Induction Machines

- 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

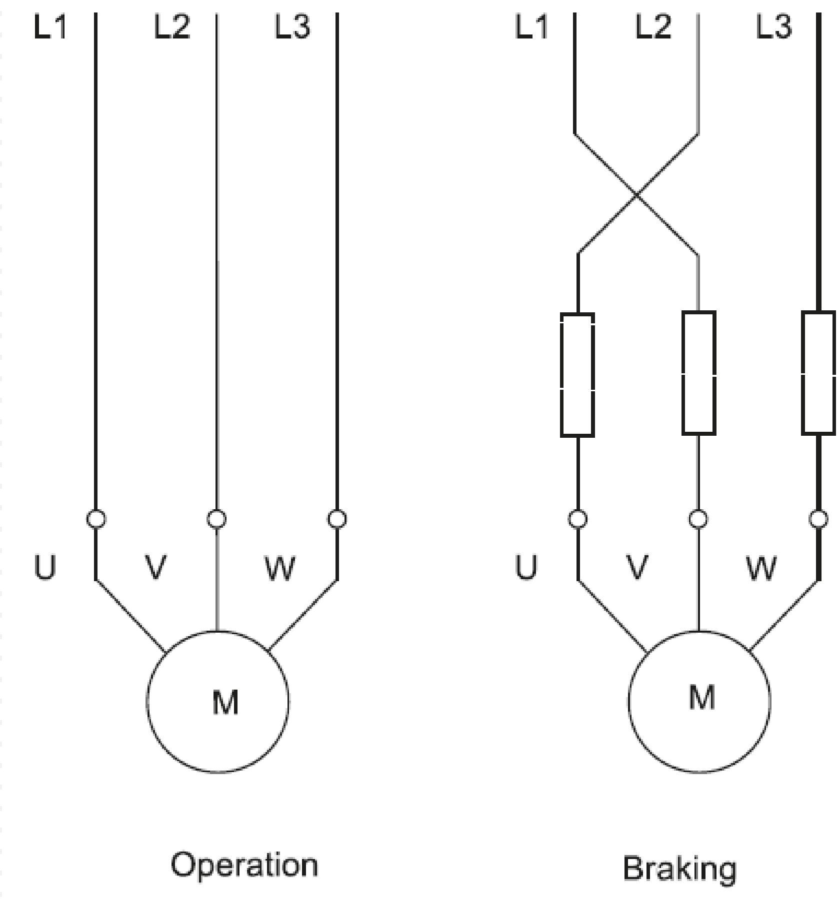
Induction Machines: Motor Braking

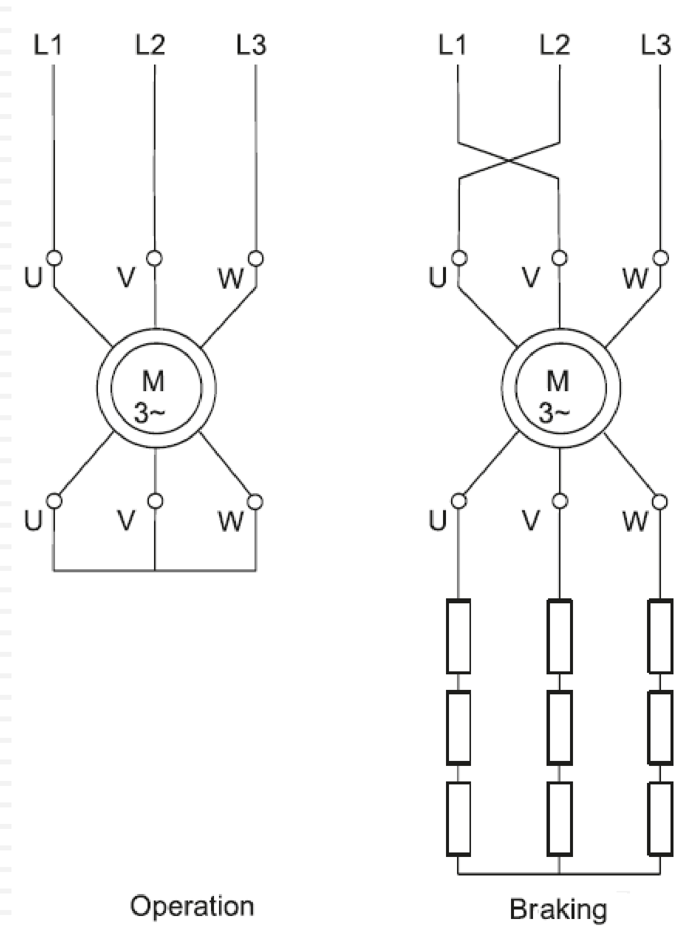
In many systems, motors are stopped simply by natural deceleration. The time this takes depends solely on the inertia and resistive torque of the machine the motor drives. However, the time often needs to be cut down and electrical braking is a simple and efficient solution.

1. *Plugging*
2. *Dynamic Braking*
3. *Regenerative Braking*

Induction Machines: Motor Braking

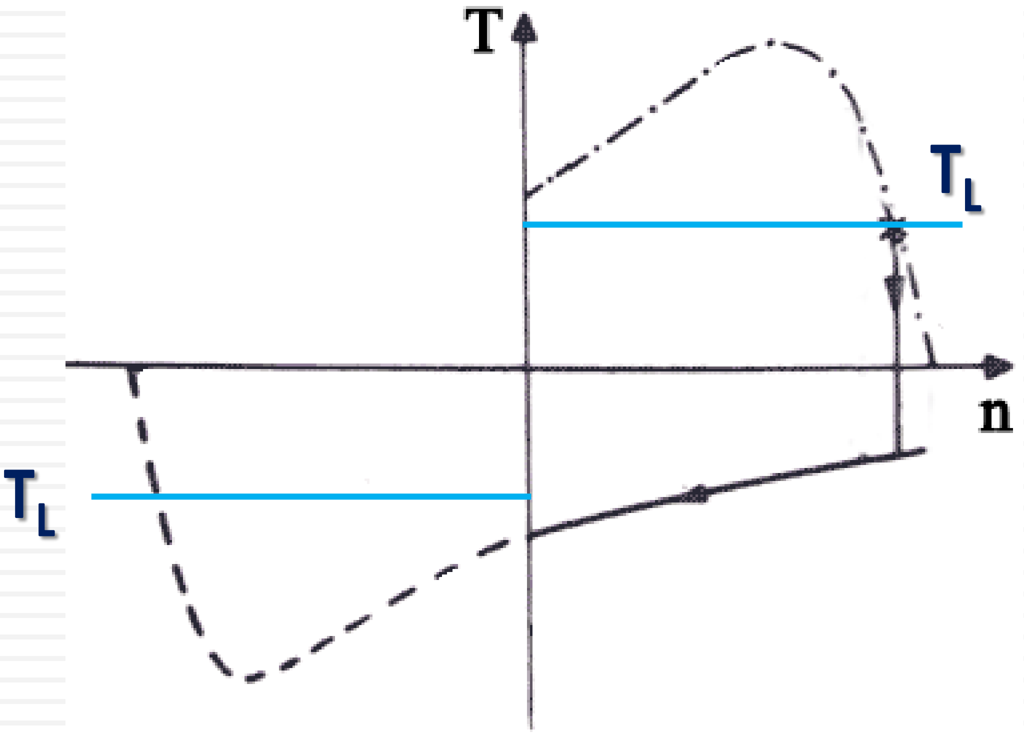
1. Plugging





Induction Machines: Motor Braking

1. Plugging



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

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

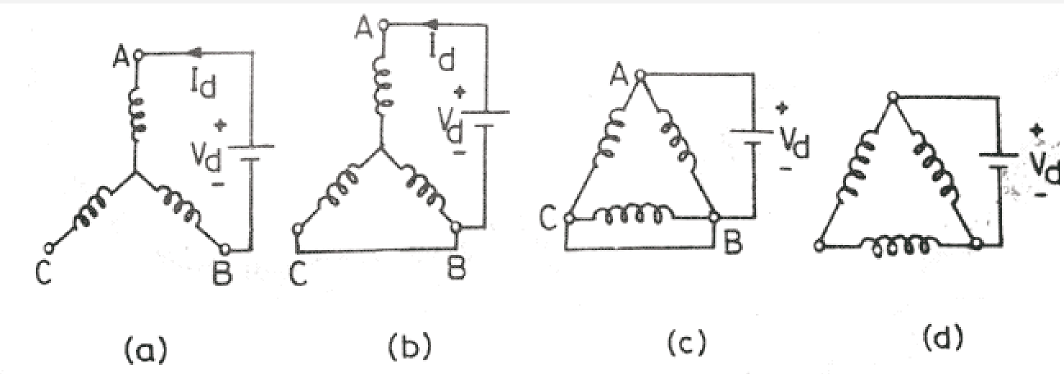
Deceleration

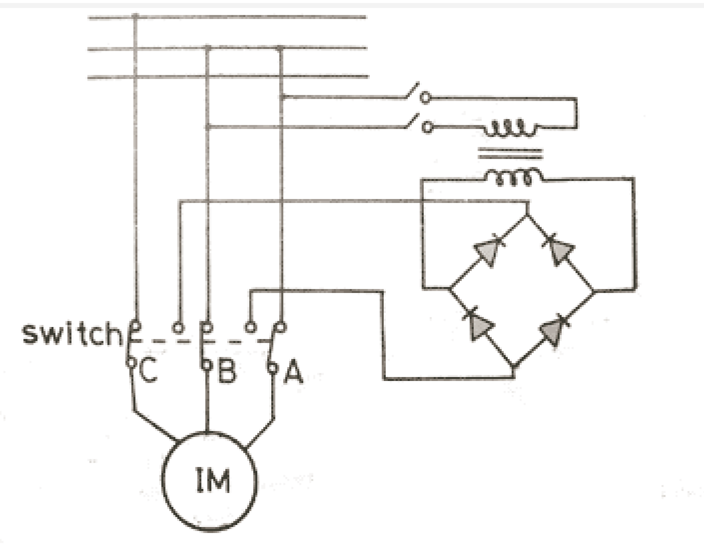
Induction Machines: Motor Braking

2. Dynamic Braking

a. DC Dynamic braking

To obtain this type of braking the stator of a running induction motor is connected to a dc supply.



