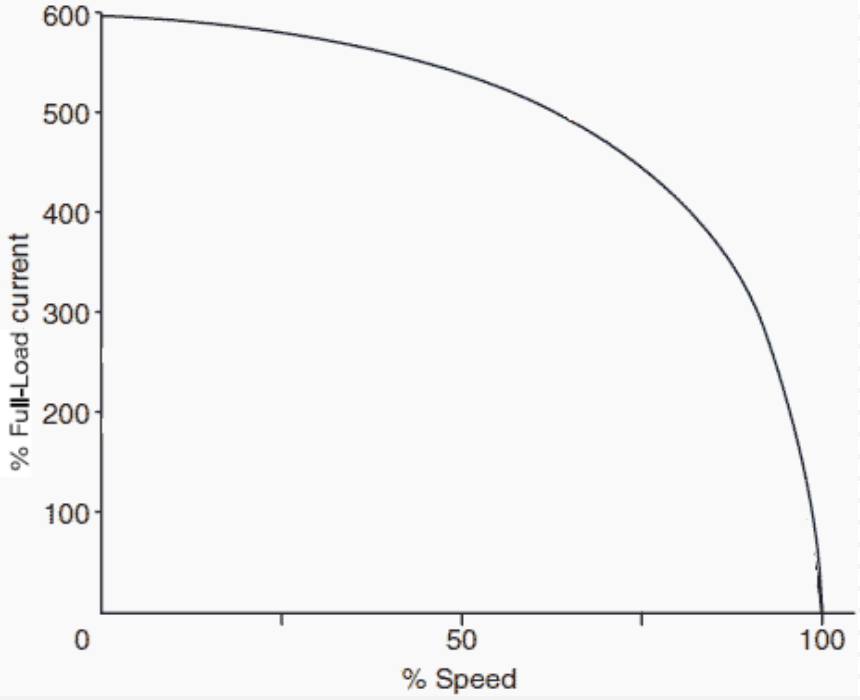
Induction Machines

- 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

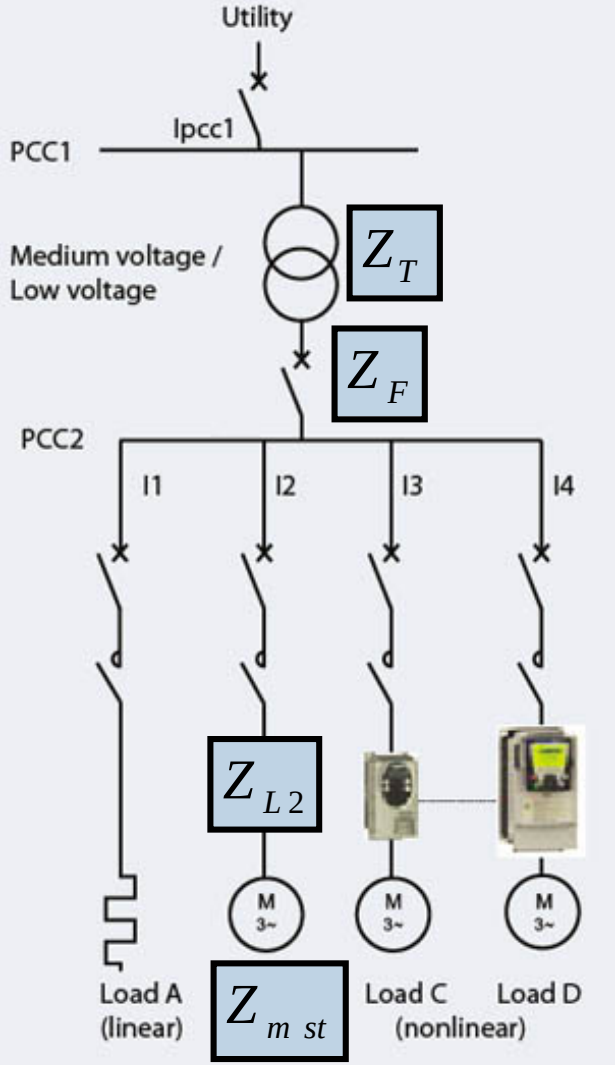
Induction Machines: Motor Starting

The induction motor is inherently self-starting, but the starting current is high (5-7 times full load current)



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

Induction Machines: Motor Starting



$$V_{PCC2} = V_{PCC1} \frac{Z_{L2} + Z_{m\ st}}{Z_T + Z_F + Z_{L2} + Z_{m\ st}}$$

$$\frac{\Delta V_{PCC2}}{V_{PCC2N}} \leq 3\%$$

Induction Machines: Motor Starting

The load, the motor and the supply network determine the most appropriate starting method. When selecting the starting method and any protective devices, the following factors must be taken into account:

- The voltage drop in the supply network when starting the motor

- The required load torque during start

- The required starting time

Induction Machines: Motor Starting

1. *Direct Online Starting (DOL)*
2. *Star-delta Switching*
3. *Resistance/Reactance Stator Starting*
4. *Auto-transformer Starting*
5. *Soft Starters*
6. *Current displacement cages*
7. *Resistance Rotor Starting (wound rotor only)*

Induction Machines: Motor Starting

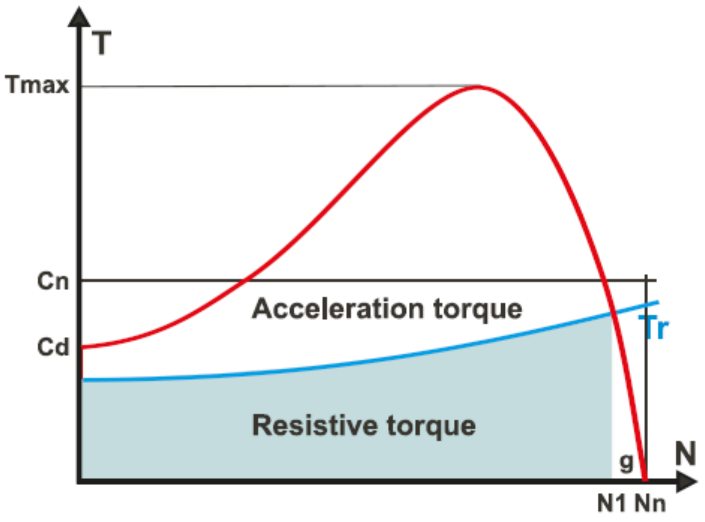
1. Direct Online Starting (DOL)

