Energy conversion I

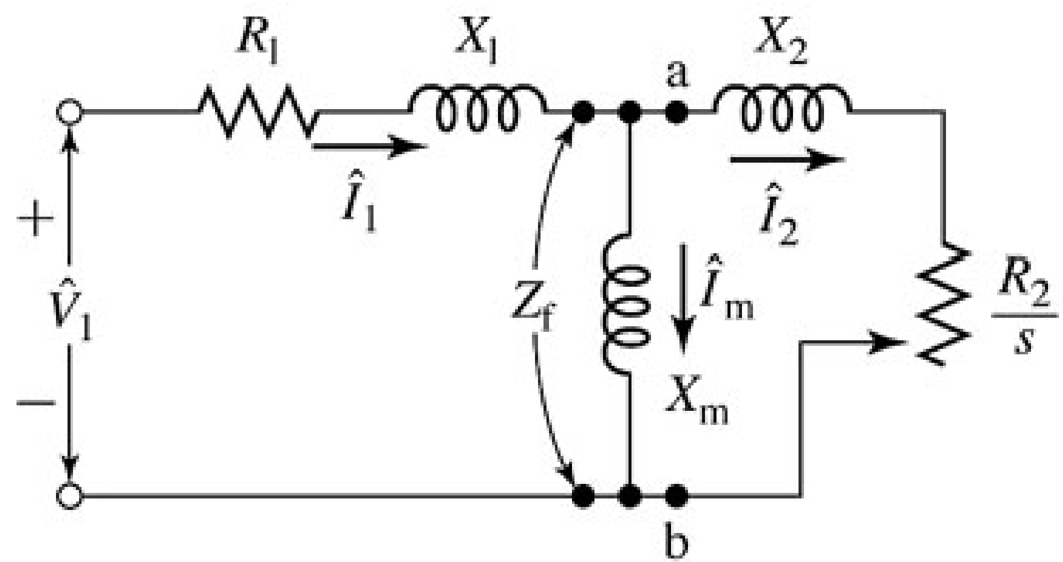
Lecture 20:

Topic 5: Induction Motors (S. Chapman ch. 7)

- Induction Motor Construction.
- Basic Induction Motor Concepts.
- The Equivalent Circuit of an Induction Motor.
- Power and Torque in Induction Motor.
- Induction Motor Torque-Speed Characteristics.
- Starting Induction Motors.
- Speed Control of Induction Motor.
- **Determining Circuit Model Parameters.**

IEEE Induction Motor Equivalent Circuit

- **Stator core loss constant**
- **Rotor core loss decreases with speed.**
- **Friction and windage increase with speed.**



core, Friction & Windage loss: Rotational loss

IEEE Standard 112 for tests to get the equivalent circuit.

Simplified Tests are : DC Test for Stator Resistance

No-Load Test

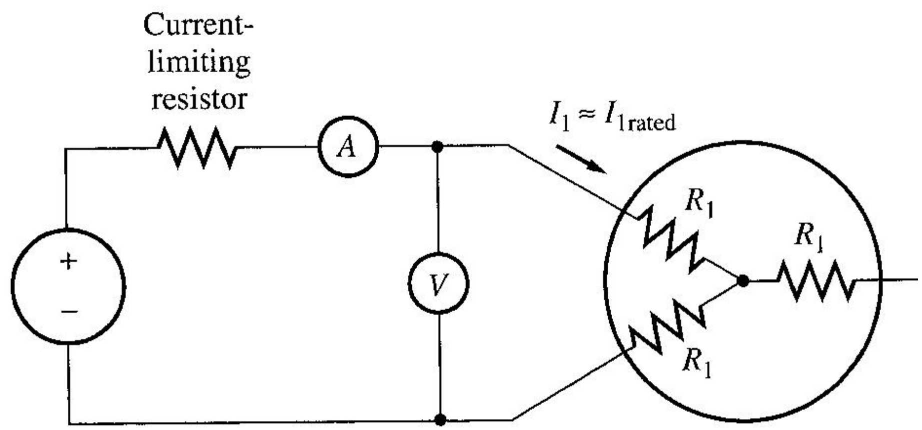
Locked-Rotor Test

Compare with transformer!