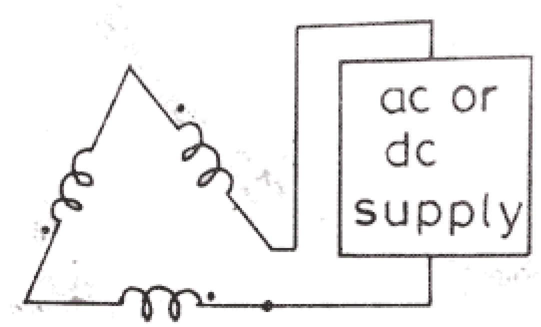


Induction Machines: Motor Braking

2. Dynamic Braking

b. Zero Sequence Dynamic braking

All the three stator phases are connected in series and single phase ac or dc is connected across them (as shown in the figure). This type of connection is called zero-sequence connection, because current in all the stator windings are co-phasal.

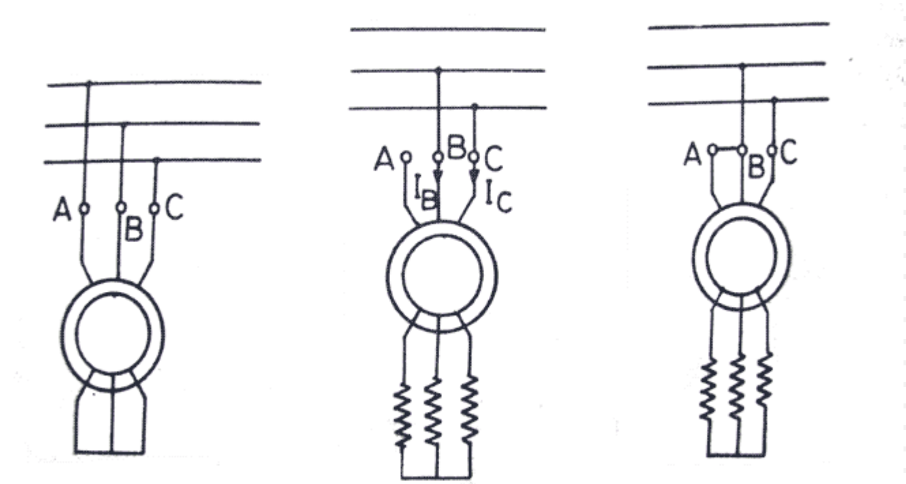


Induction Machines: Motor Braking

2. Dynamic Braking

c. AC Dynamic braking (wound rotor)

This type of braking is obtained when the motor is made to run on a single phase supply by disconnecting any one of the three phase from the source, and it is either left open or it is connected with another phase.



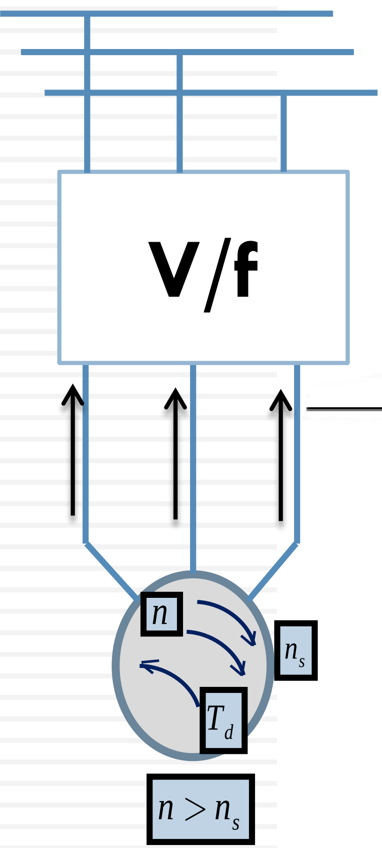
Induction Machines: Motor Braking

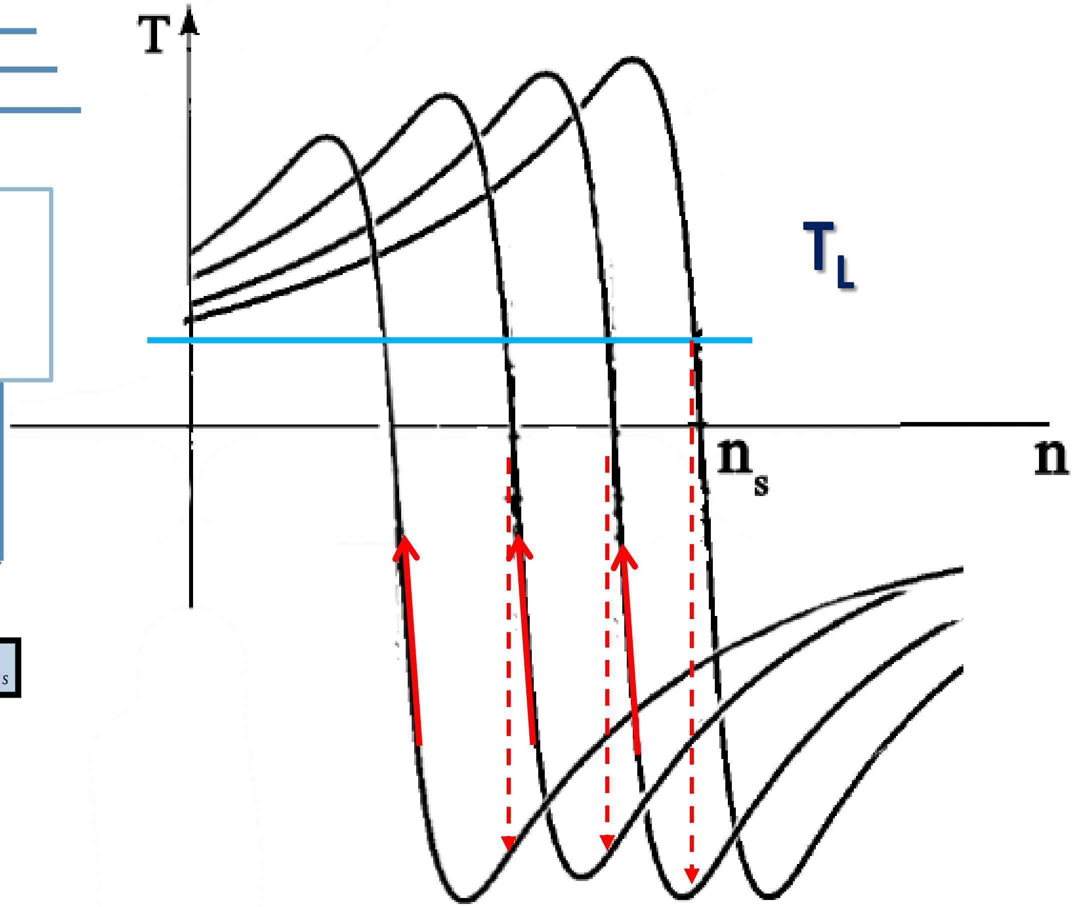
3. Regenerative Braking

It take place only if the speed of the motor is greater than synchronous speed and in the same direction as the rotating field. This happens by switching the operating frequency to a lower frequency, so the torque and slip is negative and the machine acts as a generator supplying power to the supply network.

Induction Machines: Motor Braking

3. Regenerative Braking





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

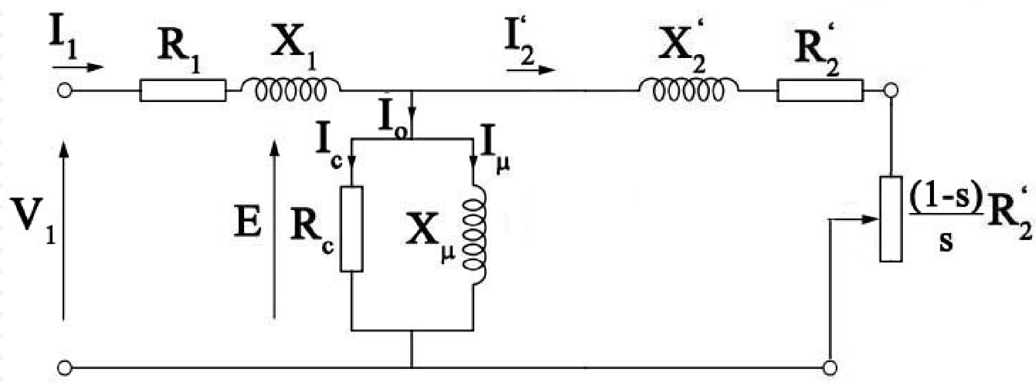
$$-T_m - T_L = J\frac{d\omega}{dt}$$

Deceleration

Induction Machines: Testing

Squirrel Cage Machine

1. *DC Test*
2. *Locked rotor test*
3. *No-load test*



Wound Rotor Machine

1. *DC Test*
2. *Locked rotor test*
3. *Open Circuit test*
4. *No-load test*

Squirrel Cage Machine

1. DC Test

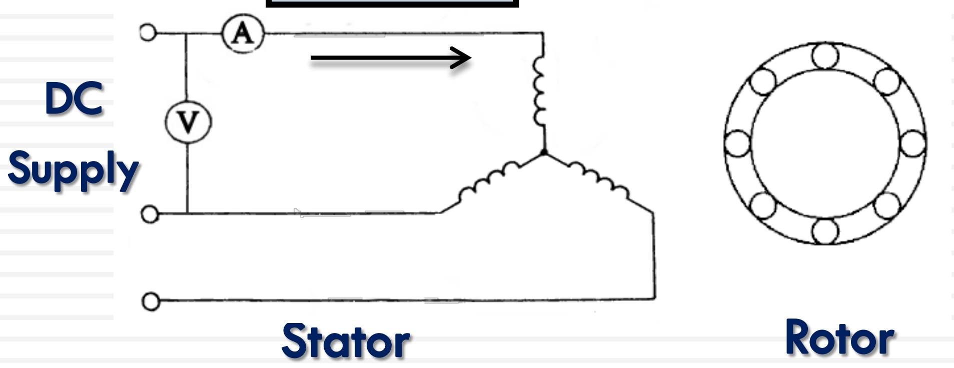
DC voltage is adjusted such that stator current = full load current