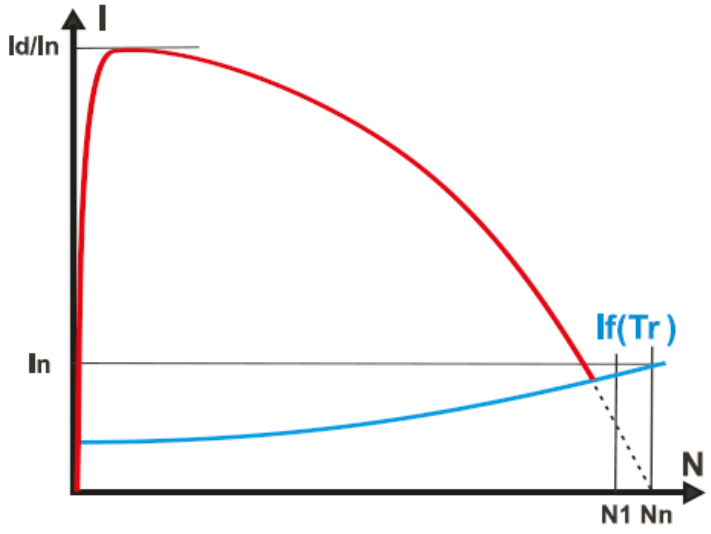
Direct on-line starting is only suitable when:

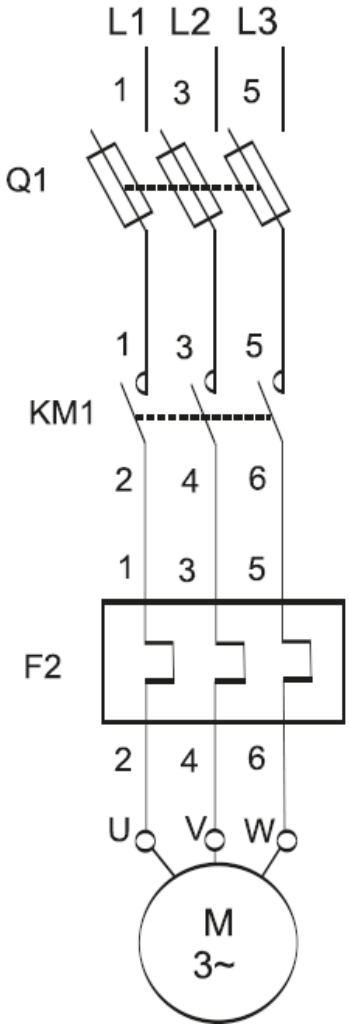
- *the power of the motor is low compared to that of the mains, which limits voltage drop from starting current,*
- *the machine to drive does not need to speed up gradually or has a damping device to limit the shock of starting,*
- *the starting torque can be high without affecting machine operation or the load that is driven.*

