# Techniques Used For Induction Motor Starting

Induction motors do not present the types of starting problems that synchronous motors do. In many cases, induction motors can be started by simply connecting them to the power line. However, there are sometimes good reasons for not doing this. For example, the starting current required may cause such a dip in the power system voltage that *across-the-line starting is not acceptable.*

For wound-rotor induction motors, starting can be achieved at relatively low currents by inserting extra resistance in the rotor circuit during starting. This extra resistance not only increases the starting torque but also reduces the starting current.

- When an induction motor is at standstill, n is zero and s is 1. In this case when a full (nominal) voltage is applied to the stator windings of the motor, the motor draws dangerously large currents from the supply as much as 5-6 times of the rated current. If high rated motors are fed from a weak power supply, voltage drop at the supply will be observed. If there are many machines connected to this supply, the supply will not be able to feed these machines. For this reason, starting current of the motor must be limited.
- The starting process of the induction motor is defined as to increase its speed from standstill to the nominal speed without drawing excessive currents from the supply meanwhile making the starting torque as big as possible.

From the approximate equivalent circuit, the rotor current and torque;

$$I'_R = \frac{V_s}{\sqrt{(R_s + \frac{R'_R}{s})^2 + (X_s + X'_R)^2}}$$

$$T = \frac{R'_R}{s\omega_s} \frac{V_s^2}{[(R_s + R'_R/s)^2 + (X_s + X'_R)^2]}$$

From the above equations it can be easily seen that; s=1 when the motor stops and therefore $I'_R$ current gets as big as 5-6 times of its rated value and the torque decreases. Motors with a few HP can be started directly without considering these negative effects. If the power network is enough powerfull, much bigger rated motors can be also started directly.

For cage induction motors, the starting current can vary widely depending primarily on the motor’s rated power and on the effective rotor resistance at starting conditions. To estimate the rotor current at starting conditions, all cage motors now have a starting *code letter (not to be confused with their design class letter)* on their nameplates. The code letter sets limits on the amount of current the motor can draw at starting conditions.

These limits are expressed in terms of the starting apparent power of the motor as a function of its horsepower rating. Figure given below is a table containing the starting kilovoltamperes per horsepower for each code letter. To determine the starting current for an induction motor, read the rated voltage, horsepower, and code letter from its nameplate. Then the starting apparent power for the motor will be

$$S_{start} = (\text{ rated horsepower})*(\text{code letter factor})$$

and the starting current can be found from the equation

$$I_L = \frac{S_{start}}{\sqrt{3}V_T}$$

| Nominal code letter | Locked rotor, kVA/hp | Nominal code letter | Locked rotor, kVA/hp |
|---|---|---|---|
| A | 0–3.15 | L | 9.00–10.00 |
| B | 3.15–3.55 | M | 10.00–11.20 |
| C | 3.55–4.00 | N | 11.20–12.50 |
| D | 4.00–4.50 | P | 12.50–14.00 |
| E | 4.50–5.00 | R | 14.00–16.00 |
| F | 5.00–5.60 | S | 16.00–18.00 |
| G | 5.60–6.30 | T | 18.00–20.00 |
| H | 6.30–7.10 | U | 20.00–22.40 |
| J | 7.10–8.00 | V | 22.40 and up |
| K | 8.00–9.00 | | |

**FIGURE**
Table of NEMA code letters, indicating the starting kilovoltamperes per horsepower of rating for a motor. Each code letter extends up to, but does not include, the lower bound of the next higher class.

The starting techniques used for induction motors can be listed as;