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

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

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

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

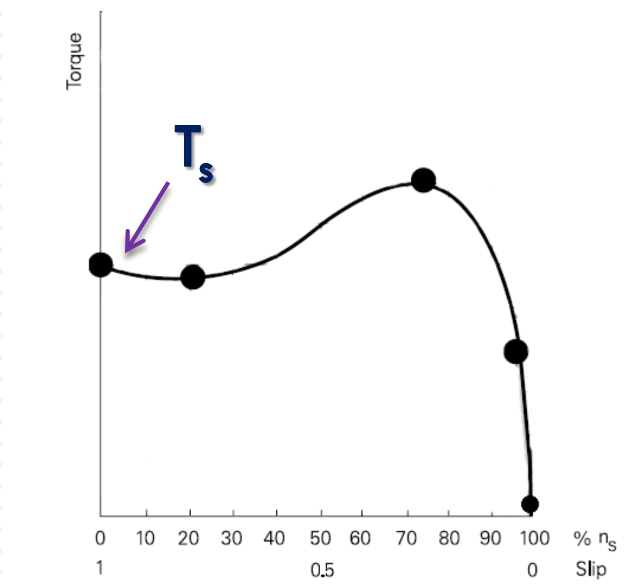


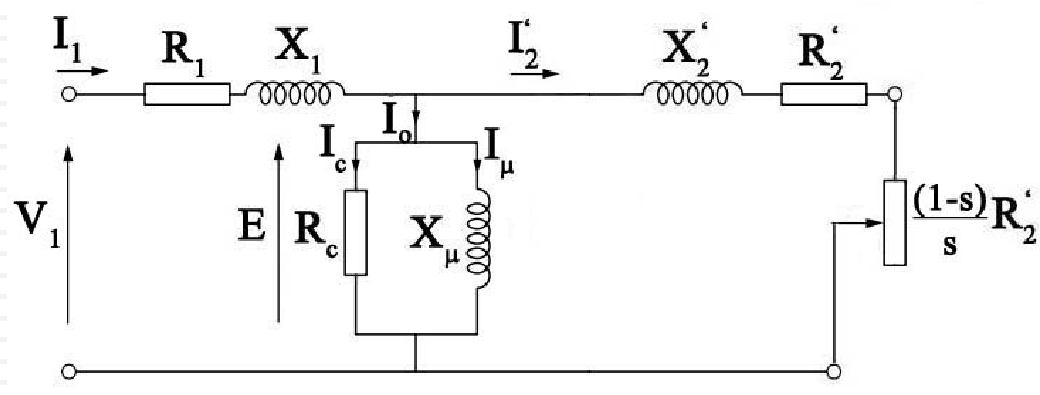
Induction Machines: Testing

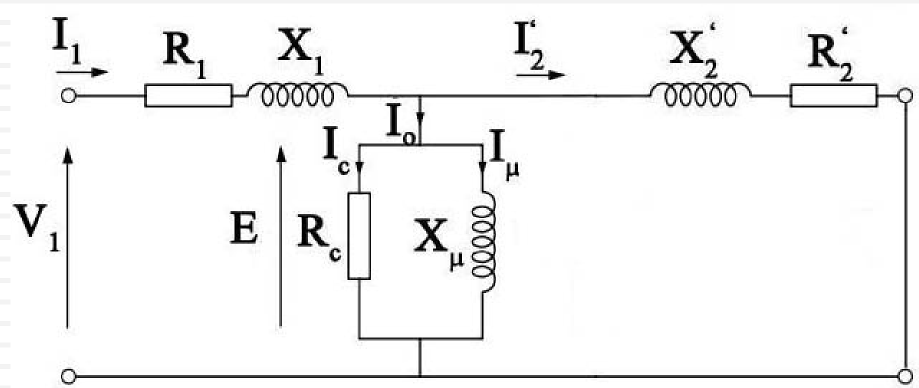
Squirrel Cage Machine

2. Locked (Blocked) Rotor Test

Motor is forced to standstill







$n_{LR} = 0$

$s = 1$

$R_2, X_2 \ll R_c, X_m$

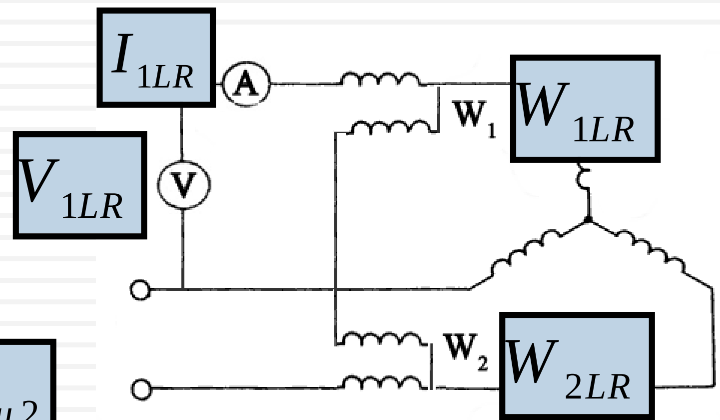
Induction Machines: Testing

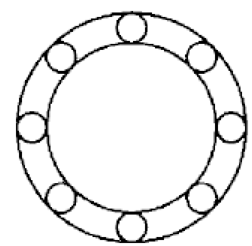
Squirrel Cage Machine

2. Locked (Blocked) Rotor Test

Voltage is adjusted such that stator current ≤ full load current

Reduced Voltage



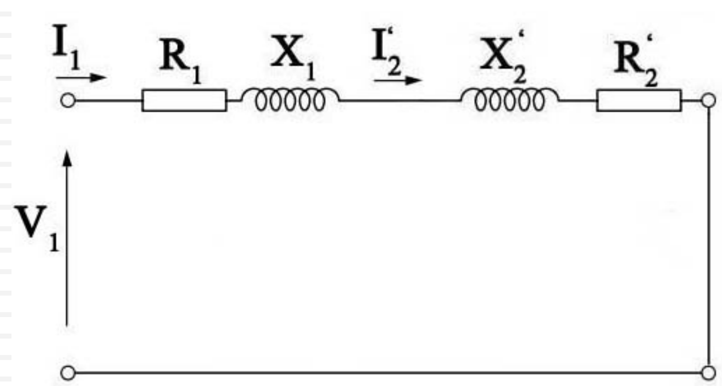


$$W_{1LR} \pm W_{2LR} = P_{cu1} + P_{cu2}$$

$$W_{1LR} \pm W_{2LR} = 3 I_{LR\phi}^{2} R_{LR}$$

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

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

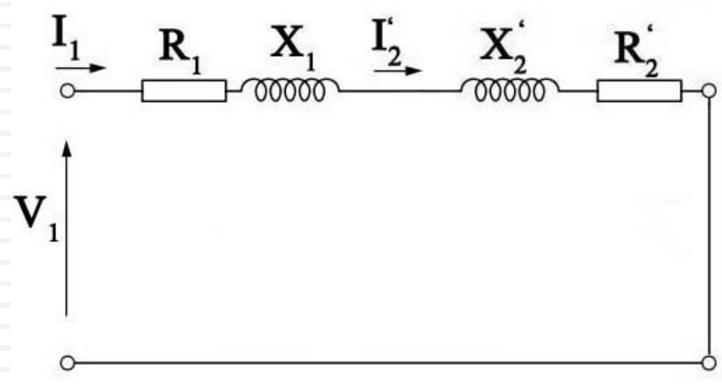


Induction Machines: Testing

Squirrel Cage Machine

2. Locked (Blocked) Rotor Test

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



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

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

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

Motor class	Description	Fraction of $X_1 + X_2$: X_1	Fraction of $X_1 + X_2$: X_2
A	Normal starting torque, normal starting current	0.5	0.5
B	Normal starting torque, low starting current	0.4	0.6
C	High starting torque, low starting current	0.3	0.7
D	High starting torque, high slip	0.5	0.5
Wound rotor	Performance varies with rotor resistance	0.5	0.5

Source: IEEE Standard 112.