DC Test for Stator Resistance

•Stator resistance can be measured directly by an Ohmmeter or by applying DC voltage and measuring the current:

$$2R_{1,dc} = \frac{V_{dc}}{I_{dc}}$$



R_1 can be considered as the average of three measurements of $R_{1,dc}$

Effect of temperature and skin effect can be considered to have correct value of R_1.

No-Load Test

Stator feed by nominal voltage

No mechanical load

Stator voltage, current and power are measured

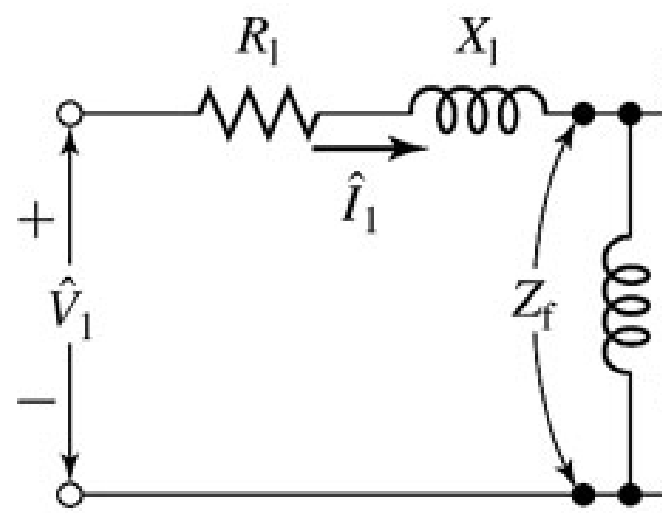
$s \approx 0$

$I_2 \approx 0$

$$P_{in} = P_{nl} = P_{SCL} + P_{rot}$$

$$P_{rot} = P_{nl} - 3R_1 I_{1,nl}^2$$

$$Z_{nl} = \frac{V_{1,nL}}{I_{1,nL}} \approx X_1 + X_M$$



+ rotational loss

Per phase equivalent circuit at No-load

X_{nl} can be calculated from Q_{nl} too
$Q_{nl} = 3\ X_{nl}\ I_{nl}^2$ $X_{nl} = X_1 + X_M$ (more usual)

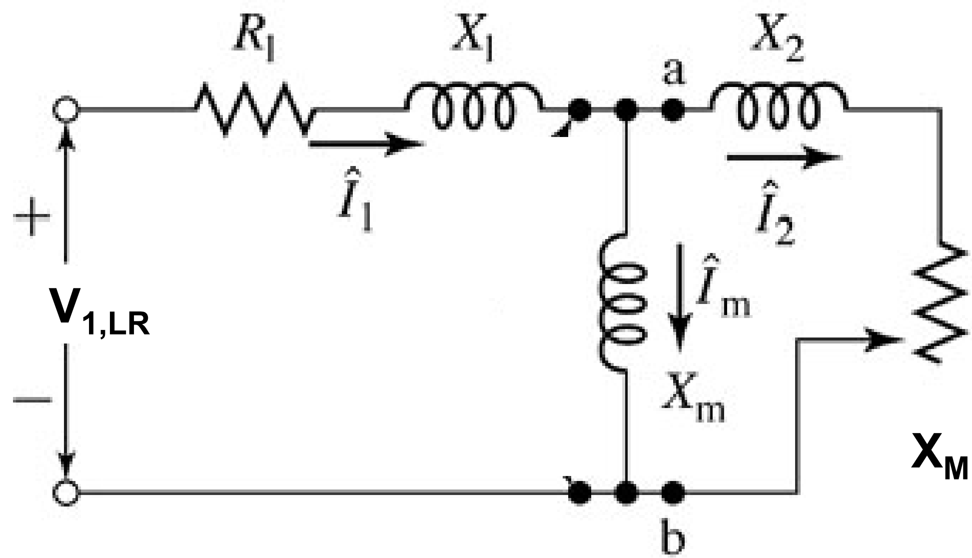
Locked-Rotor Test

Rotor is locked not to move.

Voltage is applied to motor to have full-load current.

