Energy conversion I

Lecture 19:

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.

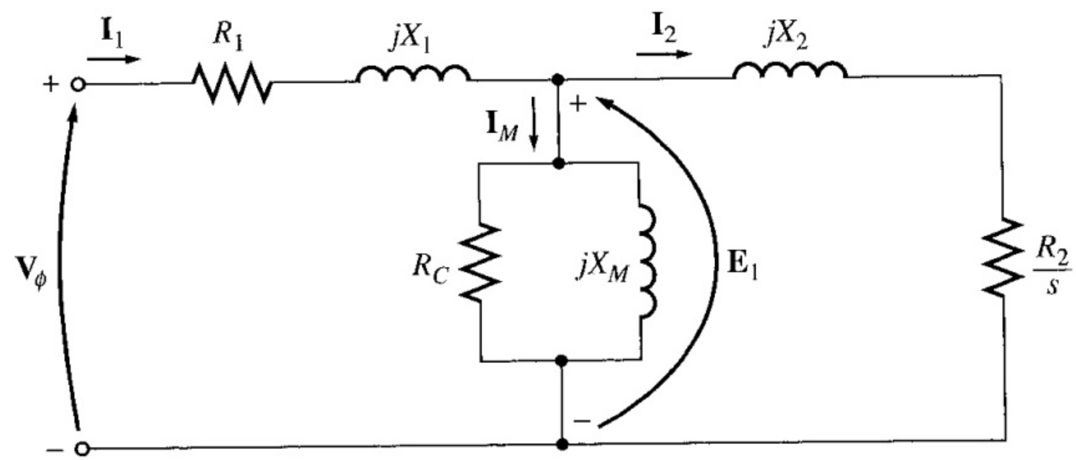
Start-Up Current

@start-up: s=1

Z_{in} : smallest

I_1 : largest (can reach up to 9 times rated current)

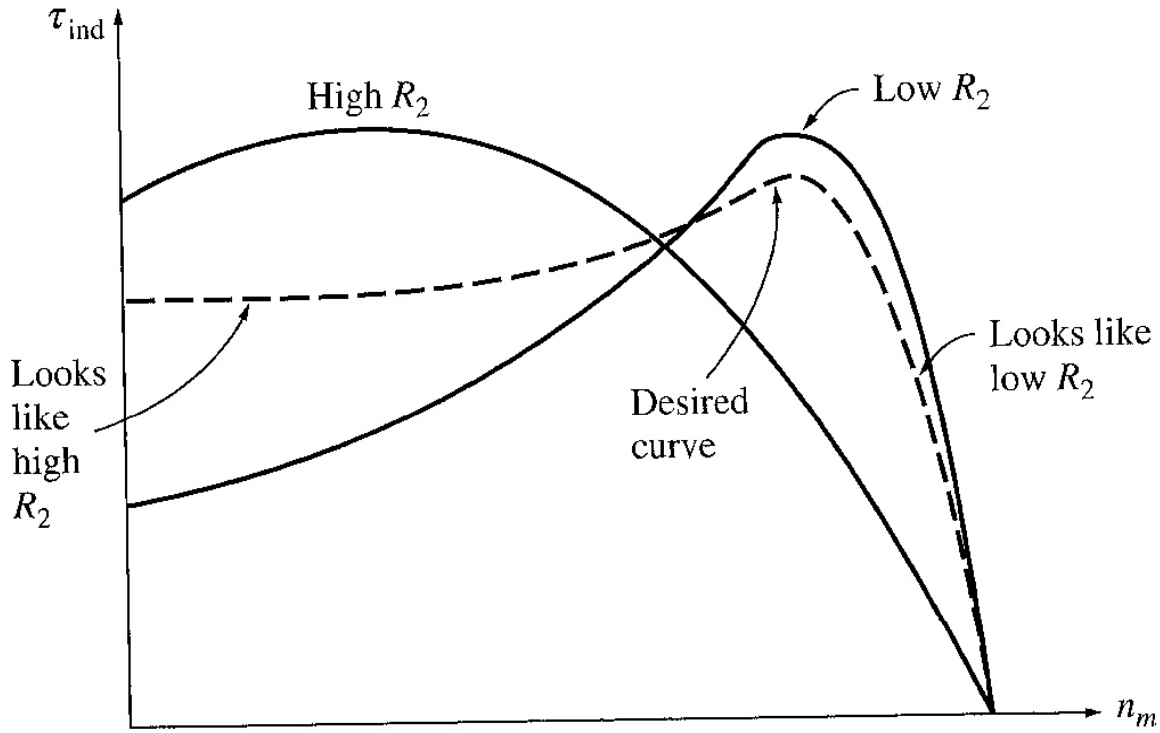
Additional losses + Mechanical stress on windings



Can be limited in Wound rotor motors by adding external resistor in series with rotor winding

Effect of Cage Rotor Design

$R_2 \uparrow \quad T_{s=1} \uparrow \quad I_{1,s=1} \downarrow \quad \eta \downarrow$



To avoid lower efficiency

R_2 decreases after start-up

Needs wound rotor and

External resistance

In cage rotor machines, using deep-bar / double-cage rotor variable resistance rotor can be achieved !