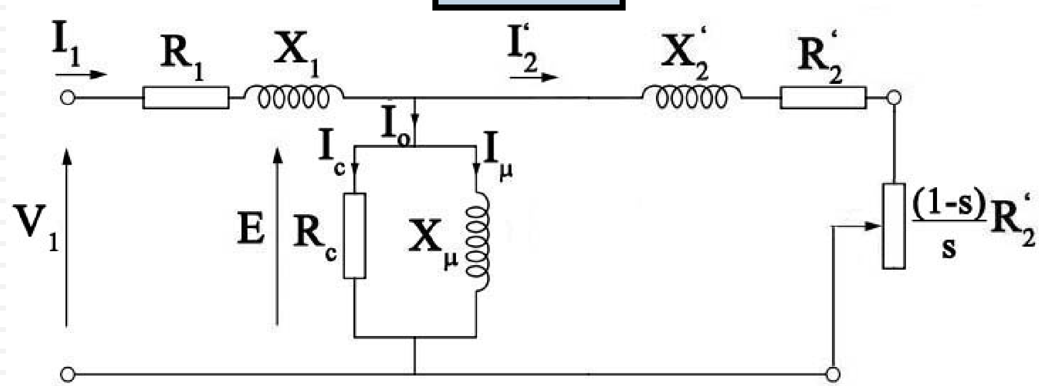
Induction Machines: Testing

Squirrel Cage Machine

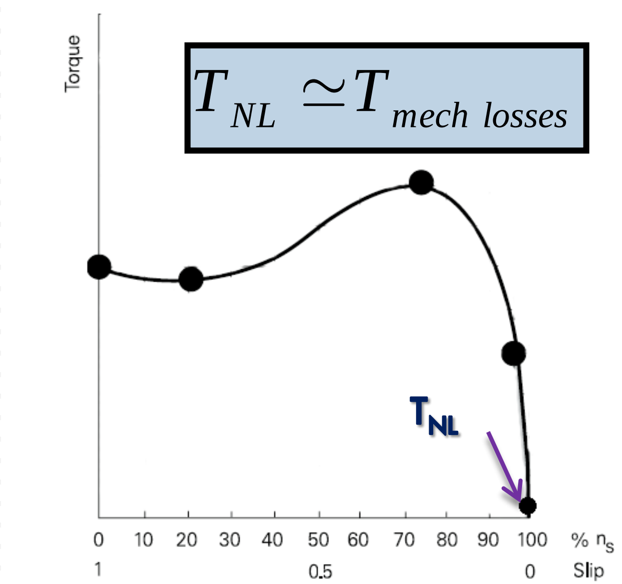
3. No-Load Test

Motor running at no mech. Load

$I_2^{'} \approx 0$

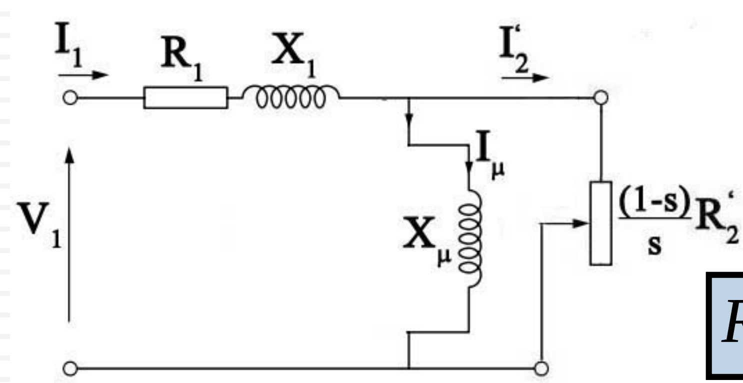


$T_{NL} \simeq T_{mech\ losses}$



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

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



$n_{NL} \approx n_s$

$s \approx 0$

$R_{mech\,\&\,iron}$

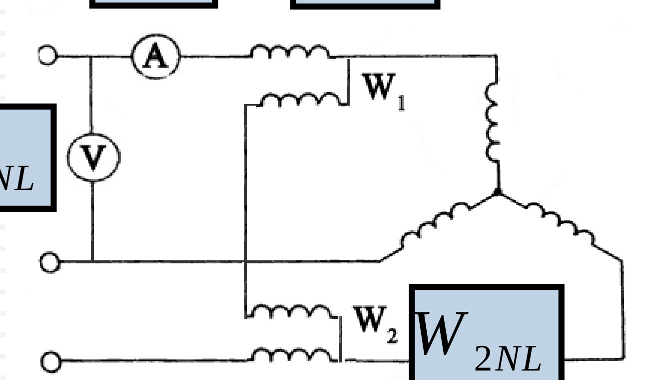
Induction Machines: Testing

Squirrel Cage Machine

3. No-Load Test

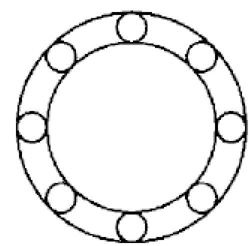
I_{1NL} W_{1NL}

Rated Voltage V_{1NL}



W_{2NL}

Squirrel Cage Rotor

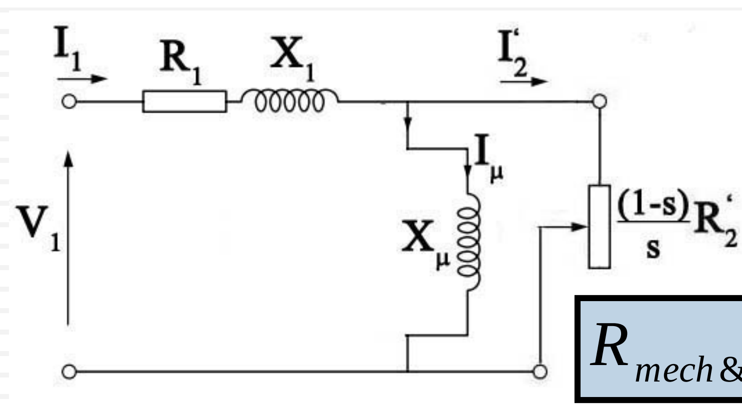


$$W_{1NL} \pm W_{2NL} = P_{iron} + P_{mech} + P_{cu1}$$

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

$$\Rightarrow P_{mech} + P_{iron}$$

$$\Rightarrow P_{mech\&iron}$$



$R_{mech\&iron}$

Induction Machines: Testing

Squirrel Cage Machine

3. No-Load Test

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

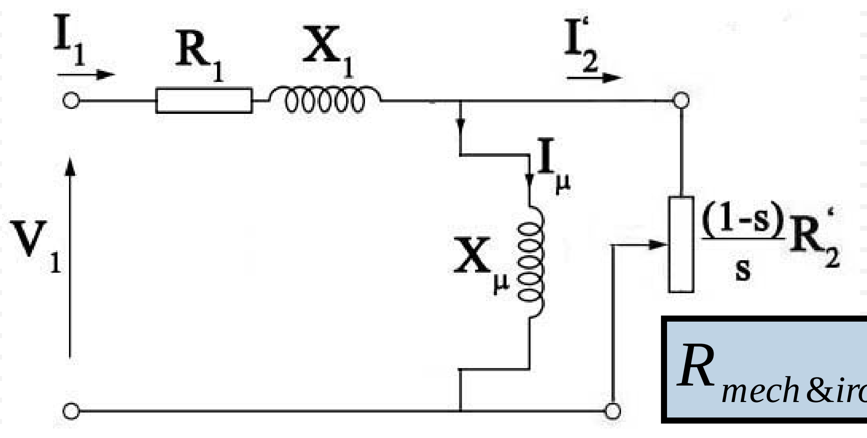
$$X_{\mu} \ll R_{mech\,\&iron}$$

$$R_{NL} = R_1$$

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

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

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



$$R_{mech\,\&iron}$$

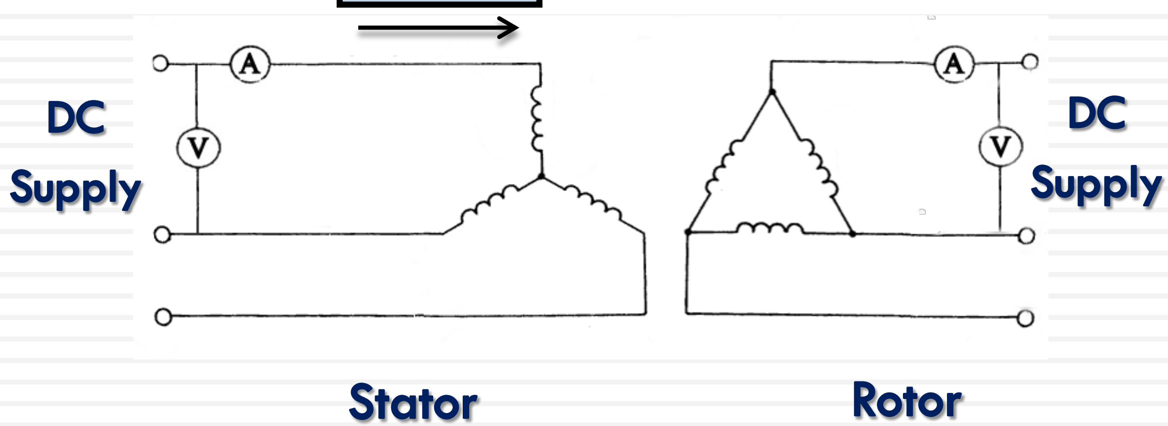
Induction Machines: Testing

Wound Rotor Machine

1. DC Test

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

$$I_1 = I_{FL}$$



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

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

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