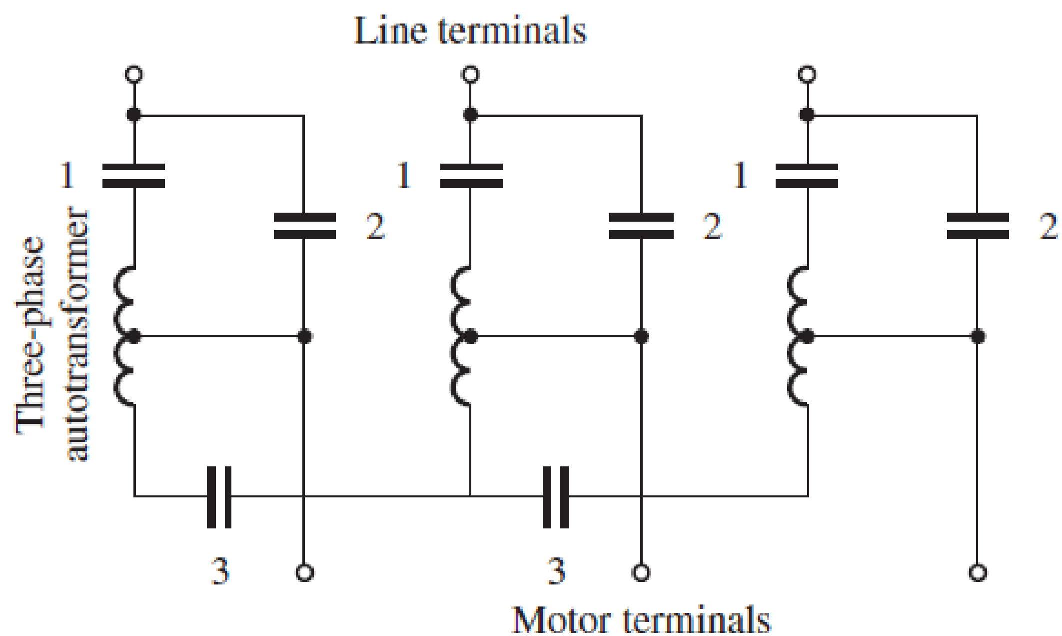
1) Starting the motor by connecting directly to the supply.
2) Starting the motor by using autotransformers
3) Starting the motor by connecting either resistors or thyristors in series to the stator windings.
4) Starting the motor by Star/Delta connection of the stator windings.
5) Starting the wound rotor induction motor by connecting either resistors or thyristors in series to the rotor windings.
6) Starting the motor by using double squirrel cage in the rotor.

# 1) Starting the motor by connecting directly to the supply

Rating of the power supply determines the power of the motor which is aimed to start with this technique. When an induction motor is at standstill, and nominal voltage is applied to the stator windings, the motor draws high current from the supply as much as 6 times of the rated current. This current may cause such a dip in the power system voltage . If several motors are connected simultaneously to the power system, this voltage change in the power system will be much bigger. Since it takes longer time to reach nominal speeds for high power rated motors , high currents during the acceleration of the motor from standstill will result heating of the stator windings. That heat may damage isolation of the windings. That is why this technique is applied to the motors having a few hourse powers (HP). The advantage of this technique is that it is simple and cheap. In addition, acceleration of the motor with high curents is big resulting to reach its nominal speed in short time.

# 2) Starting the motor by using autotransformers

Another way to limit the starting current is to reduce the line voltage. The motor’s terminal voltage during starting can be reduced by using autotransformers to step it down. During starting, contacts 1 and 3 shown in figure below are shut, supplying a lower voltage to the motor. Once the motor is nearly up to speed, those contacts are opened and contacts 2 are shut. These contacts put full line voltage across the motor.




Starting sequence:

(*a*) Close 1 and 3
(*b*) Open 1 and 3
(*c*) Close 2

**FIGURE**
An autotransformer starter for an induction motor.

# 3) Starting the motor by connecting either resistors or thyristors in series to the stator windings

Another way to reduce the starting current is to insert extra inductors or resistors into the power line during starting. The aim of this technique is to reduce the voltage applied to the stator at starting. During acceleration the voltage is increased step by step either by extracting the resistors (or inductors) or by controlling the firing angle of the thyristors which are used in AC chopper configuration. If the line voltage is reduced by the chopper circuit, the efficiency will be high because of the low power losses of the thyristors. The starting technique by connecting extra resistors or inductors into the power line is inefficient because of the power loss in the resistors. Therefore, this technique is limited to the small power induction motors.