Deep-bar / Double-Cage Rotor

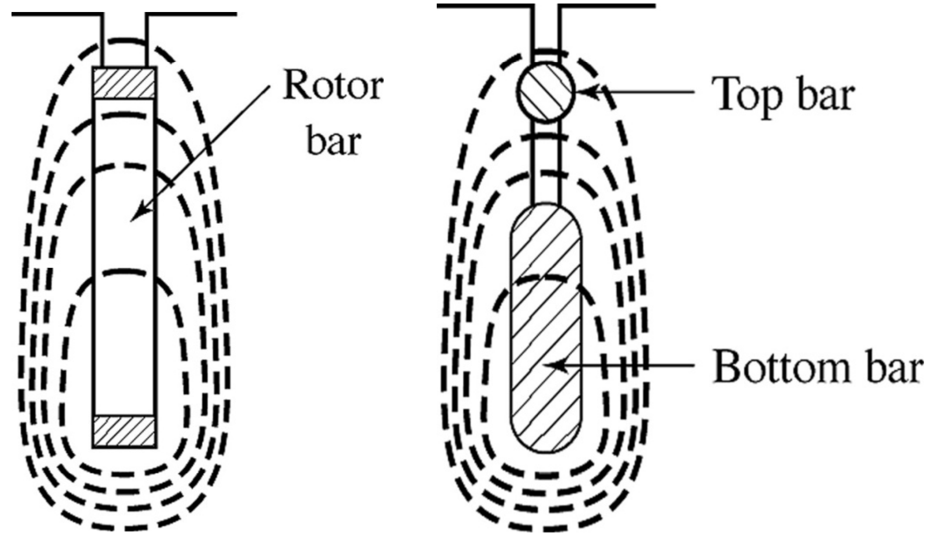
Higher inductance of inner layers

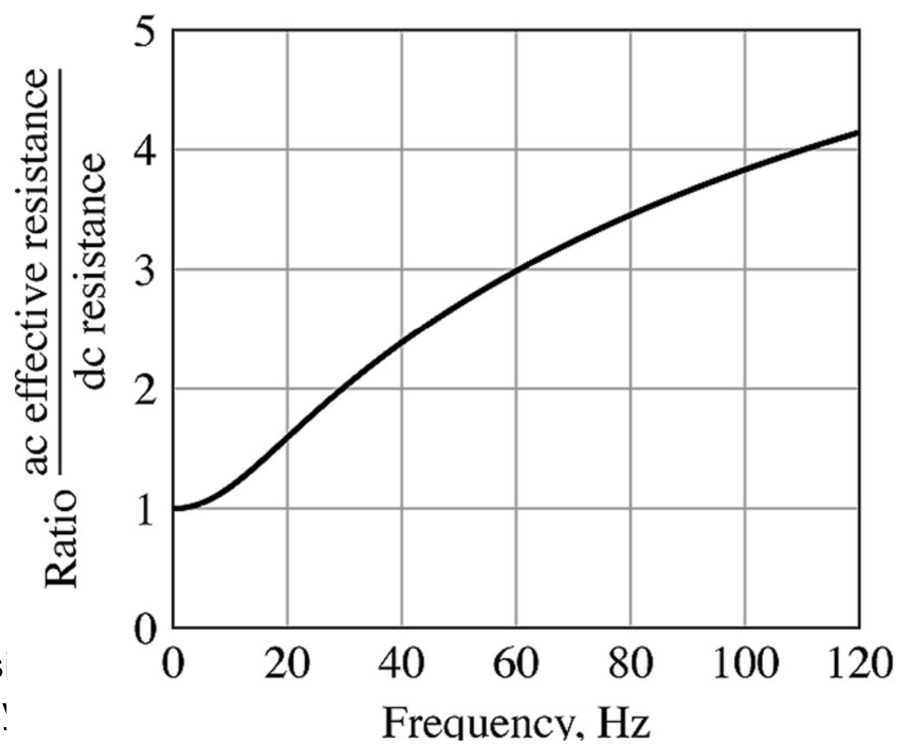
Higher current density in outer layers

Higher effective rotor resistance

Uniform current distribution in low frequency

Frequency dependant rotor resistance (higher resistance @ higher frequency)





Induction Motor Design Classes

Class A:

Normal starting torque(1-2) and current(5-8), T_{max}:200%-300%, low slip(<0.05), fans, blower, pumps

Class B:

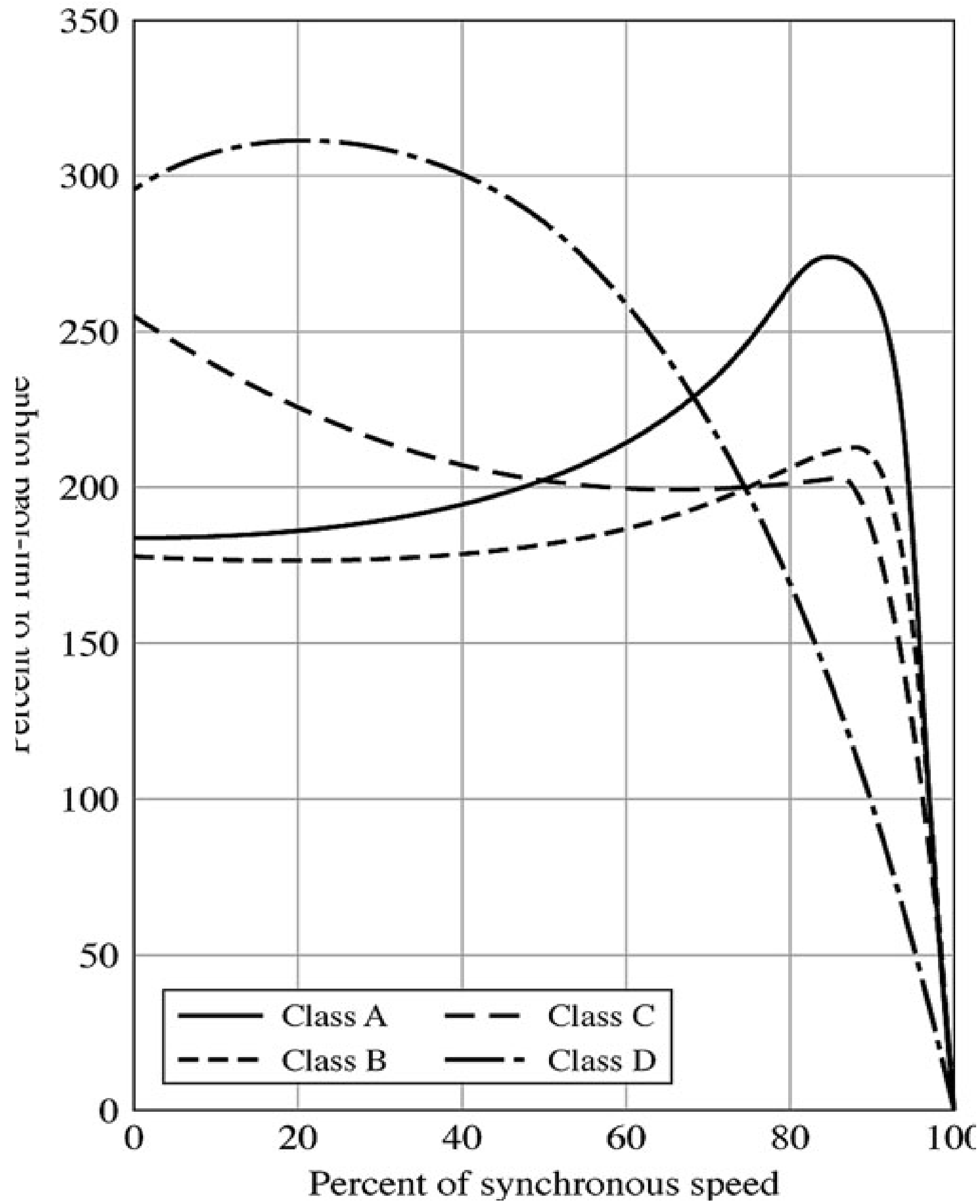
More often, <u>lower starting current</u>, more preferable,