$$R_{2eq} = \frac{V_{2DC}}{I_{2DC}}$$

$$R_{2eq} = \frac{2}{3} R_{2DC}$$

$$R_2 = \frac{3}{2} R_{2eq}$$

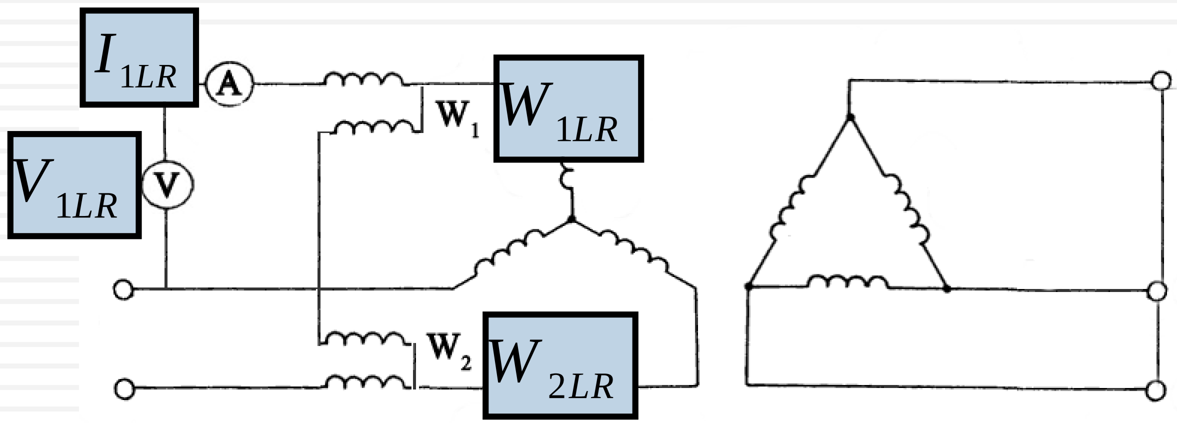
Induction Machines: Testing

Wound Rotor Machine

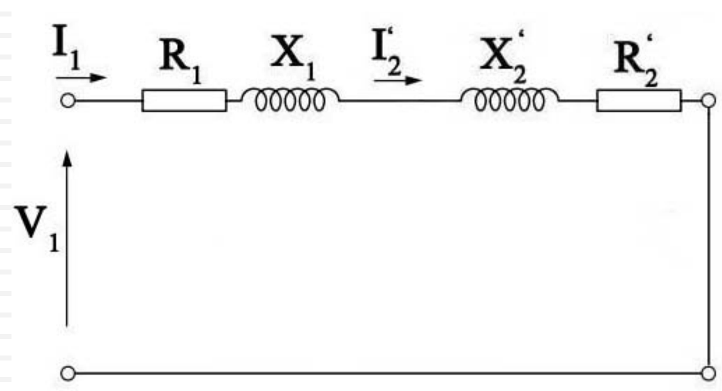
2. Locked (Blocked) Rotor Test

Voltage is adjusted such that stator current ≤ full load current

Reduced Voltage



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

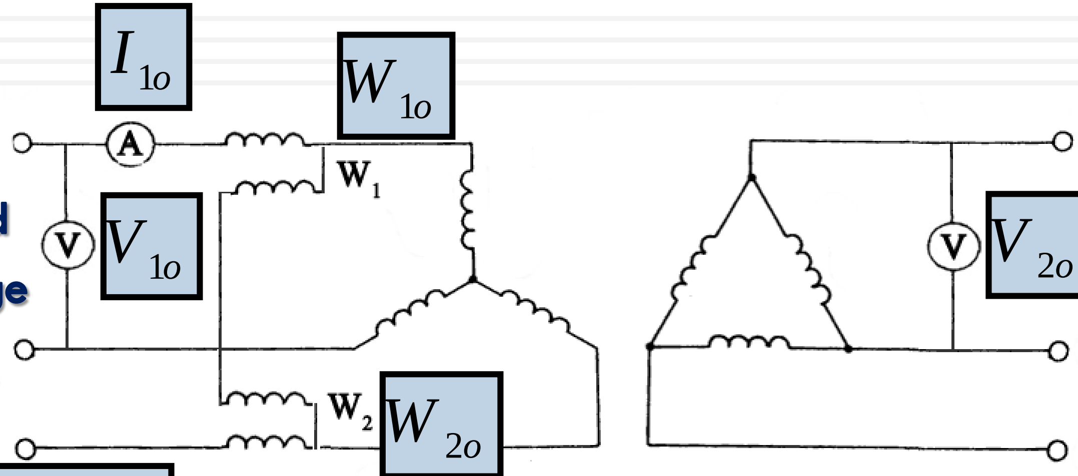


Wound Rotor Machine

3. Open Circuit Test (for wound rotor)

$$a_{eff} = \frac{V_{1o\phi}}{V_{2o\phi}}$$

Rated Voltage

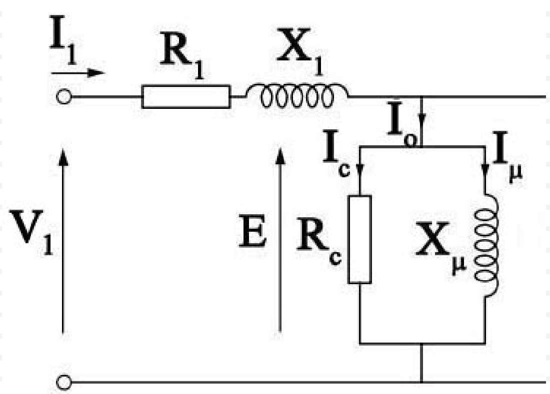


$$W_{1o} \pm W_{2o} = P_{iron} + P_{cu1}$$

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

$$E_o = V_{1\phi} - I_{1o}|Z_1|$$

$$P_{iron} = 3E_o I_{1o\phi} \cos\phi_o$$



$$R_c = \frac{E_o}{I_{1o\phi} \cos\phi_o}$$

$$X_\mu = \frac{E_o}{I_{1o\phi} \sin\phi_o}$$

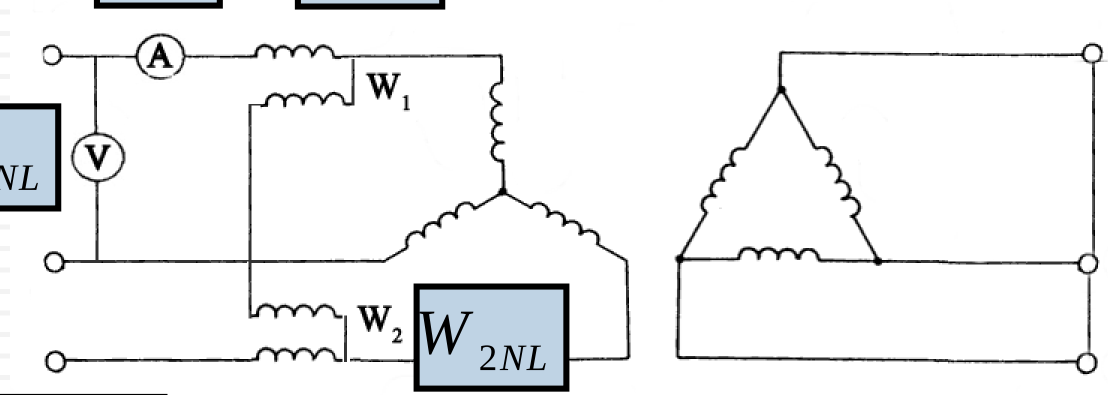
Induction Machines: Testing

Wound Rotor Machine

4. No-Load Test

I_{1NL} W_{1NL}

Rated Voltage V_{1NL}

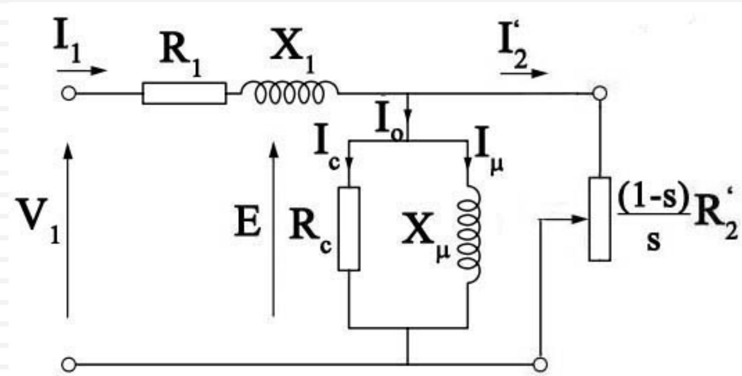


W_{2NL}

$$W_{1NL} \pm W_{2NL} = P_{iron} + P_{mech} + P_{cu1}$$

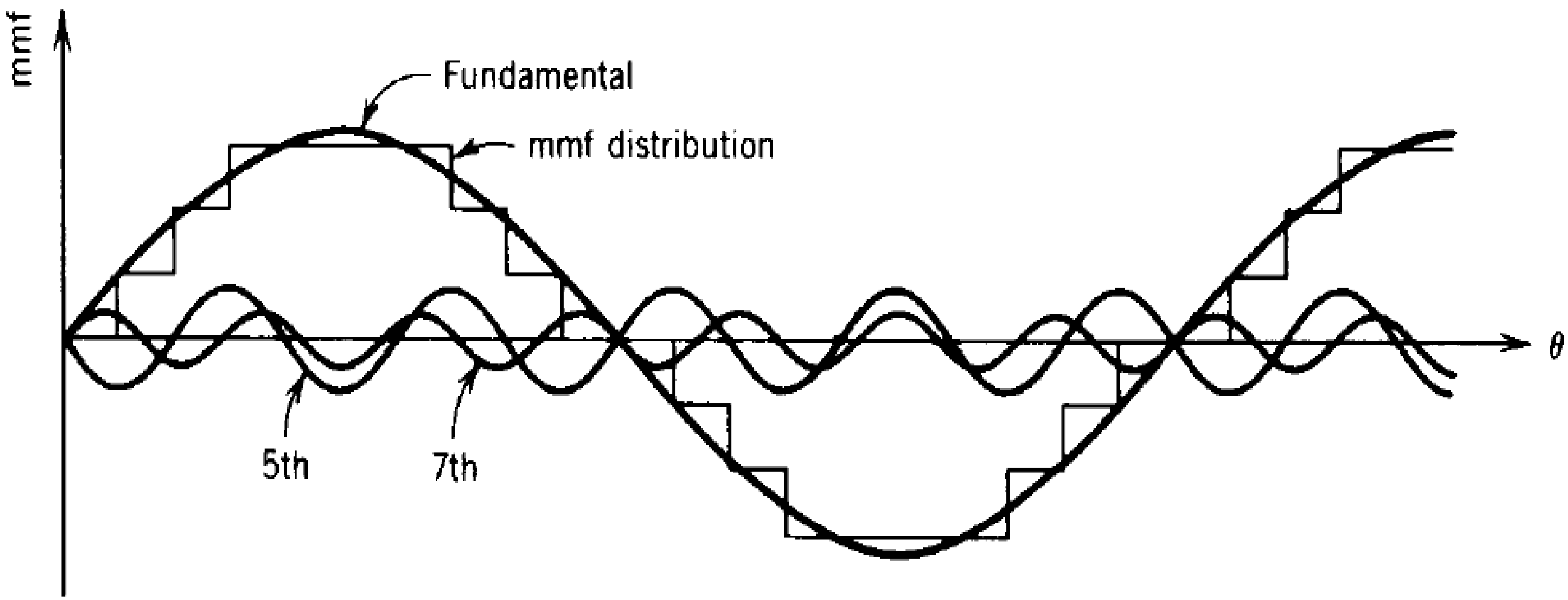
$$P_{cu1} = 3I_{1NL}^{2} R_1$$

→ P_{mech}



Induction Machines: Practical Motors

Space Harmonics



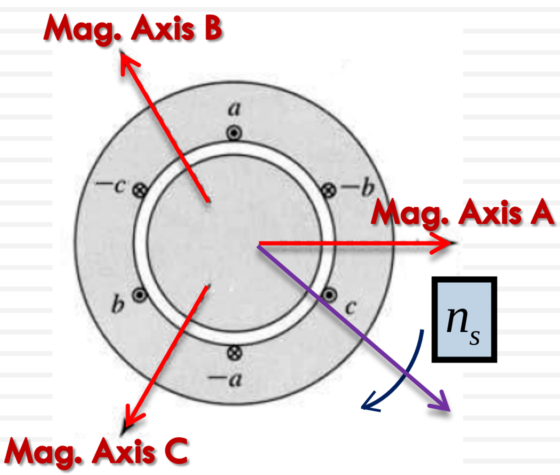
$$B_g = B_1 \cos\theta + B_3 \cos 3\theta + B_5 \cos 5\theta + \ldots$$

$$n_{s(h)} = \frac{n_s}{h} = \pm \frac{60f}{hp}$$

Induction Machines: Practical Motors

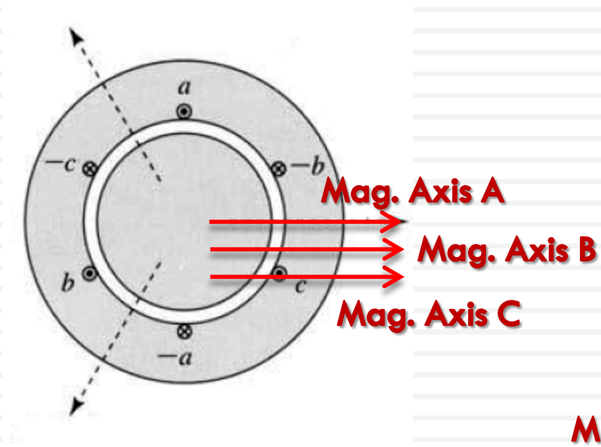
Space Harmonics

Forward Rot. Field



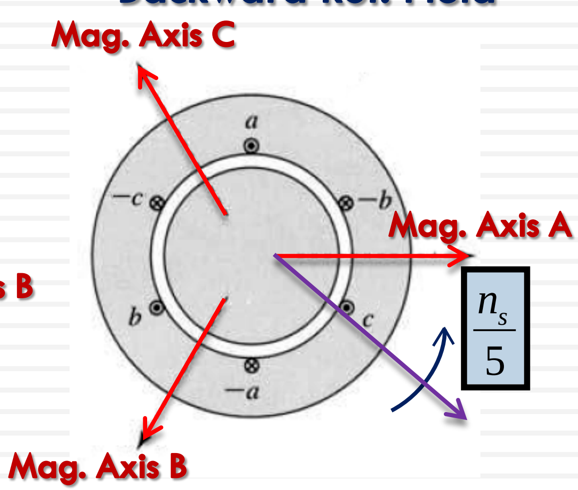
Fundamental (h=1)