Induction Machines: Motor Starting

1. Direct Online Starting (DOL)







Induction Machines: Motor Starting

2. Star-Delta (Y-D) Starting

$$I_{y\phi} = \frac{V_L}{\sqrt{3} Z_{eq\phi}}$$

$$I_{yL} = I_{y\phi}$$

$$I_{D\phi} = \frac{V_L}{Z_{eq\phi}}$$

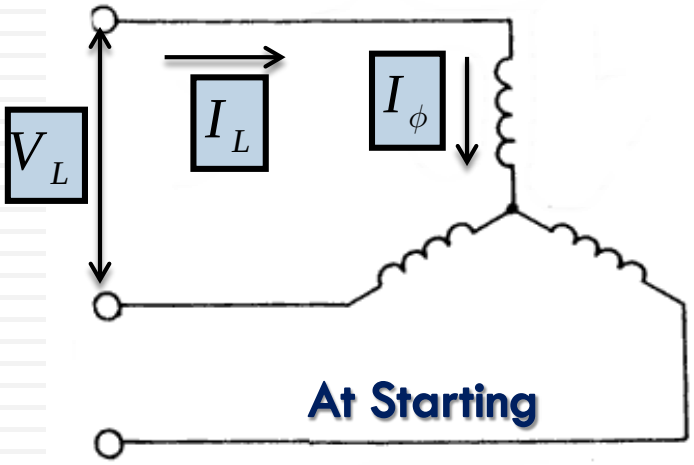
$$I_{DL} = \sqrt{3} I_{D\phi}$$

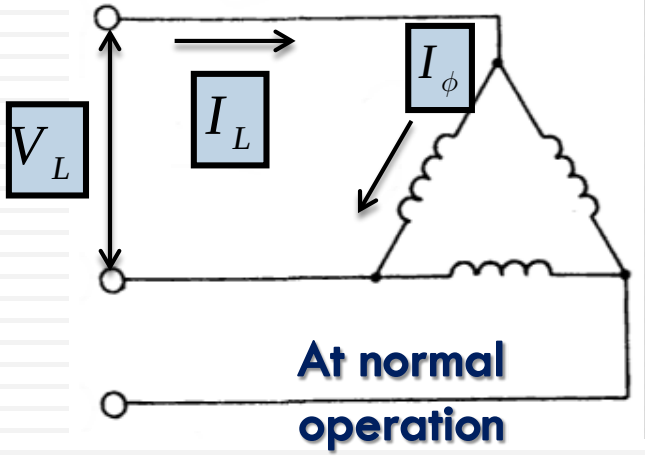
$$\frac{I_{yL}}{I_{DL}} = \frac{1}{3}$$

$$\frac{V_{y\phi}}{V_{D\phi}} = \frac{1}{\sqrt{3}}$$

$$T_{st} \propto V^2$$

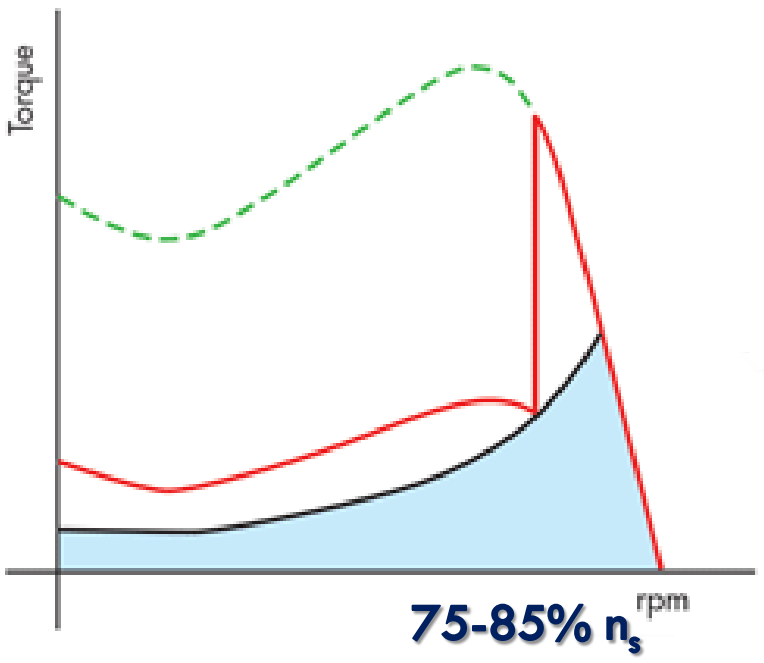
$$\frac{T_{sty}}{T_{stD}} = \frac{1}{3}$$