Class C:

High starting torque, low starting current, <u>double cage</u>, loaded pumps, compressors

Class D:

High starting torque, low starting current, high slip (7-11%), bigger size, Fly wheel punch presses/shears, high inertia loads



Typical Laminations for Cages of Induction Motors

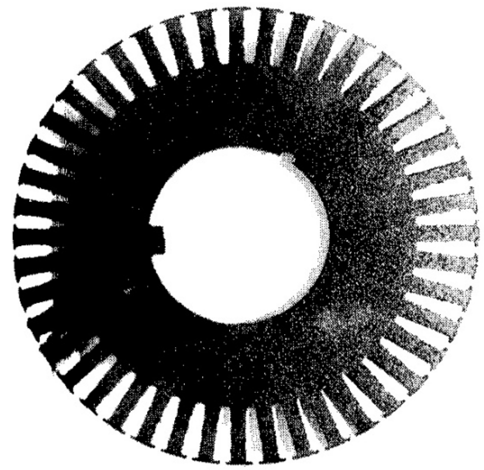
Laminations from typical cage induction motor, cross section of the rotor bars

a) class A – large bars near the surface

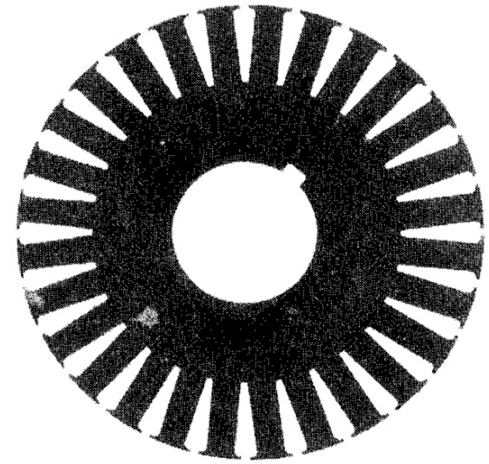
b) class B – large, deep rotor bars

c) class C – double-cage rotor design

d) class D – small bars near the surface



(a)



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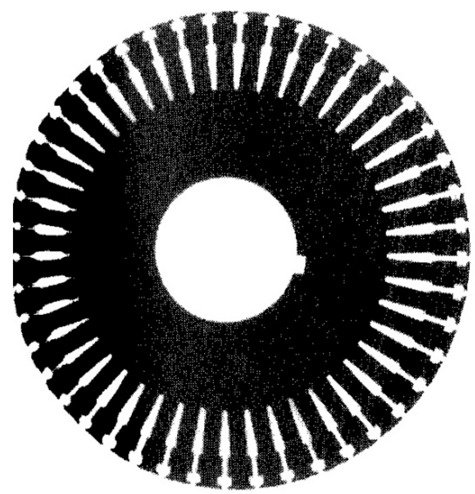

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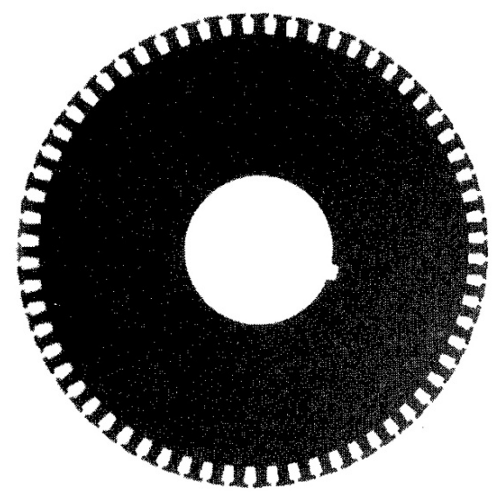


(d)

Starting Induction Motors

Induction motors have start-up torque → across-the-line starting

s = 1 → small input impedance → very high start-up current

Start-up current reduction methods

Increasing rotor resistance:

Can increase start-up torque.

Limited to wound rotor motor.

Applying reduced voltage:

Current reduces linearly.

Torque is a function of V^2.

Auto transformer.