Pulsating Field



3rd harmonic (h=3)

Backward Rot. Field



5th harmonic (h=5)

$$T = +ve$$

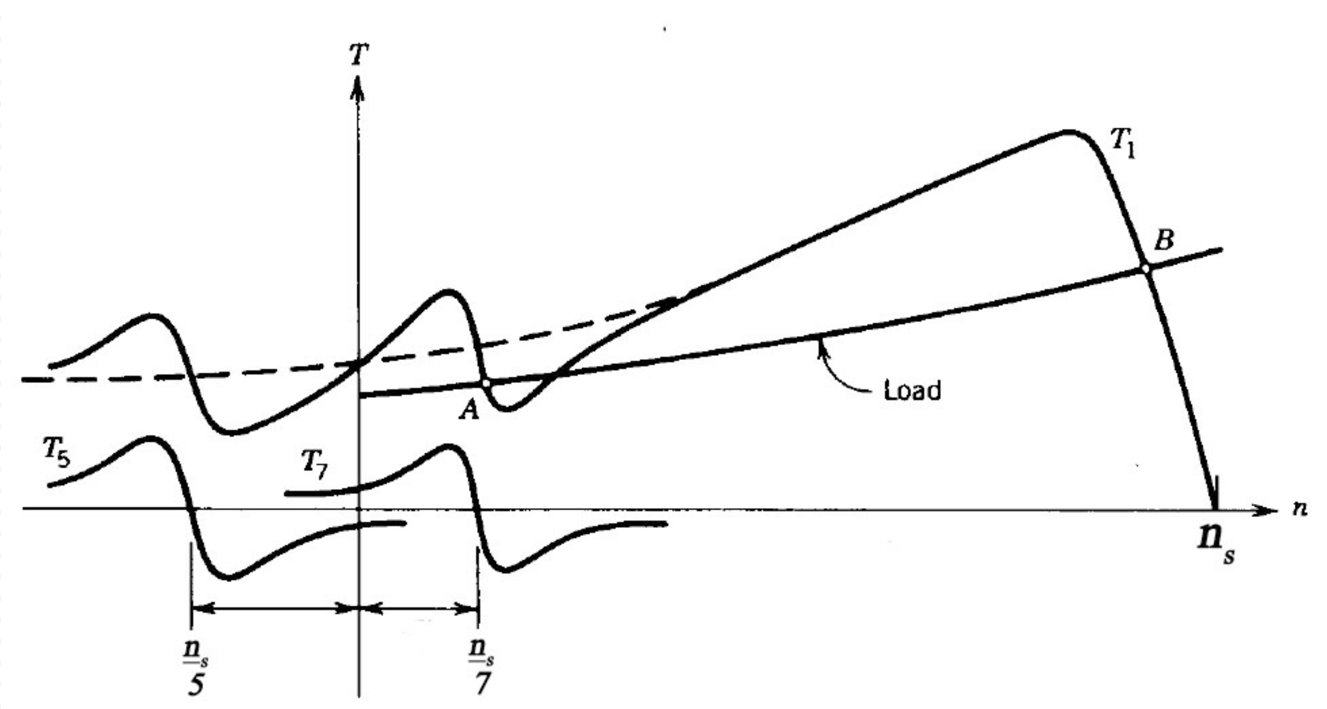
$$T = zero$$

$$T = -ve$$

Induction Machines: Practical Motors

Space Harmonics

Crawling



Crawling: Motor runs at almost 1/7 of its synchronous speed

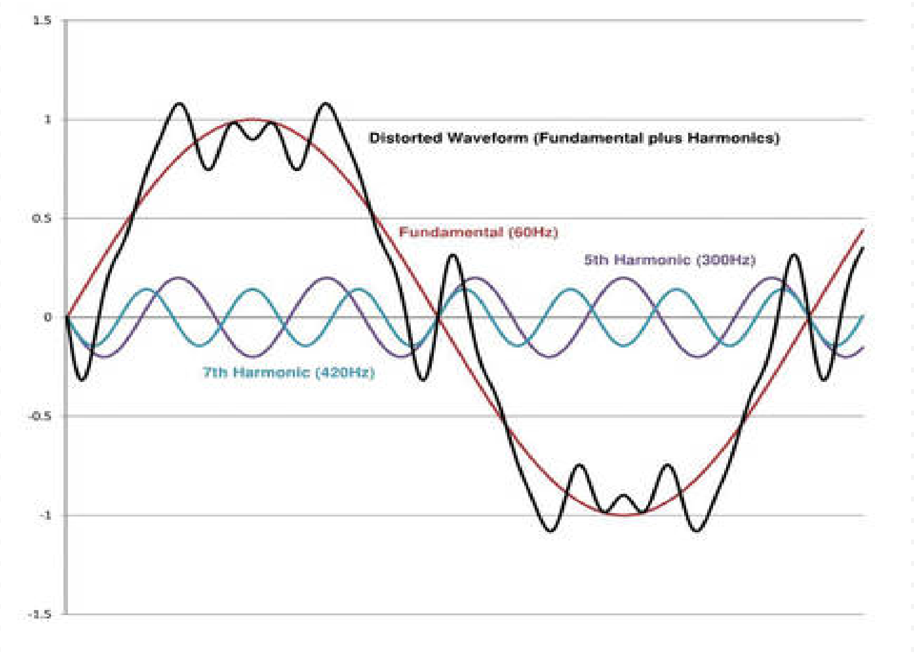
Induction Machines: Practical Motors

Time Harmonics

$$i_a = \sum_{h=1,3,5,..} I_{mh} \cos(h\omega_e t)$$

$$i_b = \sum_{h=1,3,5,..} I_{mh} \cos(h(\omega_e t - 120))$$

$$i_c = \sum_{h=1,3,5,..} I_{mh} \cos(h(\omega_e t + 120))$$



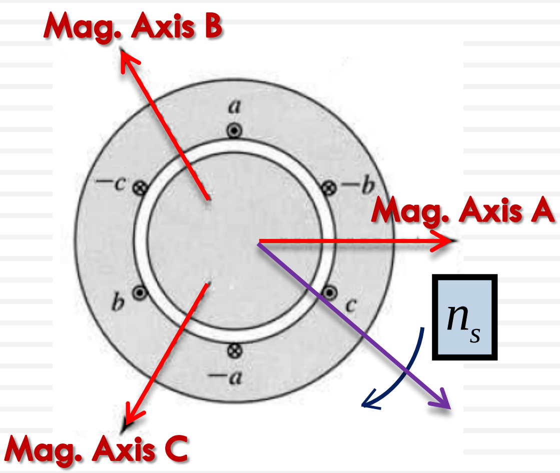
$$M_a = \frac{4}{\pi}\frac{N}{2p} \sum_{h=1,3,5,..} I_{mh} \cos(h\omega_e t)\cos p\theta$$

$$M_b = \frac{4}{\pi}\frac{N}{2p} \sum_{h=1,3,5,...} I_{mh} \cos(h(\omega_e t - 120))\cos(p\theta - 120)$$

$$M_c = \frac{4}{\pi}\frac{N}{2p} \sum_{h=1,3,5,..} I_{mh} \cos(h(\omega_e t + 120))\cos(p\theta + 120)$$

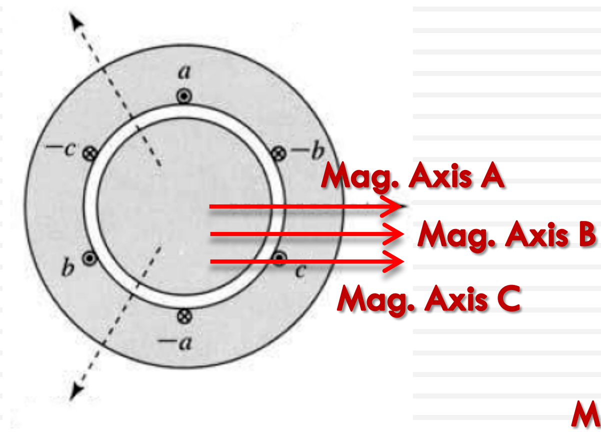
Time Harmonics

Forward Rot. Field



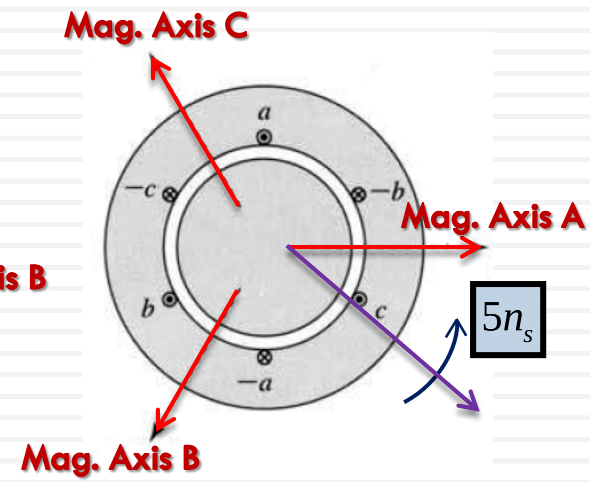
Fundamental (h=1)

Pulsating Field



3rd harmonic (h=3)

Backward Rot. Field



5th harmonic (h=5)

$$M_{th}(\theta,t)=\frac{3}{2}\frac{4}{\pi}\frac{N}{2p}I_{mh}\cos(h\omega_e t\mp p\theta)$$