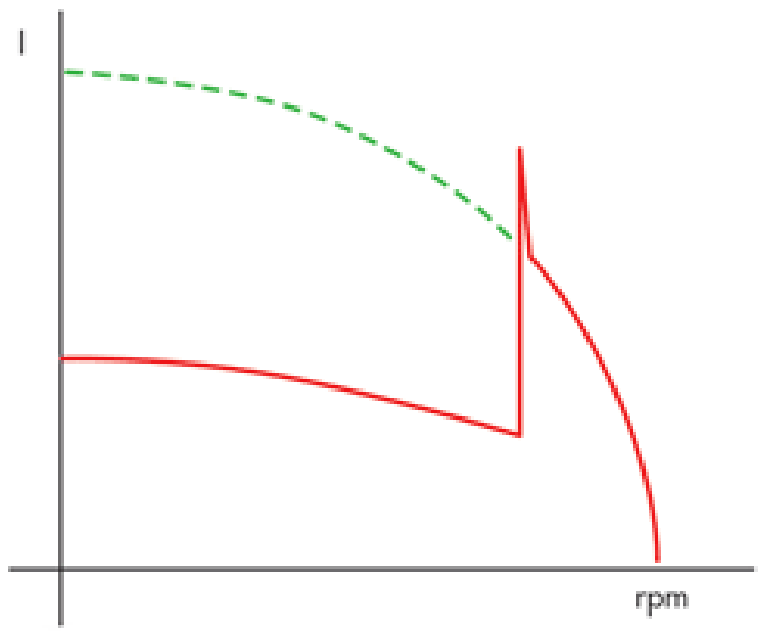




Induction Machines: Motor Starting

2. Star-Delta (Y-D) Starting





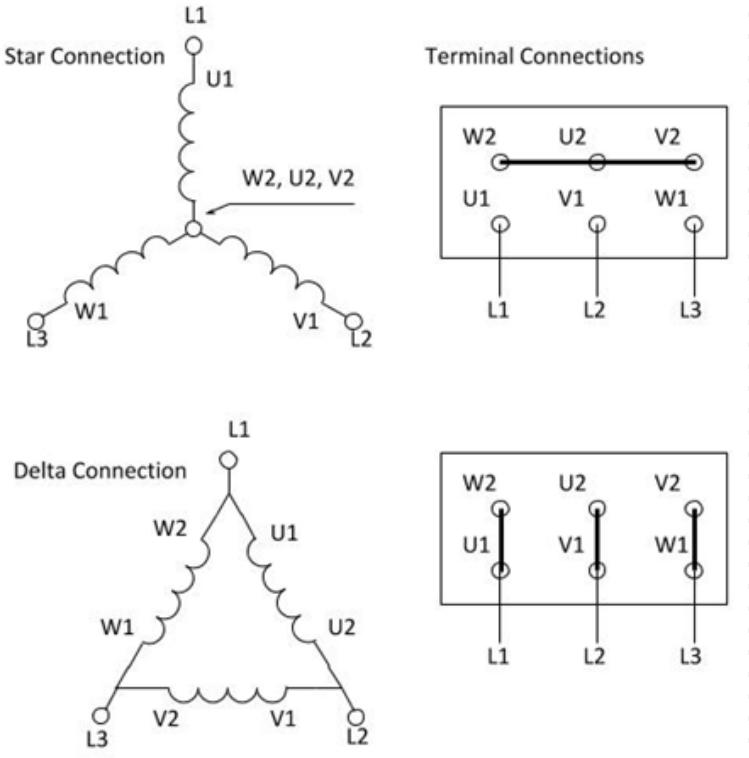
Induction Machines: Motor Starting

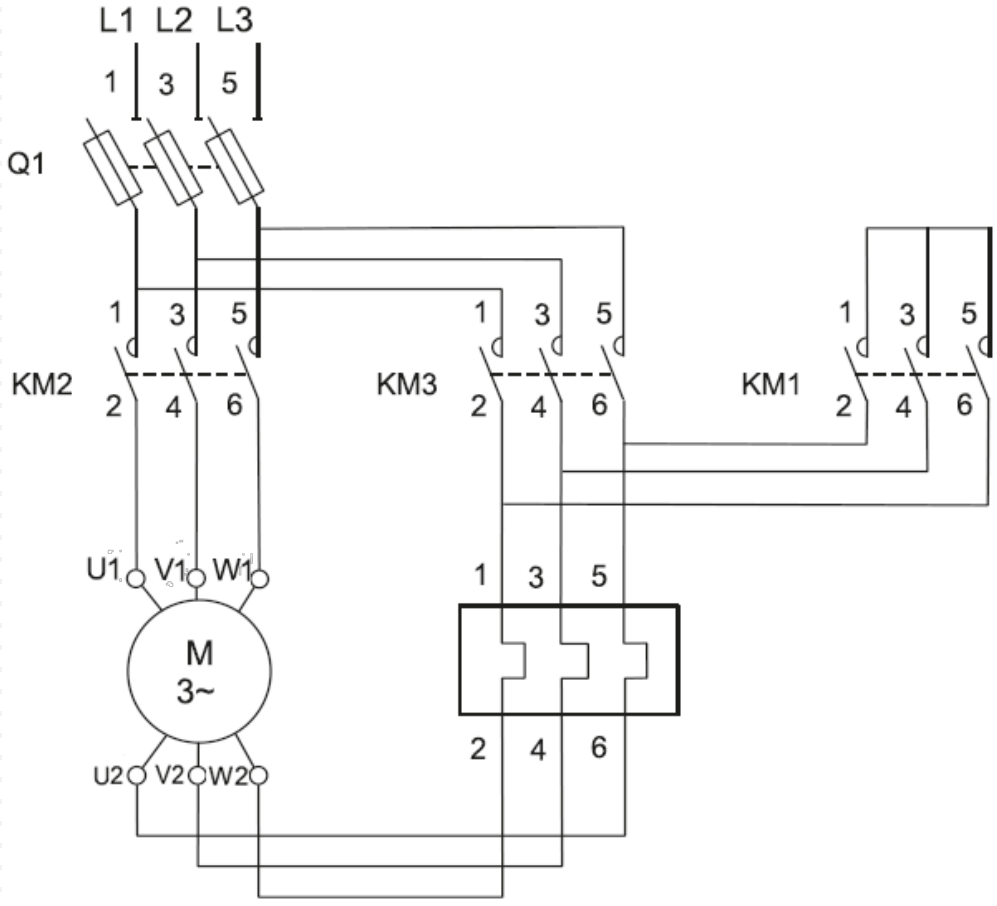
2. Star-Delta Starting

- *Star-delta starting is suitable for machines with a low load torque at starting or which start with no load*
- *This starting system can only be used with a motor where both ends of its three stator windings are fitted to a terminal board.*
- *The winding must be done so that the delta connection matches the mains voltage: e.g. a 380V 3-phase supply will need a motor with 380V delta and 660V star coiling.*

Induction Machines: Motor Starting

2. Star-Delta Starting



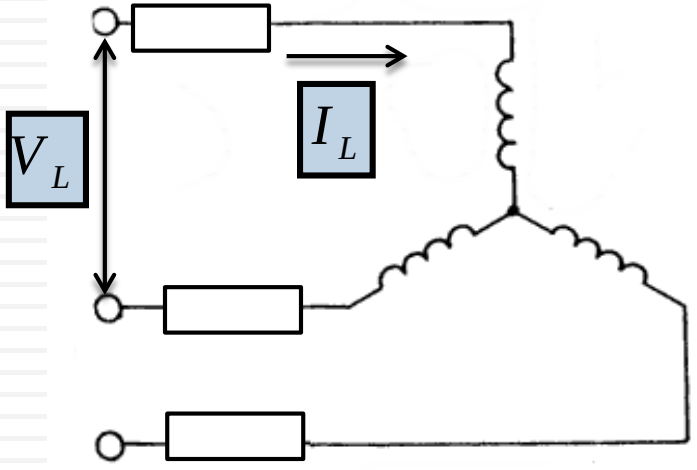


Induction Machines: Motor Starting

3. Resistance/Reactor Stator Starting

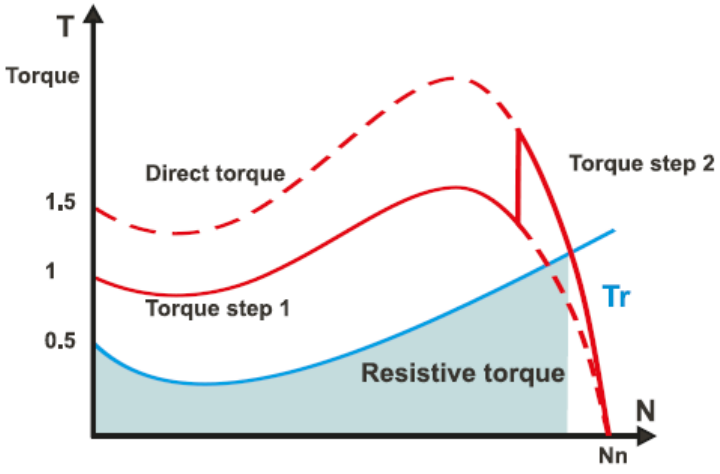
The motor starts at reduced voltage because resistors/reactors are inserted in series with the windings. When the speed stabilizes, the resistors/reactors are eliminated and the motor is connected directly to the mains.

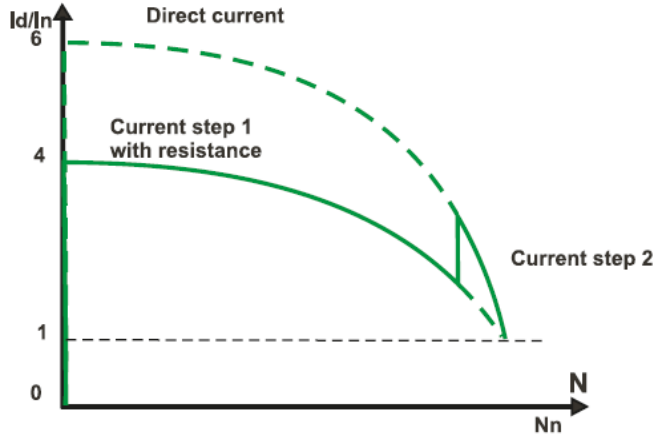
$$I_{st} = \frac{V_L}{\sqrt{3}(Z_{eq\phi} + Z_{add})}$$