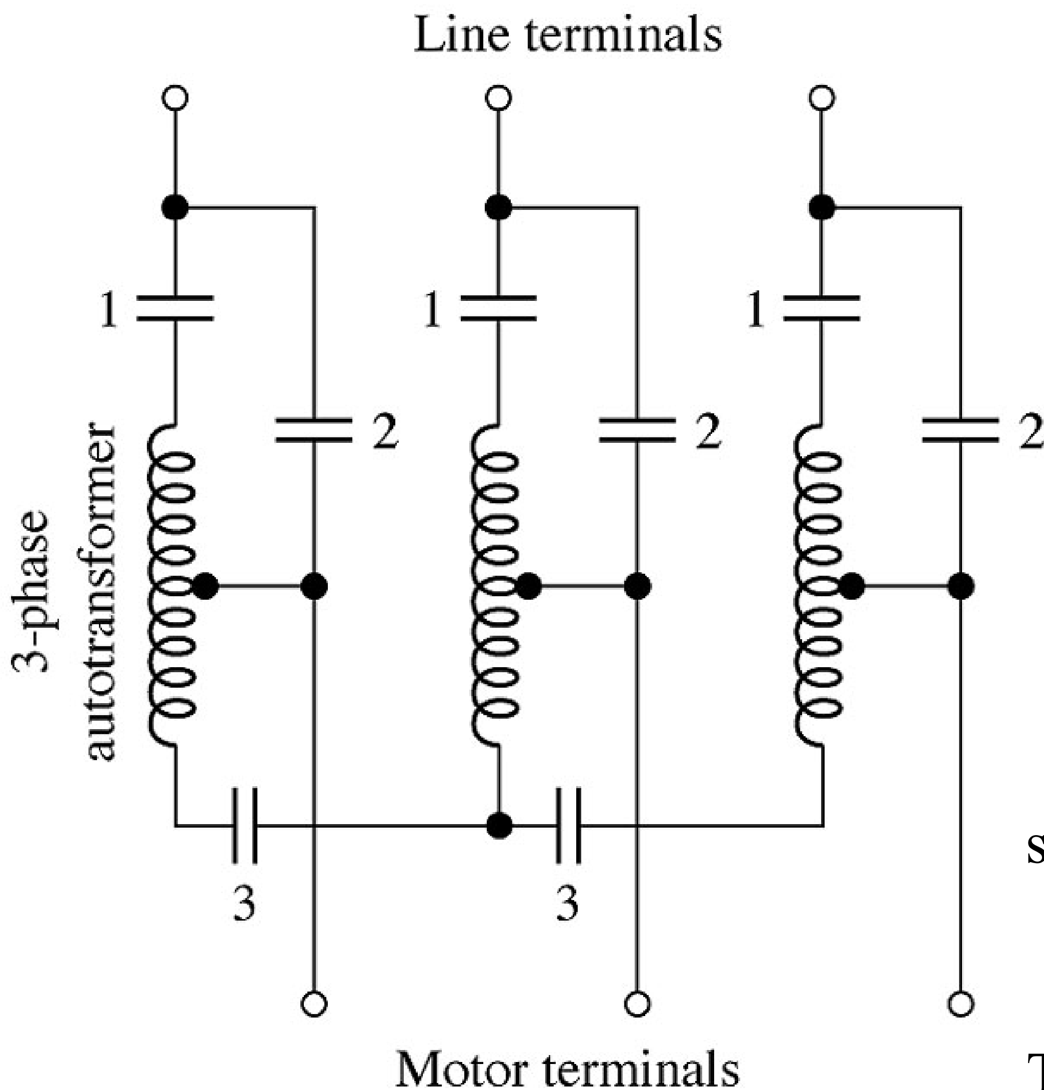
Electronic soft starter.

Star-delta connection.

Adding stator resistance / reactance.

No more in use

Starting using reduced voltage



Starting sequence:
(a) Close 1 and 3
(b) Open 1 and 3
(c) Close 2

$$T_{st} \approx \frac{3p}{2\omega_s} \frac{V_{th}^{\ 2}}{\left(X_{th} + X_2\right)^2} R_2$$

$$I_{st} \approx \frac{V_{th}}{R_{th} + R_2 + j(X_{th} + X_2)}$$

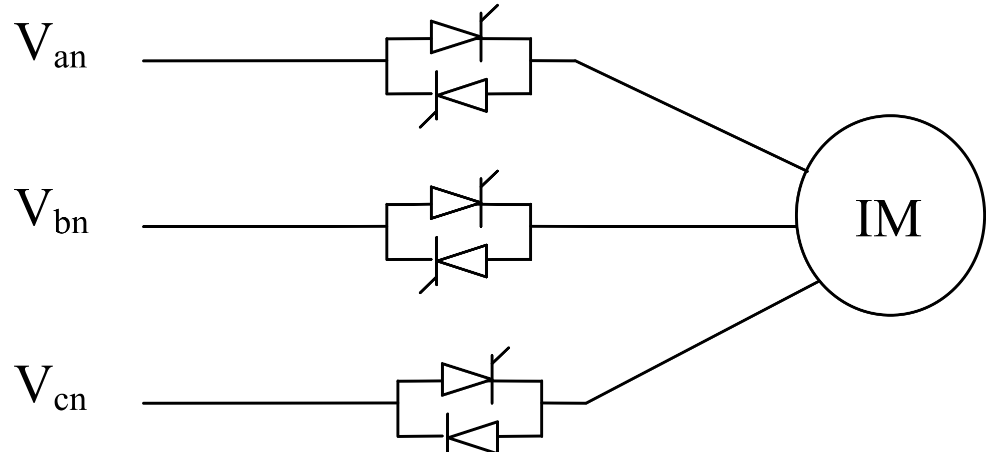
$$s_{T\max} = \frac{R_2}{\sqrt{R_{th}^2 + (X_{th} + X_2)^2}}$$

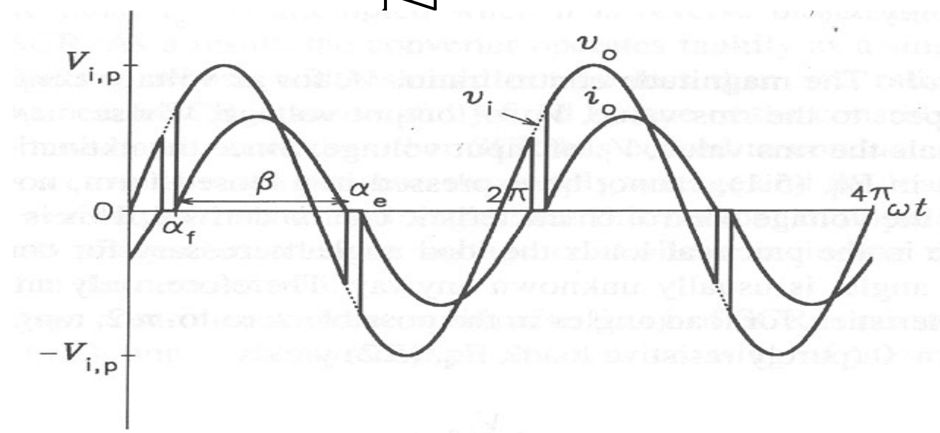
$$T_{\max} = \frac{3p}{4\omega_s} \frac{V_{th}^{\ 2}}{R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2)^2}}$$

Static Soft Starter

Control of stator rms voltage

controllable first harmonics





Starting current is reduced (good).

