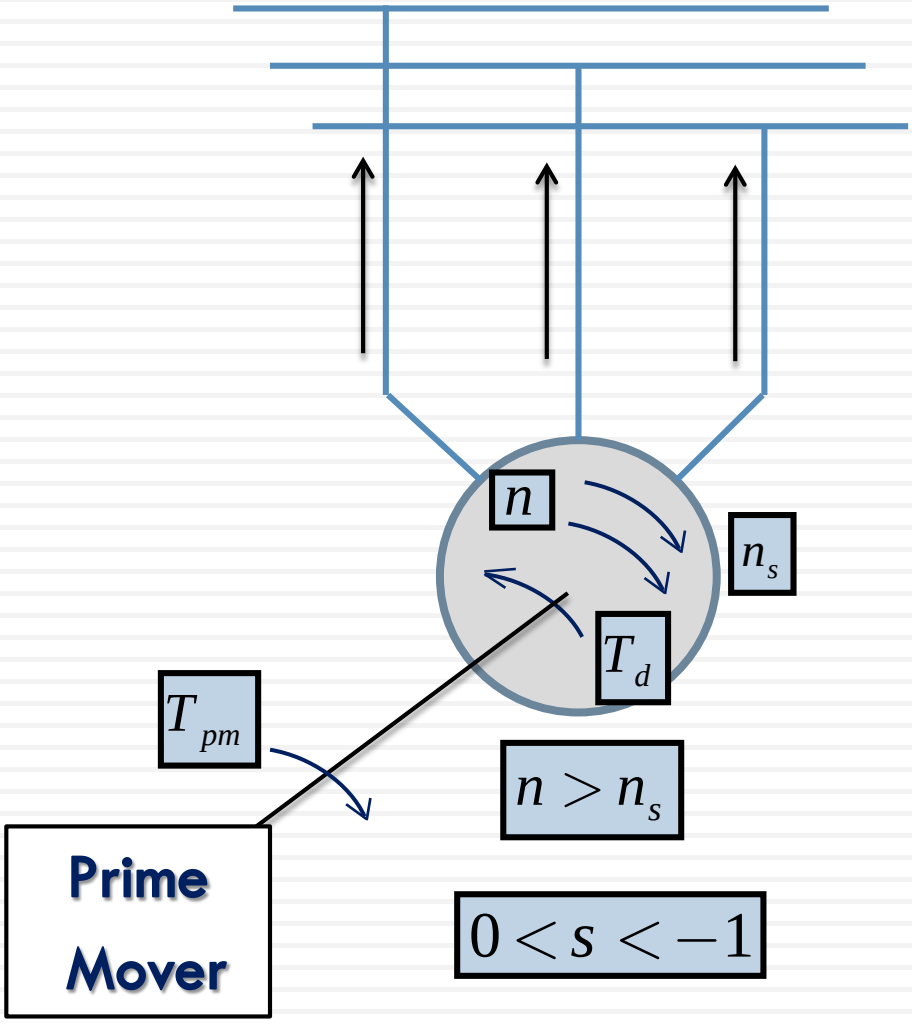


Induction Machines: Operating Modes

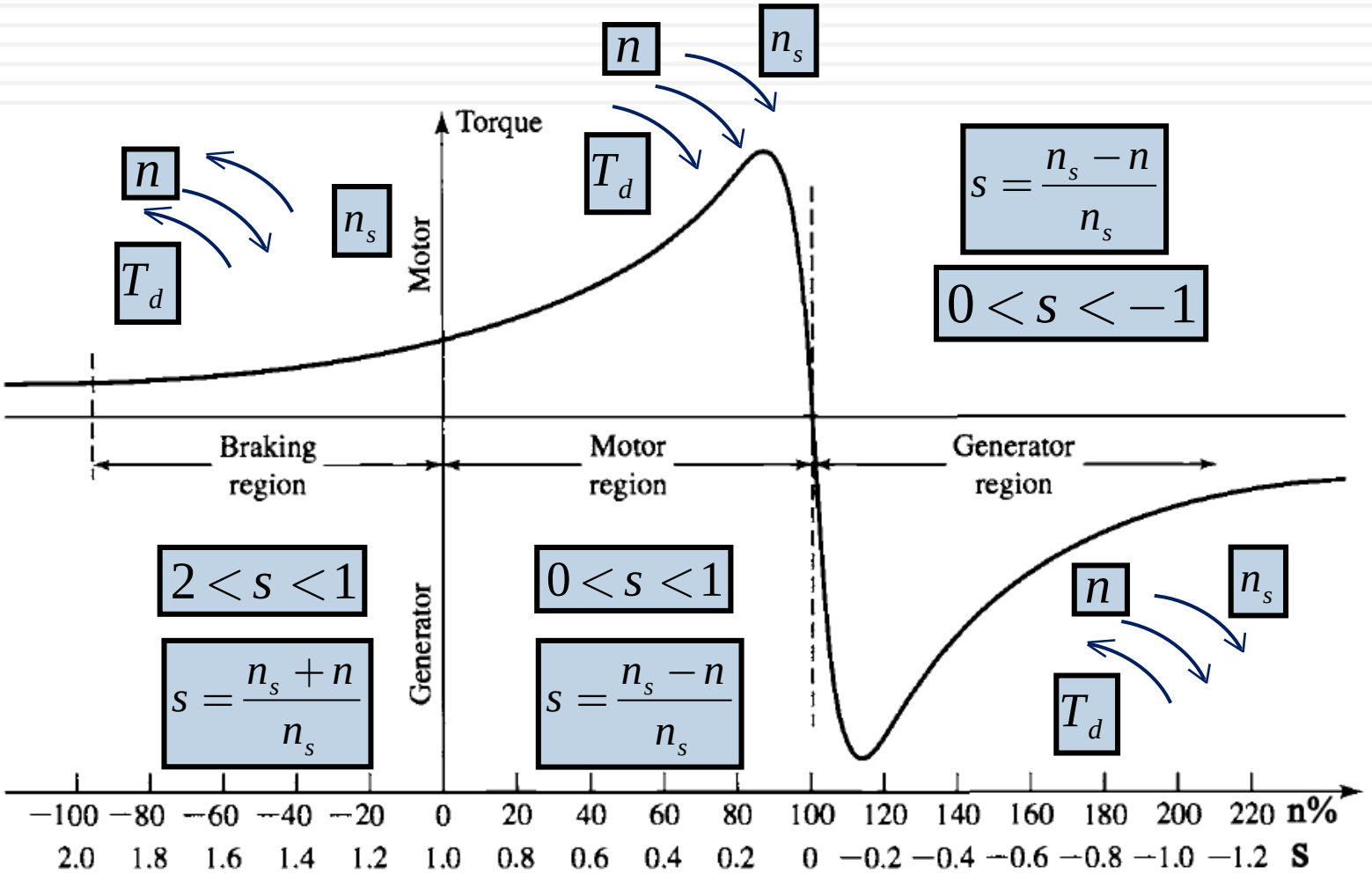
3. Generating

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