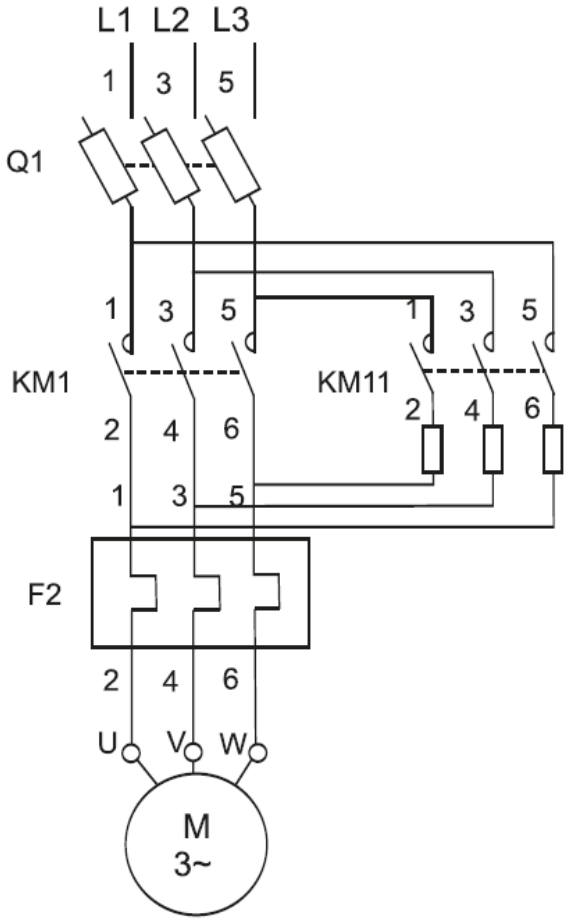


Induction Machines: Motor Starting

3. Resistance/Reactor Stator Starting

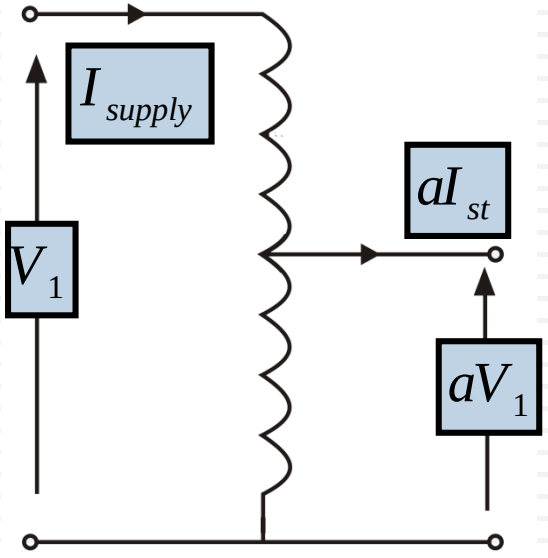






Induction Machines: Motor Starting

4. Auto-transformer Starting

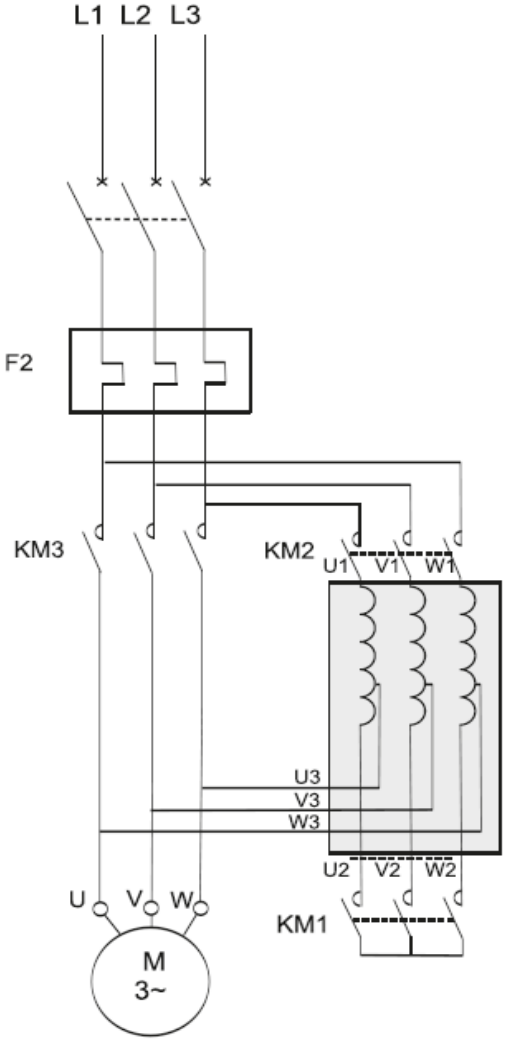


$$V_1 I_{supply} = (aV_1)(aI_{st})$$

$$I_{supply} = a^2 I_{st}$$

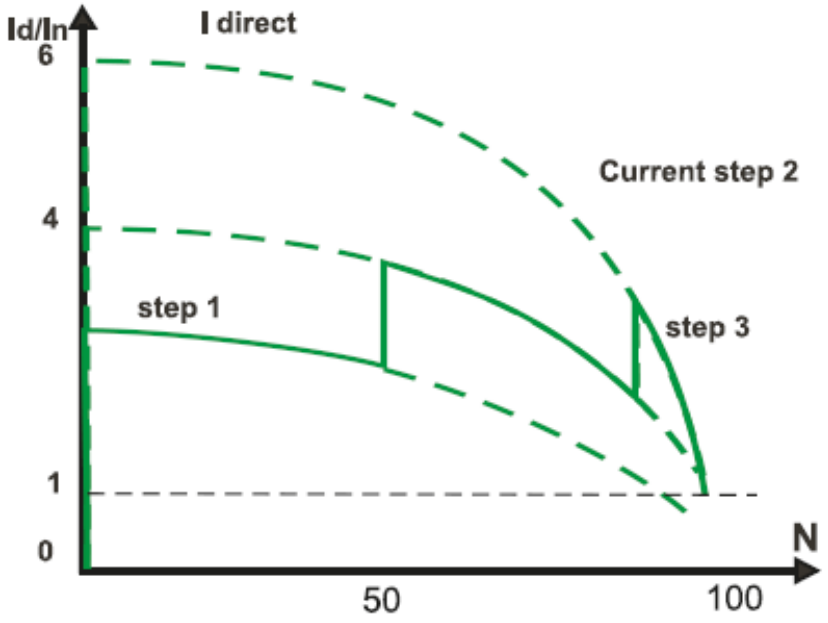
$$T_{st} \propto V^2$$

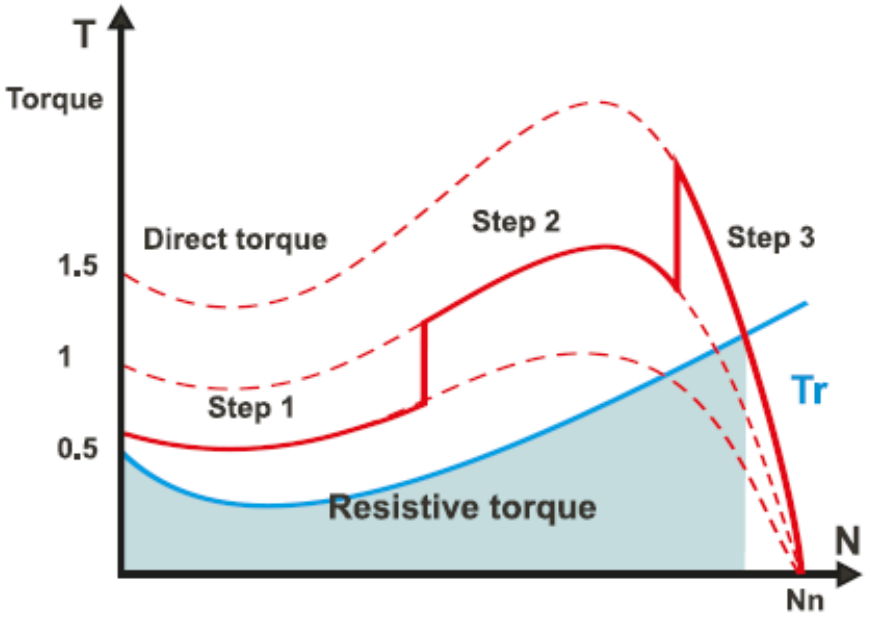
$$T_{st\ auto} = a^2 T_{st}$$



Induction Machines: Motor Starting

4. Auto-transformer Starting