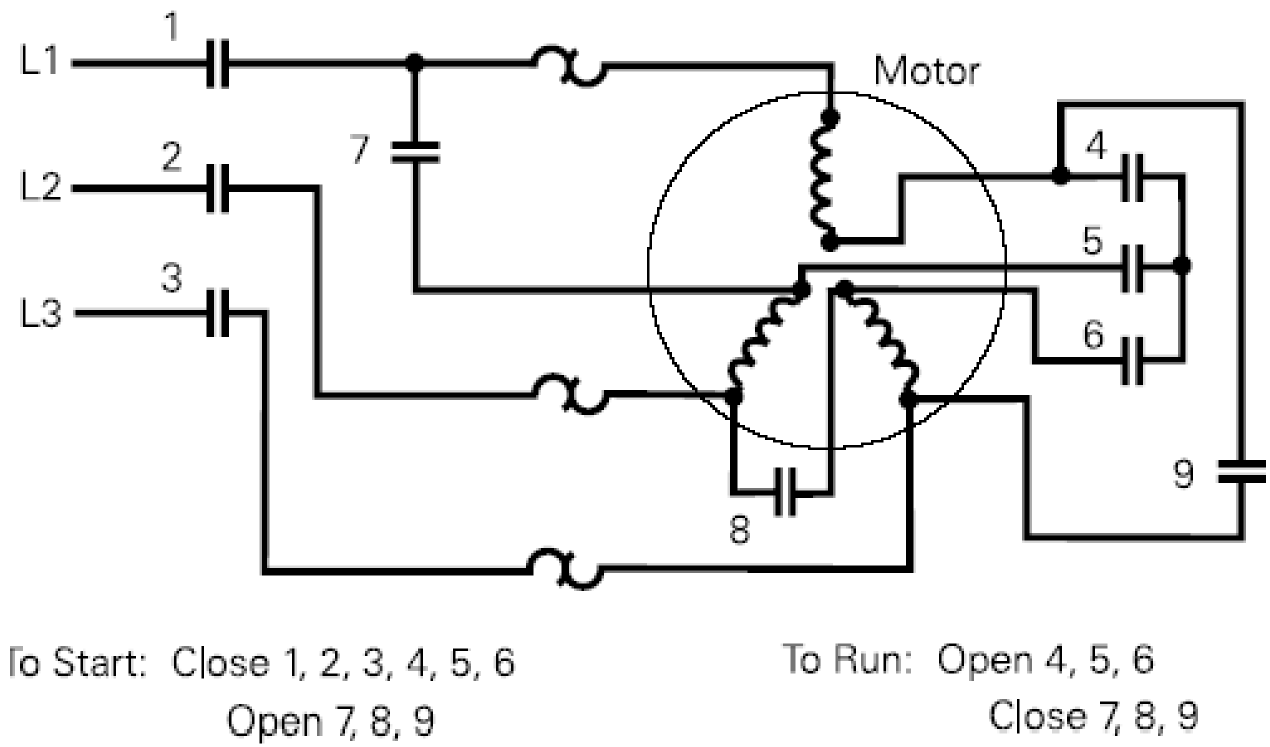
Starting torque is reduced (cannot start heavy loads).

Maximum torque is reduced (acceleration is reduced).

Speed at maximum torque is unchanged.

Star-Delta Start up

Constant line voltage



When Star connected:

$V_w = V_L/\sqrt{3}$

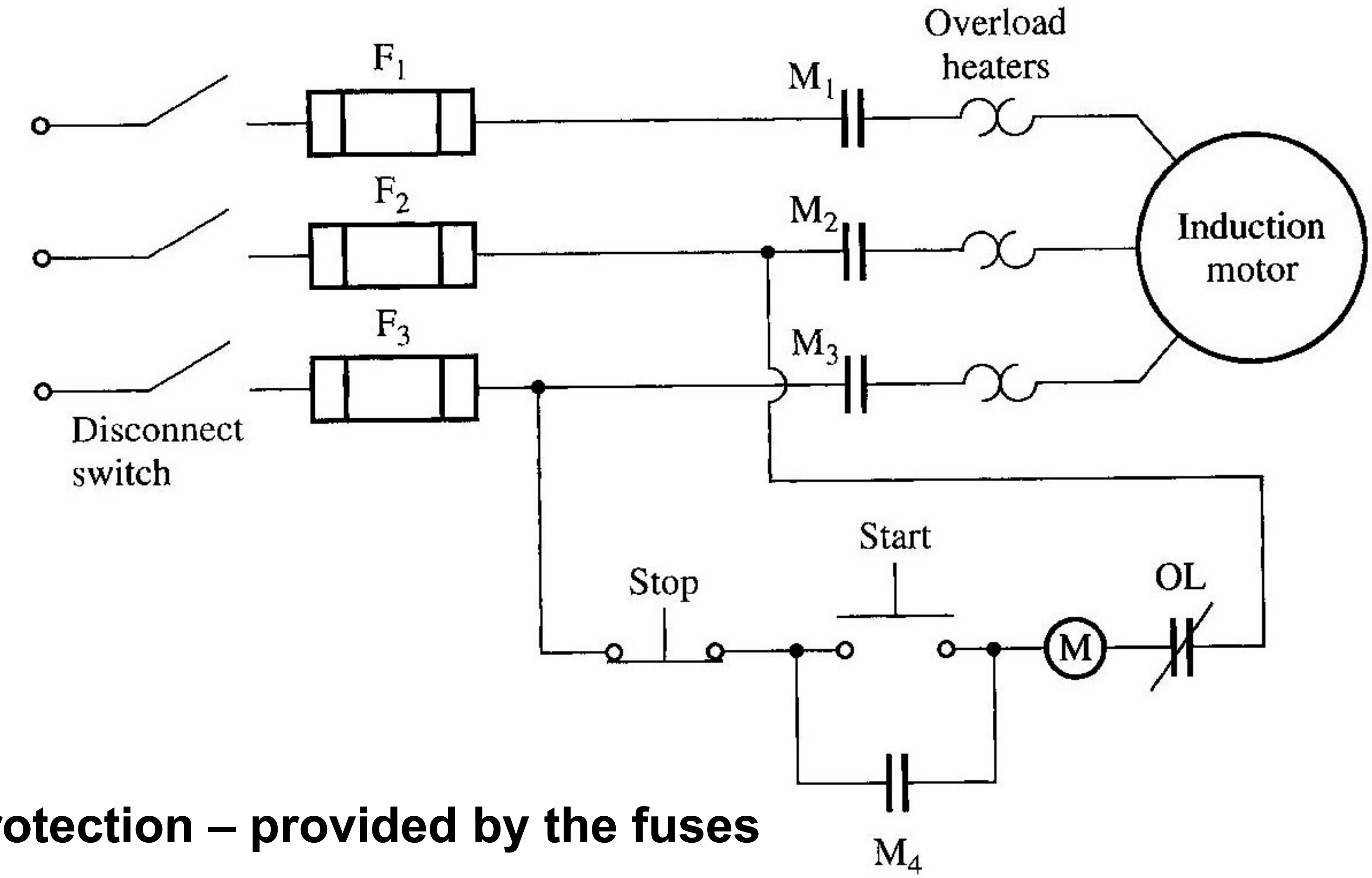
When delta connected

$V_w = V_L$

Star Connected Initially **Delta Connected finally**

High transients when changing from star to delta!

Induction motors automatic starting circuits



Short Circuit protection – provided by the fuses

Overload protection – provided by the Overload heaters (thermostats) and the overload contacts (OL)

Under voltage protection – de energising of the M relays.

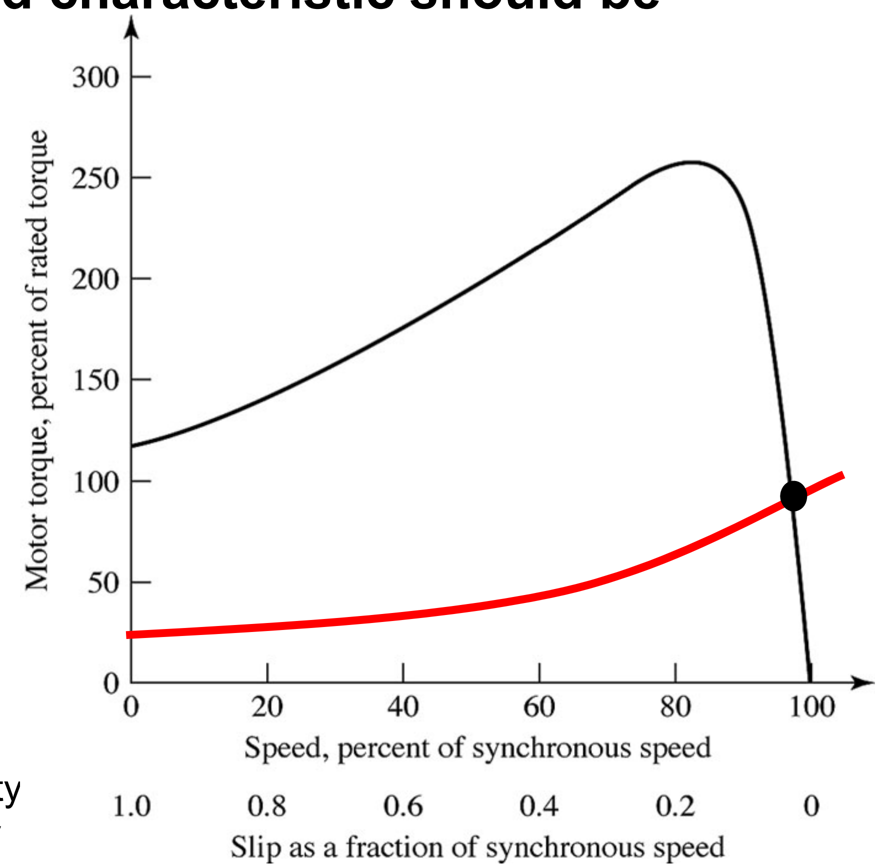
Speed Control of Induction motors

Steady state Torque speed operating point is the cross section of load torque-speed characteristic with the machine torque-speed characteristic.

Operating point is close to synchronous speed

To change the speed, motor torque-speed characteristic should be modified:

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



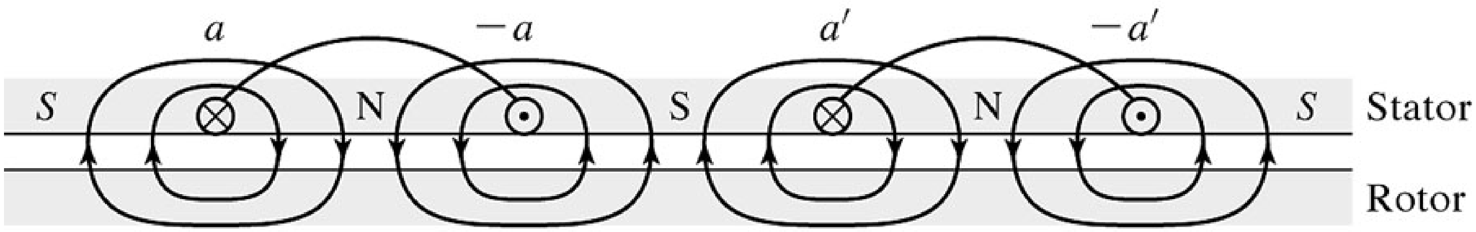
Parameters that can affect:

Poles, frequency, voltage, rotor resistance

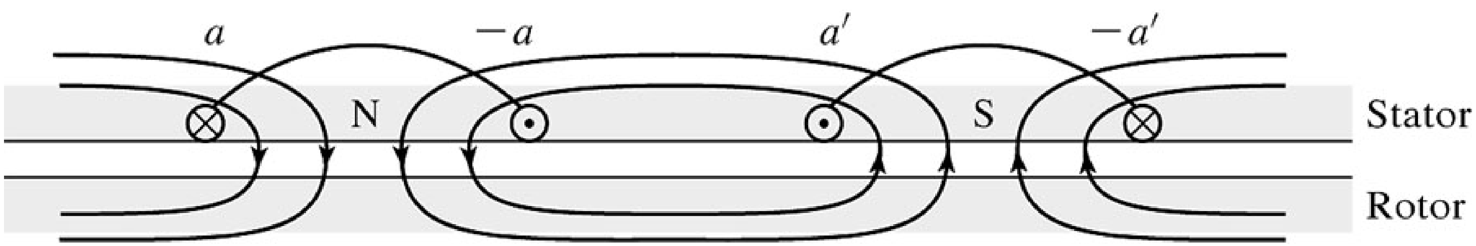
Speed changing using pole changing/ multi winding

Synchronous speed: $$n_{sync} = \frac{120 f_e}{p}$$

Operating point is close to synchronous speed.



(a)



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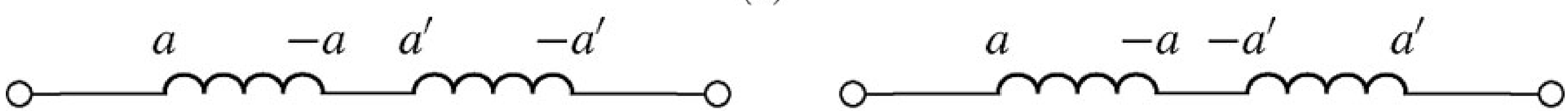


(a) **What is the speeds ratio?** (b)

Speed control using line voltage

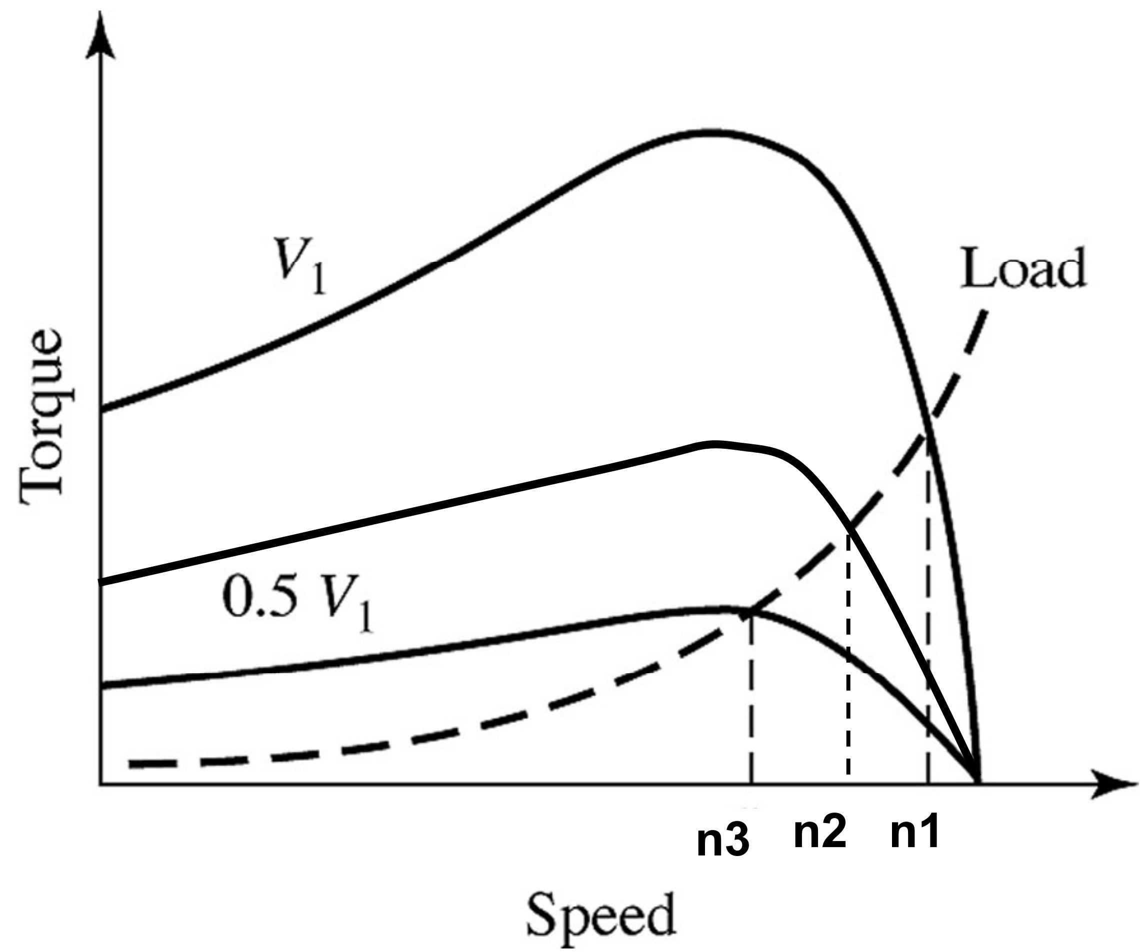
$$T_{ind} \propto V_{th}^2 \propto V_p^2$$

Speed variation is limited.