Stator voltage, current and power are measured.

s = 1



$$\frac{R_2}{s} = R_2$$

$$\left|R_2 + jX_2\right| << X_M$$

X_M can be neglected

$$Z_{LR} = \frac{V_{1,LR}}{I_{1,LR}} \approx R_{LR} + jX_{LR}$$

$$R_{LR} \approx R_1 + R_2$$

$$X_{LR} \approx X_1 + X_2$$

Attention: Locked rotor test should be done with reduced frequency (25% f_e). (why?)
In that case reactances are measured in reduced frequency and should be corrected.

Locked-Rotor Test

	X_1 and X_2 as a function of X_{LR}	
Rotor Design	X_1	X_2
Wound rotor	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Class A	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Class B	$0.4\ X_{LR}$	$0.6\ X_{LR}$
Class C	$0.3\ X_{LR}$	$0.7\ X_{LR}$
Class D	$0.5\ X_{LR}$	$0.5\ X_{LR}$

Once X_1 is known, X_M can be calculated using No-Load test results.

What about Nse / Nre for wound rotor motor?
Why is it required?

Example:

The following test data were taken on a 7.5 hp, 4-pole, 208V, 60Hz, design A, induction motor having a rated current of 28A.

DC Test: $V_{DC} = 13.6$ V $I_{DC} = 28.0$ A

No-load test:

$V_T = 208$ V $f = 60$ Hz

$I_A = 8.12$ A $P_{in} = 420$W

$I_B = 8.20$ A

$I_C = 8.18$ A

Locked-rotor test:

$V_T = 25$ V $f = 15$ Hz

$I_A = 28.1$ A $P_{in} = 920$W

$I_B = 28.0$ A

$I_C = 27.6$ A

Sketch the per-phase equivalent circuit for this motor

Solution:

From DC test: $$R_1 = \frac{V_{DC}}{2I_{DC}} = \frac{13.6}{2\times 28} = 0.243\ \Omega$$

From no-load test:

$$I_{L,av} = \frac{8.12+8.20+8.18}{3} = 8.17\ \text{A}$$

$$V_{\varphi,NL} = \frac{208}{\sqrt{3}} = 120\ \text{V}$$

$$Z_{NL} = \frac{120}{8.17} = 14.7\ \Omega \approx X_1 + X_M$$

Recalculate it Using Q!

$$P_{rot} = P_{NL} - P_{SCL,NL}$$
$$= 420 - 3\times 0.243\times 8.17^2$$
$$= 371.3\ \text{W}$$

From locked-rotor test:

$$I_{L,av} = \frac{28.1+28.0+27.6}{3} = 27.9\ \text{A}$$

$$V_{\varphi,LR} = \frac{25}{\sqrt{3}} = 14.43\ \text{V}$$

$$|Z_{LR}| = \frac{14.43}{27.9} = 0.517\ \Omega$$

$$\theta_{LR} = \cos^{-1}\frac{P_{in}}{\sqrt{3}V_T I_L} = \cos^{-1}\frac{920}{\sqrt{3}\times 25\times 27.9} = 40.4^{o}$$

$$Z_{LR} = 0.517\angle 40.4^{o} = 0.394 + j0.335$$

$$R_{LR} = 0.394 = R_1 + R_2 \Rightarrow R_2 = 0.394 - 0.243 = 0.251\,\Omega$$

$$X_{LR} = \frac{f_{rated}}{f_{test}} X'_{LR} = \frac{60}{15} 0.335 = 1.34\,\Omega$$

For a class A rotor design:

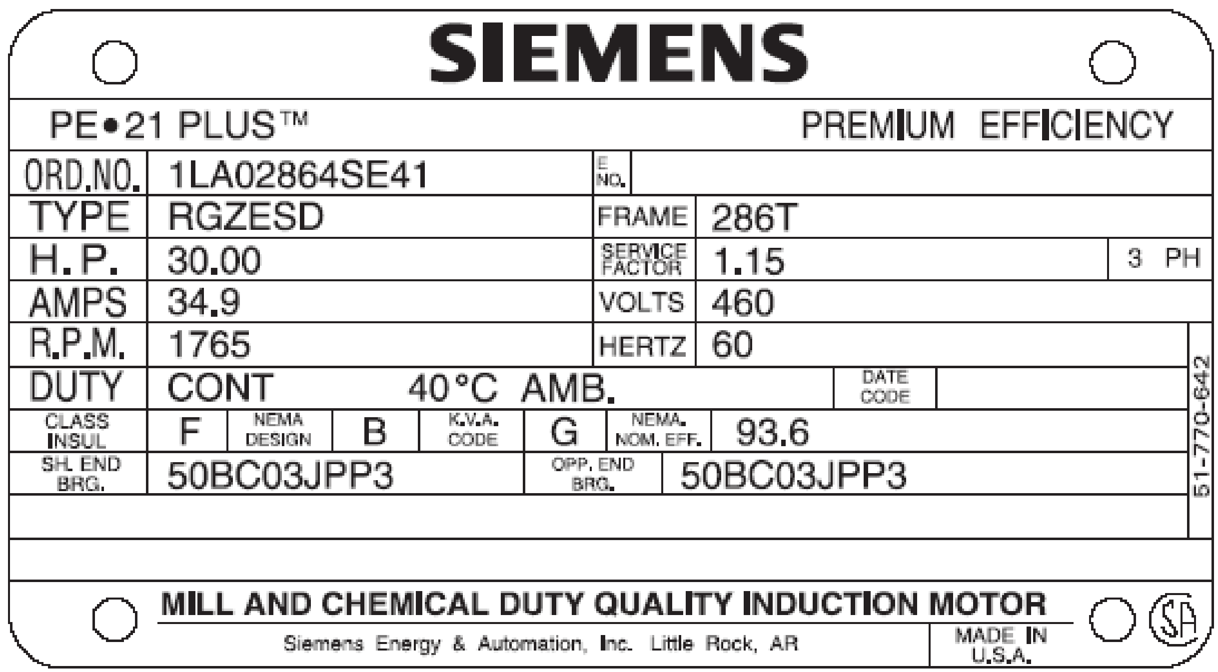
$$X_1 = X_2 = \frac{1.34}{2} = 0.67\,\Omega$$

And therefore:

$$X_M = \left|Z_{NL}\right| - X_1 = 14.7 - 0.67 = 14.03\,\Omega$$

Name Plate of Induction Motors

- Rated voltage, current and frequency (460, 34.9, 60)
- Rated horse power (30)
- Rated speed (1765)
- Service factor (times rated power) (1.15)
- Maximum Ambient Temperature (40)
- Insulation Class (A, B, H, F)
- type (A, B, C, D)
- Motor efficiency (93.6)
- K.V.A. (/Starting) code (G) (5.6-6.3)
- Enclosure



K.V.A. (/Starting) code

Code Letter	Start kVA/rated Hp
A	0 - 3.15
B	3.15 - 3.55
C	3.55 - 4.0
D	4.0 - 4.5
E	4.5 - 5.0
F	5.0 - 5.6
G	5.6 - 6.3
H	6.3 - 7.1
J	7.1 - 8.0
K	8.0 - 9.0
L	9.0 - 10.0
M	10.0 - 11.0
N	11.0 - 12.5
P	12.5 - 14.0
R	14.0 - 16.0
S	16.0 - 18.0
T	18.0 - 20.0
U	20.0 - 22.4
V	22.4 +

The 480V, 30Hp induction motor has start code G. Find the maximum current that may be expected at starting.

$S_{start} = 6.3 \times 30 = 189\text{kVA}$

$I_L = 189 \times 10^3/(\sqrt{3} \times 480)$
$I_L = 227\ \text{A}$

$I_L / I_{rated} = 227 / 34.9 = 6.5$

New High Efficiency Induction Motors

New Classification based on efficiency: Eff1(Most expensive with highest efficiency), Eff2 & Eff3 (cheapest with lowest efficiency)

General methods:

More copper in stator.

Higher core length.

More steel in stator.

High-grade steel.

Thinner steel lamination.

More uniform rotor.