Induction Machines: Operating Modes



Induction Machines: Testing

1. DC Test

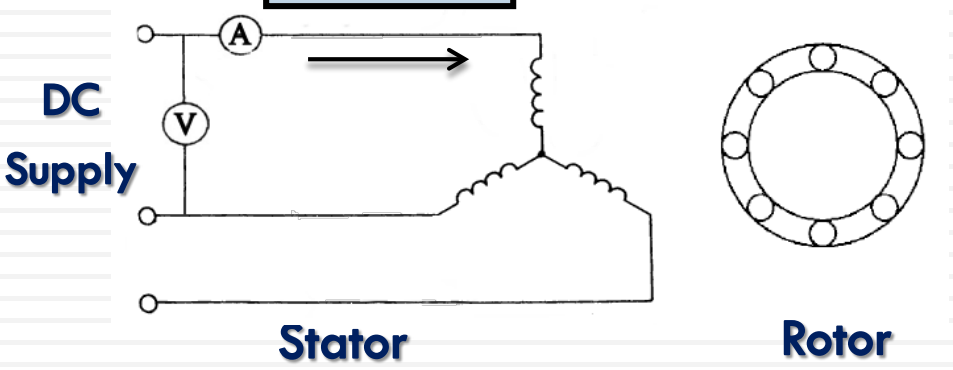
DC voltage is adjusted such that stator current = full load current