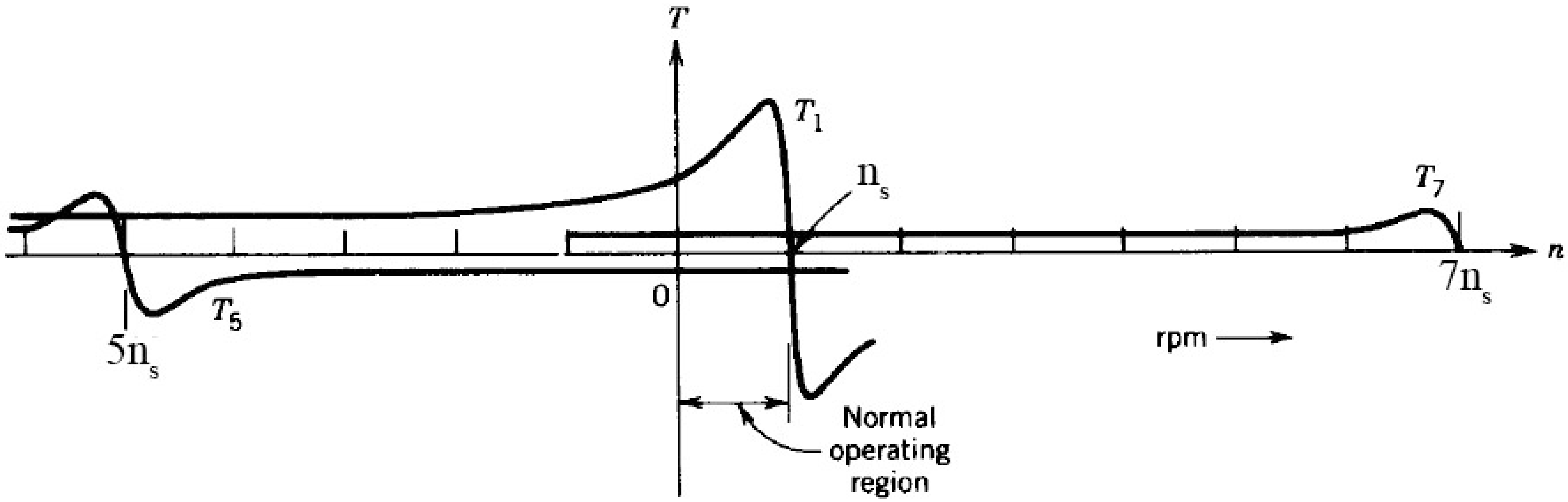
$$n_{sh}=\pm\frac{60hf}{p}$$

+ve for h=1,7,13, ….

-ve for h= 5,11,17,….

Induction Machines: Practical Motors

Time Harmonics



Cogging

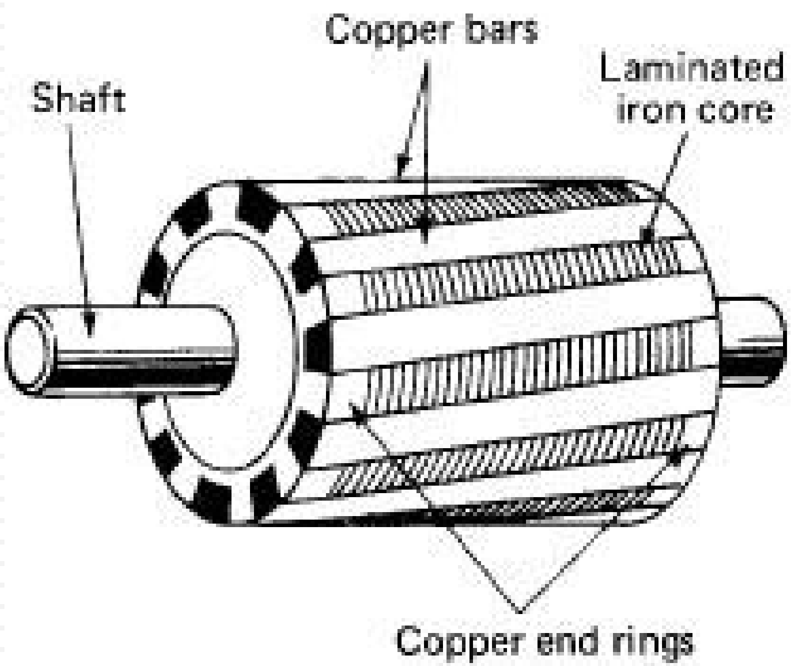
The rotor of particularly squirrel cage induction motor sometimes refuse to start at all particularly a when the voltage is low. This happens of stator teeth is equal to the number of rotor teeth ,and therefore due to the magnetic locking or cogging. It is found that the reluctance of magnetic paths is minimum when the stator and rotor teeth comes in front of each other, it is in such position of minimum reluctance that the stator tends to remain fixed thus causes serious trouble during starting.

This can be easily overcome by:

1. *Making number of rotor slots more than the number of stator slots.*
2. *Giving slightly skew to the rotor slots (skewed) i.e. to arrange the stack of rotor laminations so that the rotor slots are "skewed" or angled with respect to the axis of rotation.*

Induction Machines: Practical Motors

- Cogging
- Skewing



Induction Machines: Practical Motors

Rated Voltage (V_r)

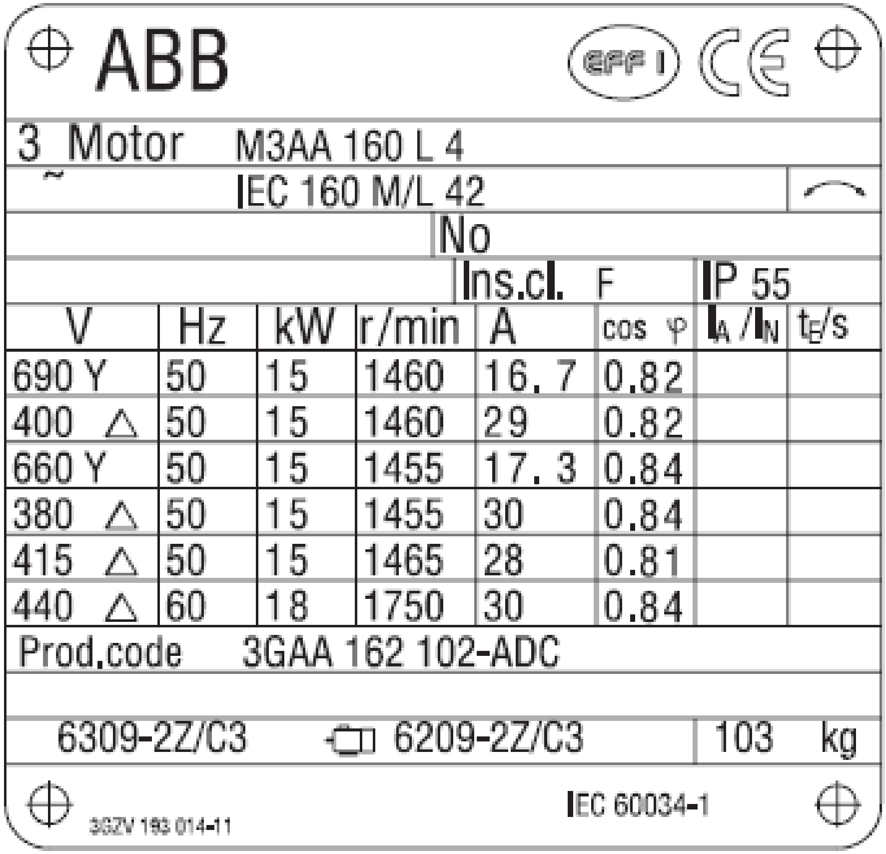
Rated Frequency (f_r)

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 △	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		

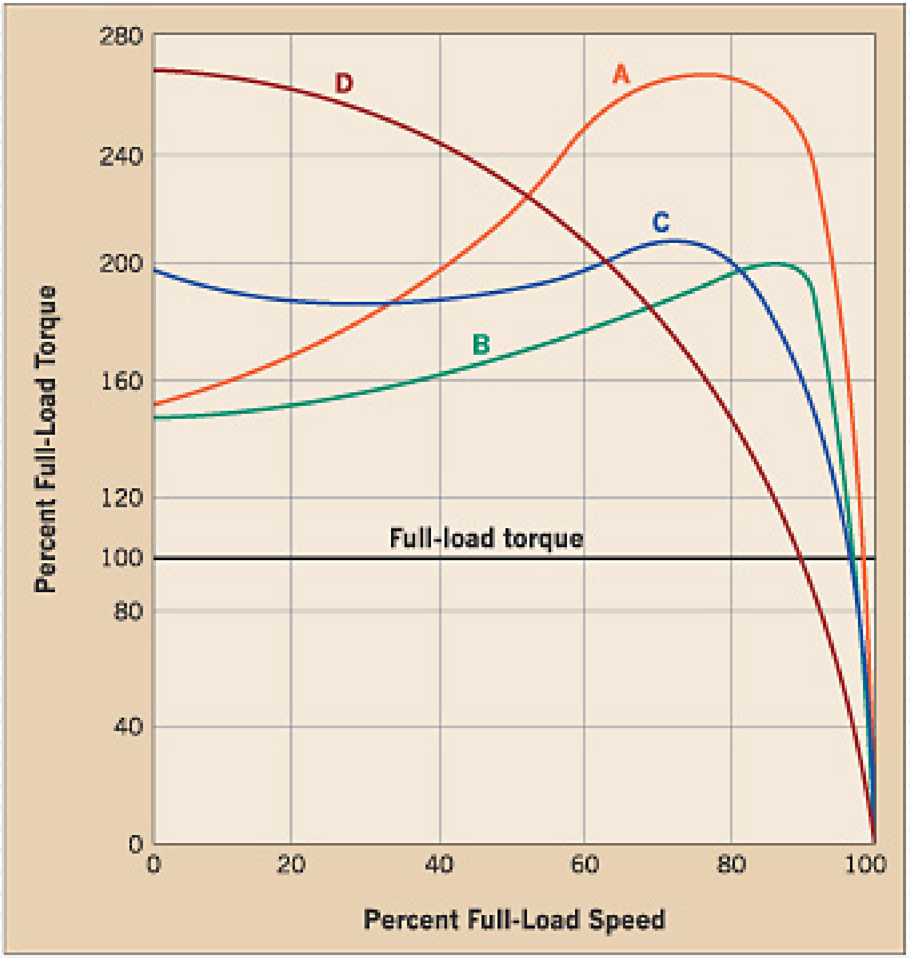
Prod.code 3GAA 162 102-ADC

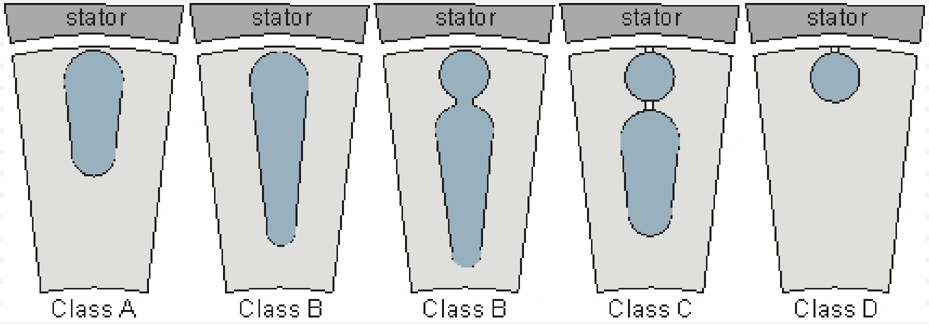
6309-2Z/C3 6209-2Z/C3 103 kg

3GZV 193 014-11 IEC 60034-1

Induction Machines: Practical Motors

Motor NEMA Classes





NEMA Locked-Rotor Code Letters kVA/hp	
A 0–3.15	G 5.6–6.3
B 3.15–3.55	H 6.3–7.1
C 3.55–4.0	I 7.1–8.0
D 4.0–4.5	J 8.0–9.0
E 4.5–5.0	K 9.0–10.0
F 5.0–5.6	L 10.0–11.2