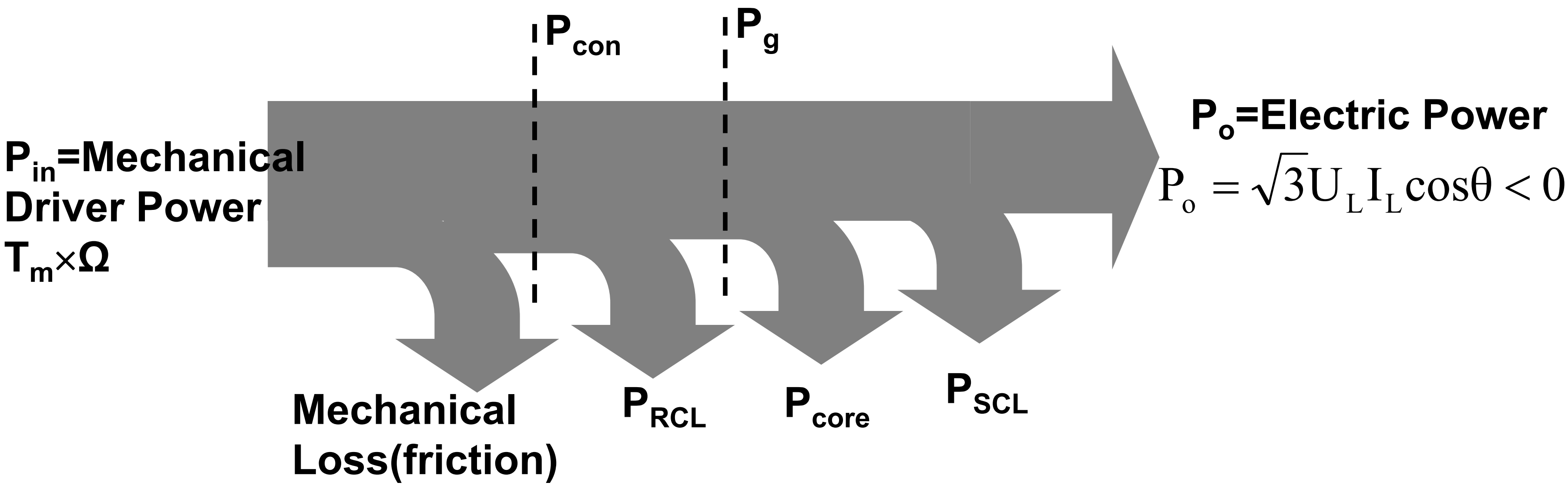
2 pole			
kW	efficiency %		
	EFF1 equal to or above	EFF2 equal to or above	EFF3 below
1.1	82.8	76.2	
1.5	84.1	78.5	
2.2	85.6	81.0	
3	86.7	82.6	
4	87.6	84.2	
5.5	88.6	85.7	
7.5	89.5	87.0	
11	90.5	88.4	
15	91.3	89.4	
18.5	91.8	90.0	
22	92.2	90.5	
30	92.9	91.4	
37	93.3	92.0	
45	93.7	92.5	
55	94.0	93.0	
75	94.6	93.6	
90	95.0	93.9	

4 pole			
kW	efficiency %		
	EFF1 equal to or above	EFF2 equal to or above	EFF3 below
1.1	83.8	76.2	
1.5	85.0	78.5	
2.2	86.4	81.0	
3	87.4	82.6	
4	88.3	84.2	
5.5	89.2	85.7	
7.5	90.1	87.0	
11	91.0	88.4	
15	91.8	89.4	
18.5	92.2	90.0	
22	92.6	90.5	
30	93.2	91.4	
37	93.6	92.0	
45	93.9	92.5	
55	94.2	93.0	
75	94.7	93.6	
90	95.0	93.9	

Induction Generators

For speeds > n_s **$s<0$ (negative)**

$P_{RCL}=R_2I_2^2 > 0$ **$P_g = P_{RCL}/ s < 0$** **$P_{con} =(1-s)P_g < 0$**



Q is always positive → **(Induction generator can not deliver reactive power!**

$$T_{ind} = \frac{3}{2}\frac{p}{\omega_s}\frac{R_2}{s}\frac{V_{th}^2}{(R_{th}+\frac{R_2}{s})^2+(X_R+X_{th})^2} < 0$$