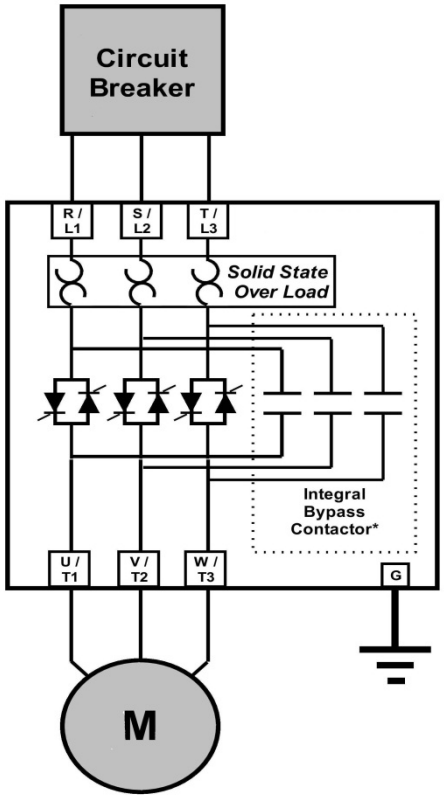




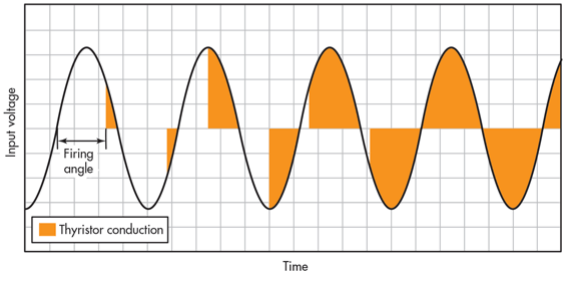
Induction Machines: Motor Starting

5. Soft starters

Soft starters are based on semiconductors, which, via a power circuit and a control circuit, initially reduces the motor voltage, resulting in lower motor torque and current During the starting process, the soft starter progressively increases the motor voltage so that the motor accelerates the load to rated speed without causing torque or current peaks. Soft starters can also be used to control the stopping of a process.