$$R_{1eq} = \frac{V_{1DC}}{I_{1DC}}$$

$$R_{1eq} = 2R_{1DC}$$

$$R_1 = \frac{1}{2}R_{1eq}$$

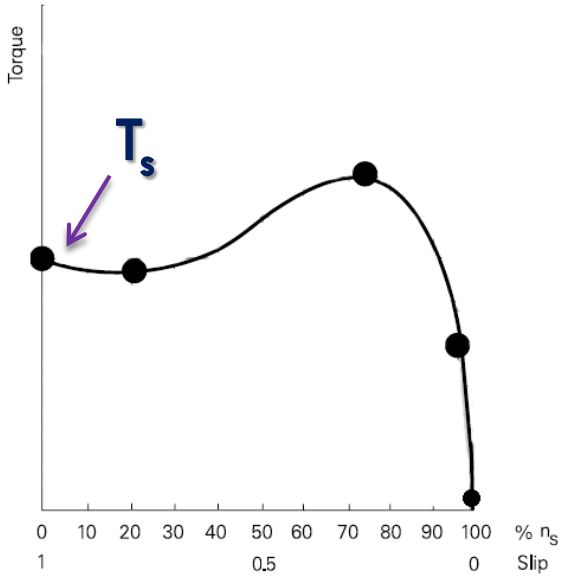
$$I_{1DC} = I_{FL}$$

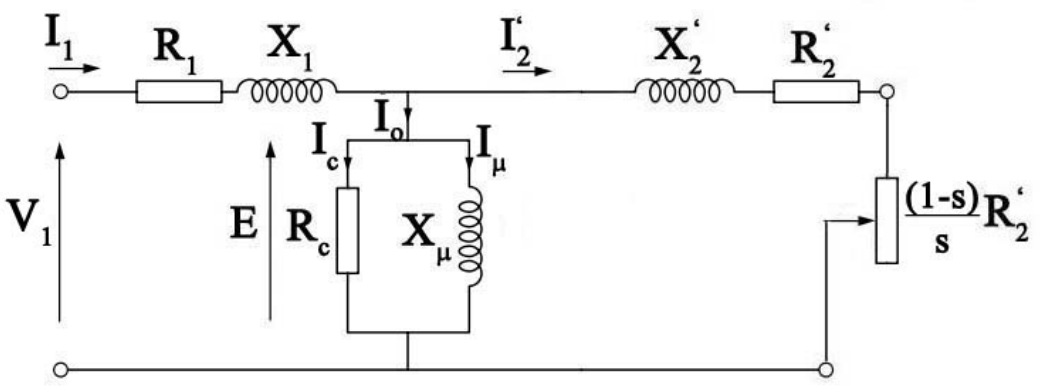


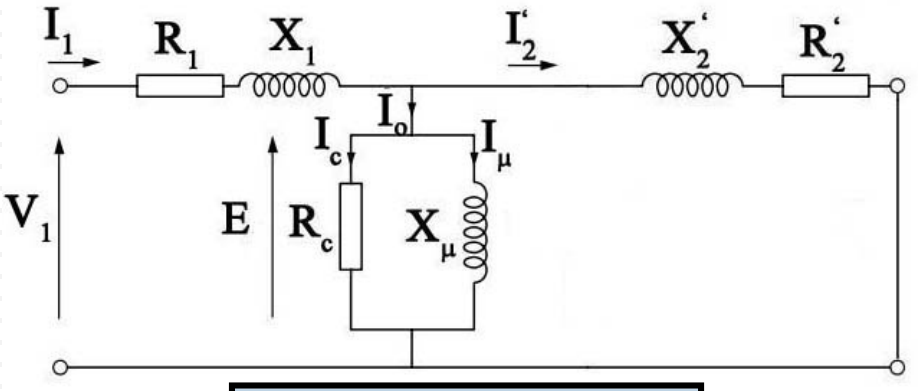
Induction Machines: Testing

2. Locked (Blocked) Rotor Test

Motor is forced to standstill







$n_{LR} = 0$ $\quad$ $s = 1$

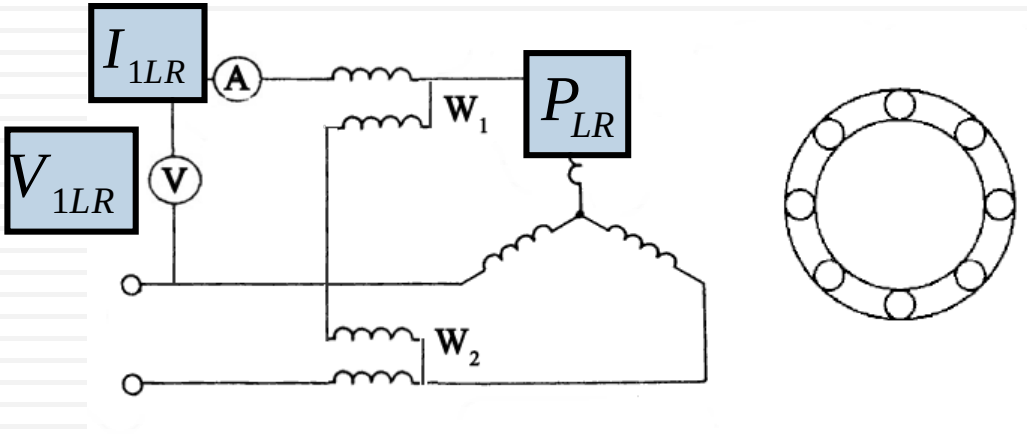
$$R_2, X_2 \ll R_c, X_m$$

Induction Machines: Testing

2. Locked (Blocked) Rotor Test