NEMA MG 1-2011 Motors and Generators

Induction Machines: Practical Motors

Table 3. **Summary of Common Applications for NEMA Motor Design Classifications**

NEMA Design Classification	Design A	Design B	Design C	Design D
Summary Description	Similar to design B but have higher starting current	Most popular motor design, commonly referred to as general purpose motors, and are used in most applications	Intended for applications that require a high starting torque	High torque and slip, designed to handle shock-loads seen in some manufacturing operations
Common Applications	Fans, blowers, centrifugal pumps, and compressors	Fans, blowers, centrifugal pumps and compressors	Conveyors, crushers, stirring motors, agitators, reciprocating pumps and compressors	Punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wire-drawing motors

Induction Machines: Practical Motors

Motor Service Factor

Service factor is defined as the permissible amount of overload a motor will handle within defined temperature limits. When voltage and frequency are maintained at nameplate rated values, the motor may be overloaded up to the horsepower obtained by multiplying the rated horsepower by the service factor shown on the nameplate.

The standard service factor is 1.15.

The service factor is required to appear on the nameplate only if it is higher than 1.0.

Induction Machines: Practical Motors

Motor Service Factor

For standard motors (60 Hz)

Table 12. Service Factor

Hp	Synchronous Speed, rpm						
	3600	1800	1200	900	720	600	514
1	1.25	1.15*	1.15*	1.15*	1.0	1.0	1.0
1.5 - 125	1.15*	1.15*	1.15*	1.15*	1.15*	1.15*	1.15*
150	1.15*	1.15*	1.15*	1.15*	1.15*	1.15*	1.0
200	1.15*	1.15*	1.15*	1.15*	1.15*	1.0	1.0
Over 200	1.0	1.0	1.0	1.0	1.0	1.0	1.0

* These service factors apply only to NEMA design A, B and C motors.

NEMA MG 1-2011 Motors and Generators

Motor Duty Cycles

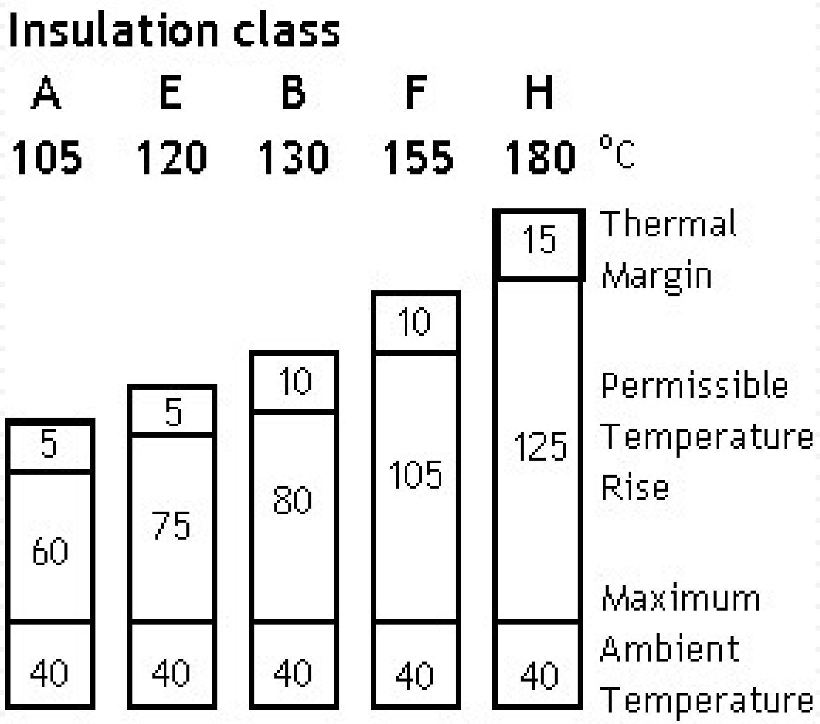
Normally, continuous duty three-phase induction motors are designed for the rated power. Most motors however are operated with a duty type which is not continuous.

- *S1: Continuous duty*
- *S2: Temporary duty*
- *S3: Intermittent periodic duty-type without starting*
- *S4: Intermittent periodic duty with starting*
- *S5: Intermittent periodic duty with starting and electrical braking*
- *S6: Continuous-operation duty type*
- *S7: Continuous-operation duty with starting and electrical braking*
- *S8: Continuous-operation periodic duty with related load/speed changes*
- *S9: Duty with non-periodic load and speed variations*

IEC 34-7 Standard

Motor Insulation Classes

Insulation systems are rated by standard NEMA classifications according to maximum allowable operating temperatures.

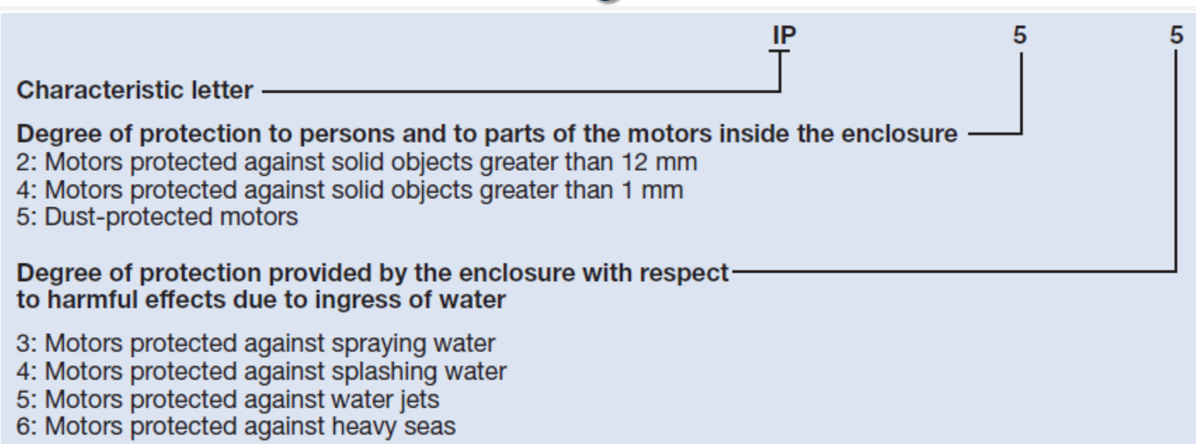


NEMA MG 1-2011 Motors and Generators

Induction Machines: Practical Motors

Motor Environmental Protection

<u>IP protection:</u> Protection of persons against getting in contact with (or approaching) live parts and against contact with moving parts inside the enclosure. Also protection of the machine against ingress of solid foreign objects. Protection of machines against the harmful effects due to the ingress of water



IEC 60034-5 Standard

Induction Machines: Practical Motors

Motor Environmental Protection

<u>IK protection:</u> Classification of degrees of protection provided by enclosure for motors against external mechanical impacts.

IK 08

International mechanical protection — IK

Characteristic group — 08

Relation between IK code and impact energy:

IK cod	**IK 0**	**IK 01**	**IK 02**	**IK 03**	**IK 04**	**IK 05**	**IK 06**	**IK 07**	**IK 08**	**IK 09**	**IK 10**
Impact energy Joule	*	0.15	0.2	0.35	0.5	0.7	1	2	5 ABB Standard	10	20

** not protected according to EN 50102*

IEC 60034-6 Standard

Induction Machines: Practical Motors

Motor Cooling (IC)

IC 4 (A) 1 (A) 6

International Cooling — IC

Circuit arrangement — 4
0: Free circulation (open circuit)
4: Frame surface cooled

Primary coolant — (A)
A for air (omitted for simplified designation)

Method of movement of primary coolant — 1
0: Free convection
1: Self-circulation
6: Machine-mounted independent component

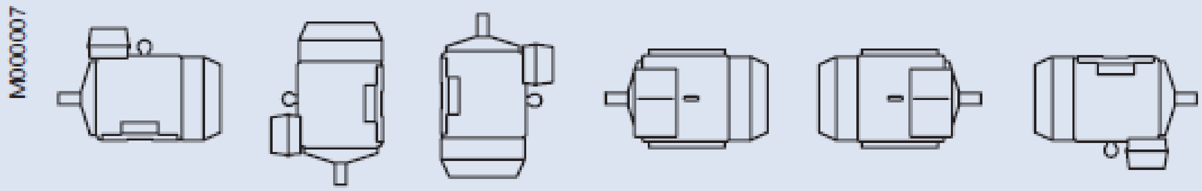
Secondary coolant — (A)
A for air (omitted for simplified designation)
W for water

Method of movement of secondary coolant — 6
0: Free convection
1: Self-circulation
6: Machine-mounted independent component
8: Relative displacement

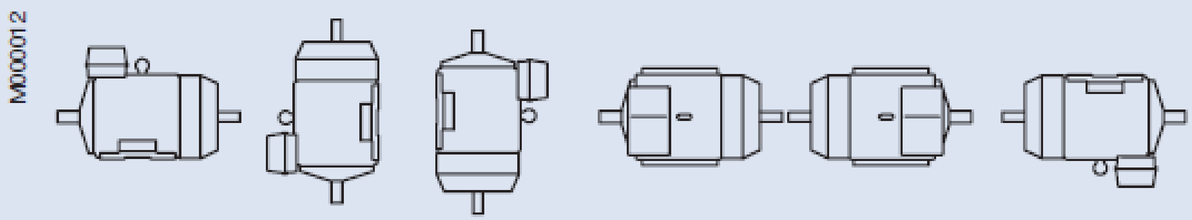
IEC 60034-6 Standard

Motor Mounting Arrangement (IM)

Foot-mounted motor.	IM B3 IM 1001	IM V5 IM 1011	IM V6 IM 1031	IM B6 IM 1051	IM B7 IM 1061	IM B8 IM 1071



Foot-mounted motor, shaft with free extensions	IM 1002	IM 1012	IM 1032	IM 1052	IM 1062	IM 1072



IEC 60034-7 Standard