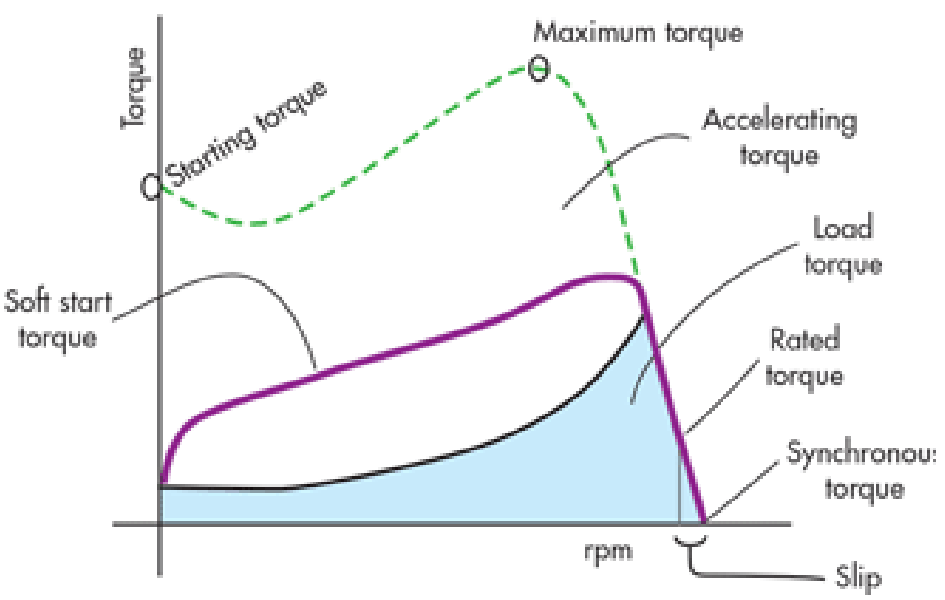


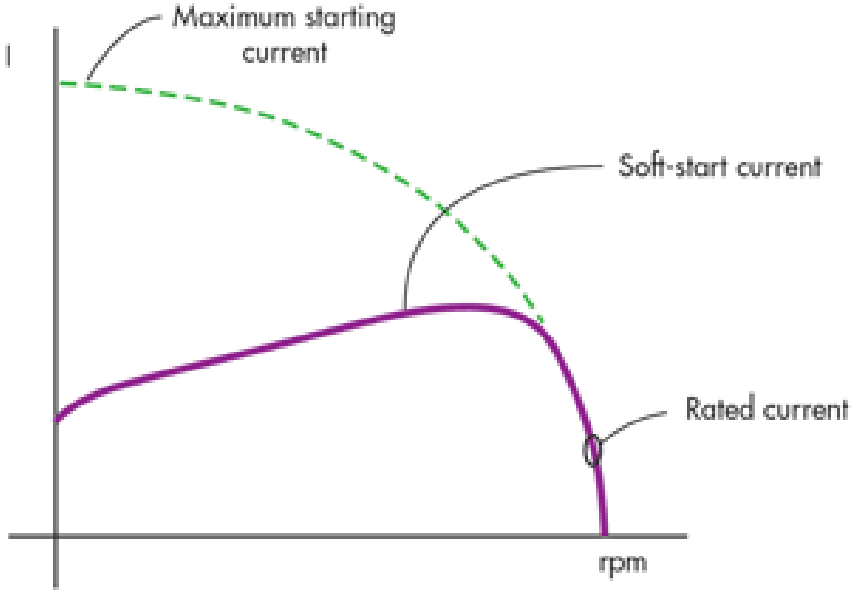
TYPICAL SOFT-START FIRING ANGLE SEQUENCE