Voltage is adjusted such that stator current ≤ full load current

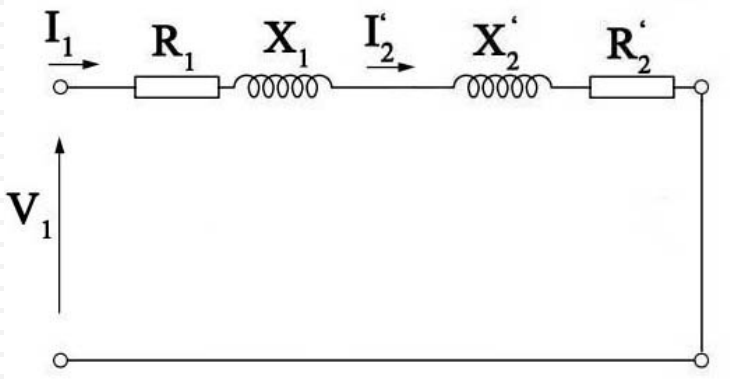
Reduced Voltage



$$P_{LR} = 3I_{LR\phi}^2 R_{LR}$$

$$R_{LR} = R_1 + R_2'$$

$$R_2' = R_{LR} - R_1$$



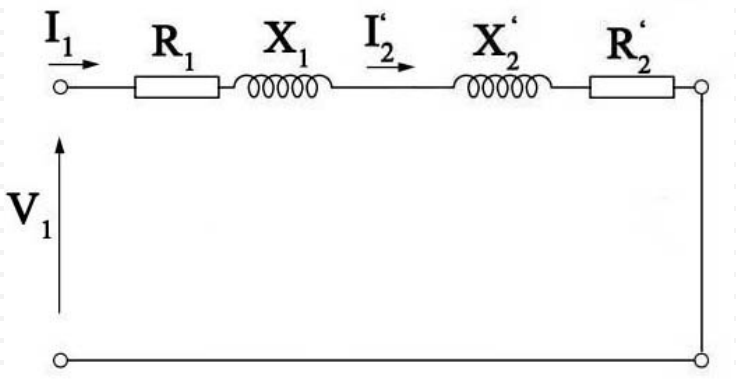
Induction Machines: Testing

2. Locked (Blocked) Rotor Test

$$Z_{LR} = \frac{V_{1LR\phi}}{I_{1LR\phi}}$$

$$Z_{LR} = \sqrt{R_{LR}^2 + X_{LR}^2}$$

$$X_{LR} = \sqrt{Z_{LR}^2 - R_{LR}^2}$$



$$X_{LR} = X_1 + X_2'$$

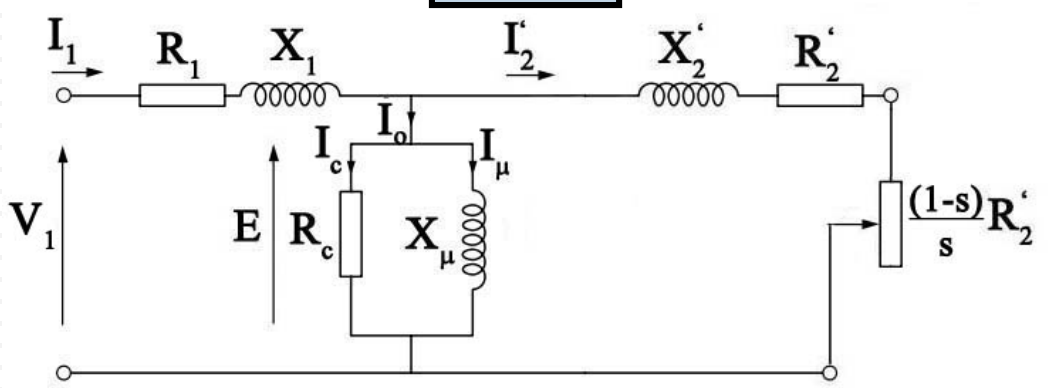
$$X_1 = X_2' = \frac{X_{LR}}{2}$$