Maximum torque decreases Rapidly.

Operating s increases .

Used for small motors with special loads.



Speed control using line frequency

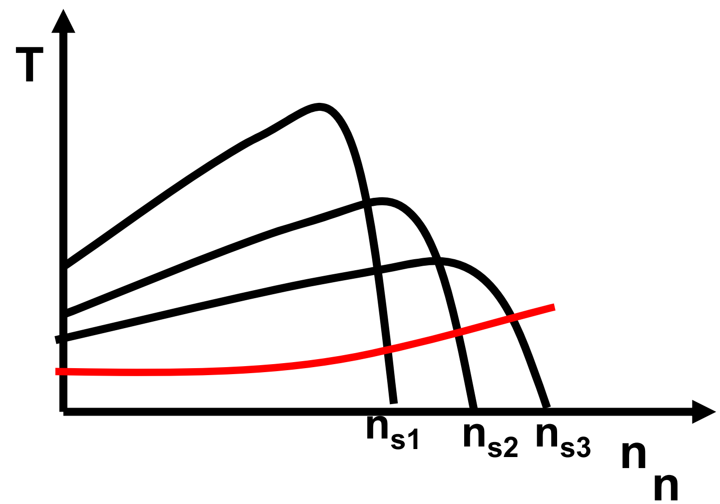
$$T = \frac{3}{2}\frac{p}{\omega_s}\frac{R_2}{s}\frac{V_{th}^2}{(R_{th}+\frac{R_2}{s})^2+(X_{th}+X_2)^2}$$

$$\frac{f}{f_s} = a \Rightarrow \frac{X}{X_s} = a$$

$$T \approx \frac{3}{2}\frac{p}{a\omega_s}\frac{R_2}{s}\frac{V_{th}^2}{(R_{th}+\frac{R_2}{s})^2+a^2(X_{th}+X_2)^2}$$

$$T_{max} \approx \frac{3p}{4a\omega_s}\frac{V_{th}^{\;2}}{R_{th}+\sqrt{R_{th}^2+a^2(X_{th}+X_2)^2}}$$

$$T_{st} \approx \frac{3p}{2a^2\omega_s}\frac{V_{th}^{\;2}R_2}{(X_{th}^2+X_2)}$$



- **An increase in the no load speed (synchronous speed).**
- **A decrease in the maximum torque.**
- **A rapid decrease in the Start-up Torque.**
- **Needs Frequency Converter.**
- **Why a is greater than 1!!**

Speed Control by Adjusting V/F constant

$E = 4.44\, f_e\, N_{se}\, \varphi_{max}$

$V \approx E$

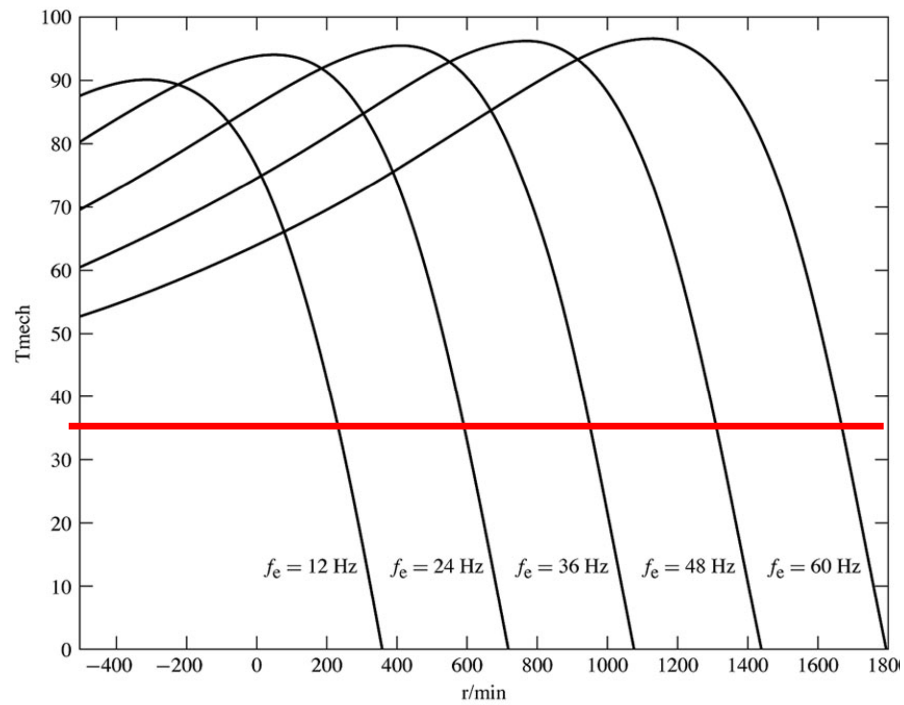
$$T = \frac{3}{2}\frac{p}{\omega_s}\frac{R_2}{s}\frac{V_{th}^2}{(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2}$$

$$\frac{f}{f_e} = a = \frac{V}{V_s} \Rightarrow \frac{X}{X_s} = a$$ Neglecting R1(/R_{th})

$$T = \frac{3}{2}\frac{p}{a\omega_s}\frac{\frac{R_2}{f_r}}{af_s}\frac{a^2V_{th}^2}{(\frac{R_2}{f_r})^2 a^2 f_s^2 + a^2(X_{th} + X_2)^2}$$

$$T = \frac{3}{2}\frac{p}{2\pi}\frac{R_2}{f_r}\frac{V_{th}^2}{(\frac{R_2}{f_r})^2 f_s^2 + (X_{th} + X_2)^2}$$

To avoid Saturation: φ_{max} =const
Voltage and frequency Should change together.



(b)

for the same slip frequency (f_r) torque is the same
Look at start up torque !
Needs Frequency Converter.

Speed Control by Adjusting Rotor Resistance

In wound rotor machine rotor starter can be used for speed control

Low efficiency operating point
Limited speed variation

Think about methods of Energy saving!!