Induction Machines: Motor Starting

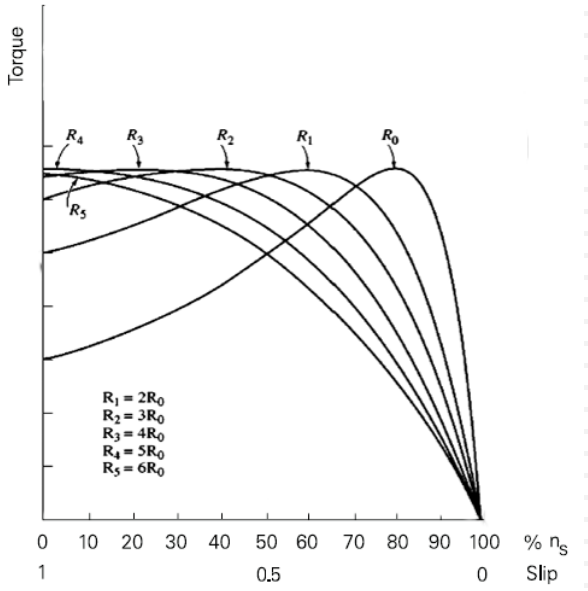
5. Soft starters

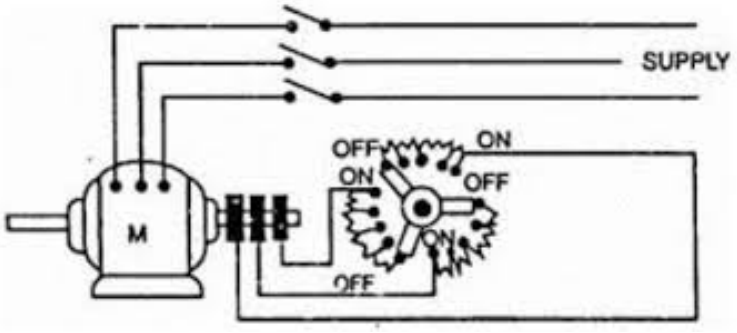


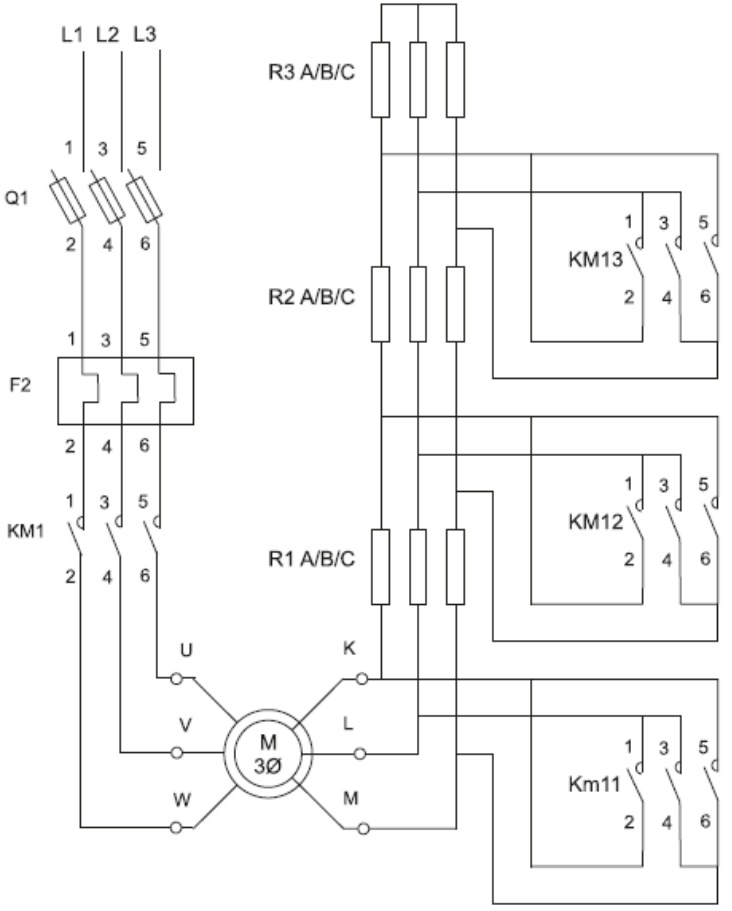


Induction Machines: Motor Starting

6. Resistance Rotor Starting (wound rotor only)







Induction Machines: Motor Starting

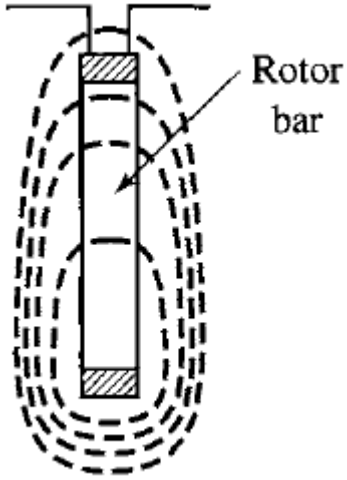
7. Current Displacement Cages

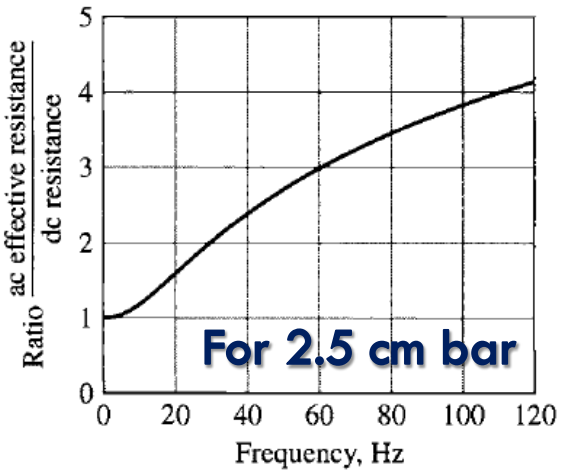
a. Deep Bar motor

At starting ($s=1$, $f_2=f_1$), the current density is much higher at the top of the bar resulting in higher effective resistance. (skin effect)

At normal operating points (s very small, f_2 tends to zero), so the current is uniformly distributed so the resistance is lower than the resistance at starting.

For bars less than 2 cm in depth, this effect is negligible.

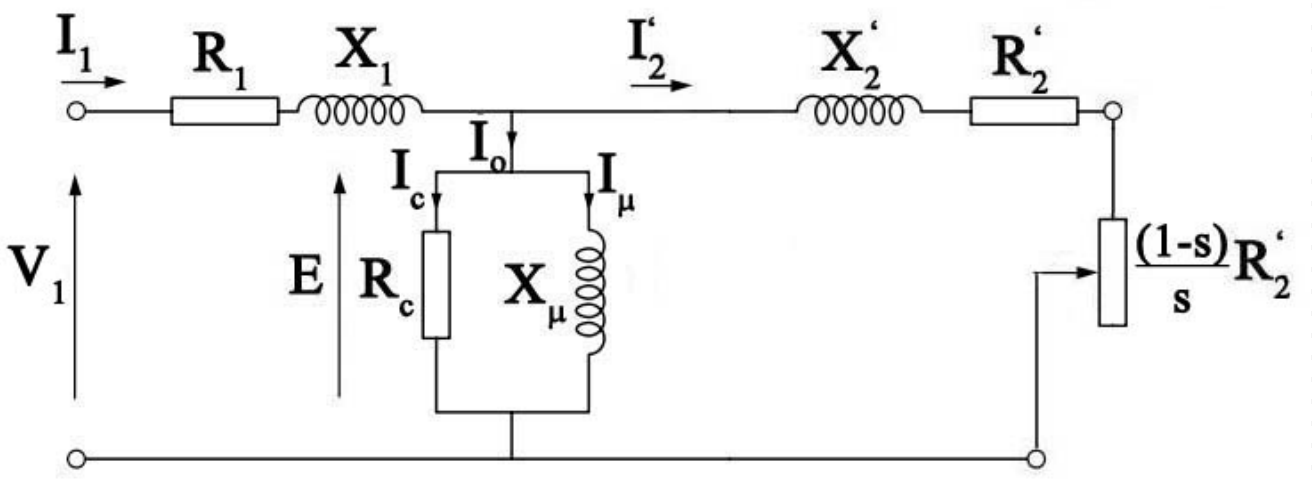


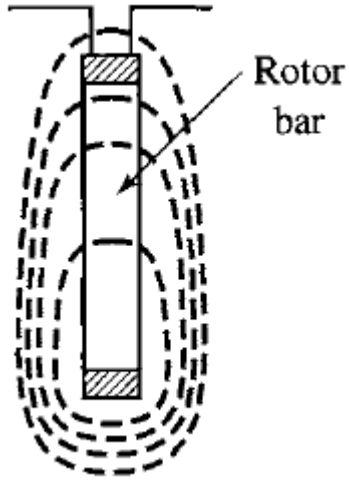


Induction Machines: Motor Starting

7. Current Displacement Cages

a. Deep Bar motor





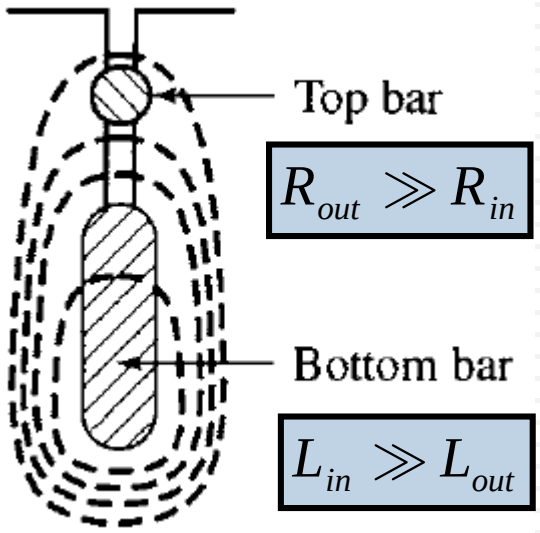
$s_m < s < 1$ ⇒ $R_2^{'} = R_{2ac}^{'}$

$0 < s < s_m$ ⇒ $R_2^{'} = R_{2dc}^{'}$

Induction Machines: Motor Starting

7. Current Displacement Cages

b. Double Cage motor



At starting ($s=1$, $f_2=f_1$), the current mostly flows in the outer cage.

At normal operating points, (s very small, f_2 tends to zero) effect of inductance is negligible so current mostly flows in the inner cage.

Induction Machines: Motor Starting

7. Current Displacement Cages

b. Double Cage motor