Induction Machines: Testing

3. No-Load Test

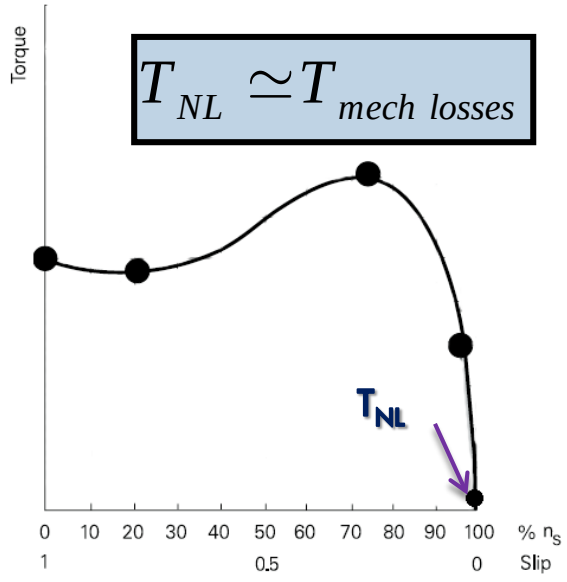
Motor running at no mech. Load

$I_2' \approx 0$

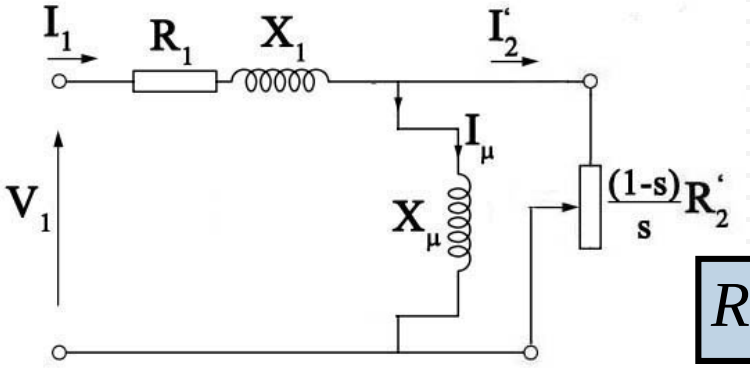


$P_{cu\,2} \ll P_{mech}$

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



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



$n_{NL} \approx n_s$

$s \approx 0$

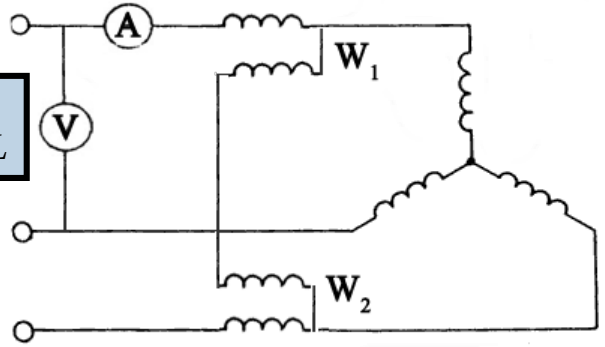
$R_{mech\&iron}$

Induction Machines: Testing

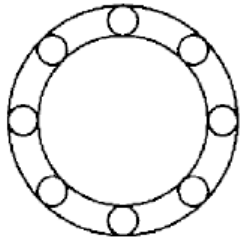
3. No-Load Test

I_{1NL} P_{NL}

Rated Voltage V_{1NL}



Squirrel Cage Rotor

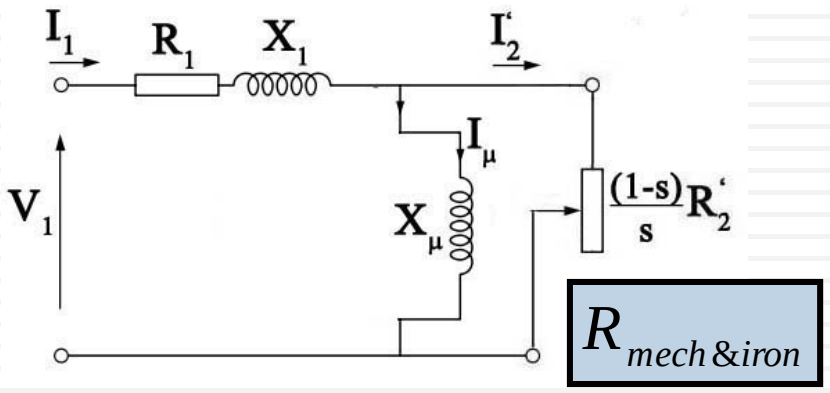


$$P_{NL} = P_{iron} + P_{mech} + P_{cu1}$$

$$P_{cu1} = 3I_{1NL}^2 R_1$$

$$P_{mech} + P_{iron}$$

$$P_{mech\&iron}$$



$$R_{mech\&iron}$$

Induction Machines: Testing

3. No-Load Test

$$Z_{NL} = \frac{V_{1NL\phi}}{I_{1NL\phi}}$$

$$X_{\mu} \ll R_{mech\&iron}$$

$$\Rightarrow \quad R_{NL} = R_1$$

$$Z_{NL} = \sqrt{R_{NL}^2 + X_{NL}^2}$$

$$X_{NL} = \sqrt{Z_{NL}^2 - R_1^2} = X_1 + X_{\mu}$$

$$\Rightarrow \quad X_{\mu} = X_{NL} - X_1$$