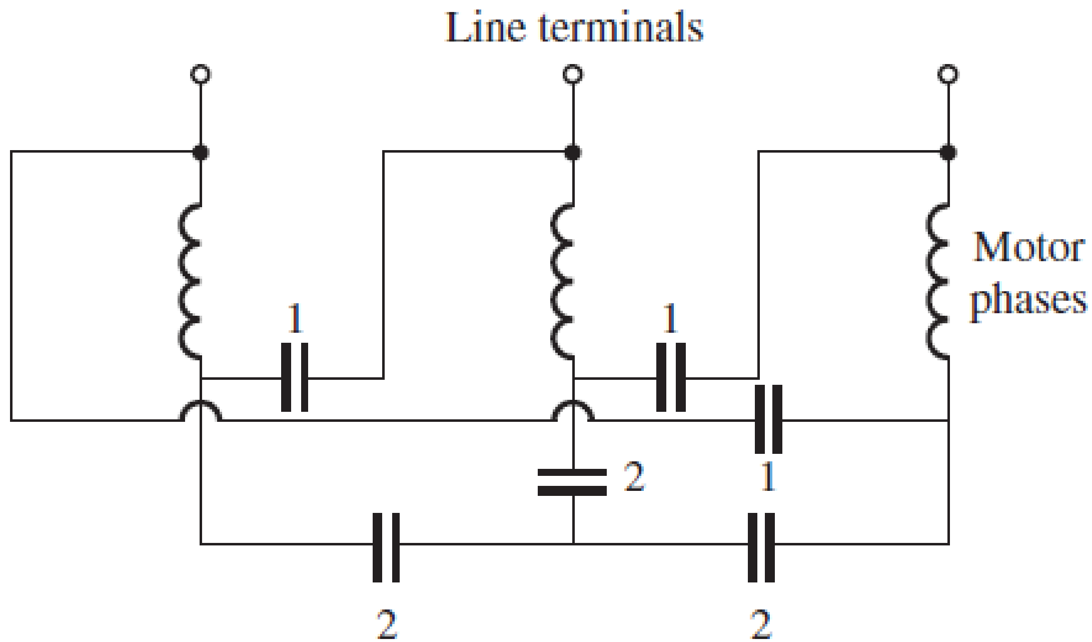
While formerly common, this approach is rare today.

# 4) Starting the motor by Star/Delta connection of the stator windings

One way to reduce the starting current is to change a normally delta connected motor into a star connected motor during the starting process. If the stator winding of the motor is switched from a delta connection to a star connection, then the phase voltage across the winding will decrease from $V_L$ *to* $V_L/\sqrt{3}$ . When the motor accelerates to close to full speed, the stator windings can be opened and reconnected in a delta configuration (see figure given in the next slide).

When the motor is connected in star, a phase voltage ($V_L/\sqrt{3}$) is applied to the stator windings, If the stator impedance per phase is Z, the winding current will be (phase current is also equal to the line current in star connection);

$$I_\lambda = \frac{V_L}{\sqrt{3}Z}$$




Starting sequence:

(*a*) Close 1
(*b*) Open 1when motor is turning
(*c*) Close 2

**FIGURE**
A Y-Δ induction motor starter.

If the motor windings are delta connected and the supply voltage is applied to the motor, the motor phase current will be;

$$I_{\Delta} = \frac{V_L}{Z}$$

The line current in delta connection is $\sqrt{3}$ times of the phase current. Then, if the line currents for star and delta connections are compared;

$$\frac{I_{\Delta line}}{I_{\text{ʎ}line}} = \frac{\frac{\sqrt{3}V_L}{Z}}{\frac{V_L}{\sqrt{3}Z}} = 3 \rightarrow I_{\Delta line} = 3.\, I_{\text{ʎ}line}$$

For this reason, the delta connected motor draws current from the line 3 times bigger than that of the star connected motor at starting.

Since the starting torque is proportional with the square of the applied voltage, the torque in delta connected motor is 3 times bigger than the torque in star connected motor. In practice, mechanical switches (known as star-delta switch) are used to connect the windings in star and delta for small power rating motors. At high power rating motors, contacts (2) are shut to connect the windings in star during acceleration then after reaching a certain speed, the windings are connected in delta by opening contacts (2) and shutting contacts (1).

Transient events are happened when the star connected winding is connected in delta during starting process because of the increase in the winding voltage by $\sqrt{3}$ times. However, since the motor already reaches to a certain speed, the impedance seen by the line is high and the current value could be maximum three times of the rated current.

It is important to realize that while the starting current is reduced in direct proportion to the decrease in terminal voltage, the starting torque decreases as the *square of the applied voltage. Therefore, only a certain amount of current reduction* can be done if the motor is to start with a shaft load attached.

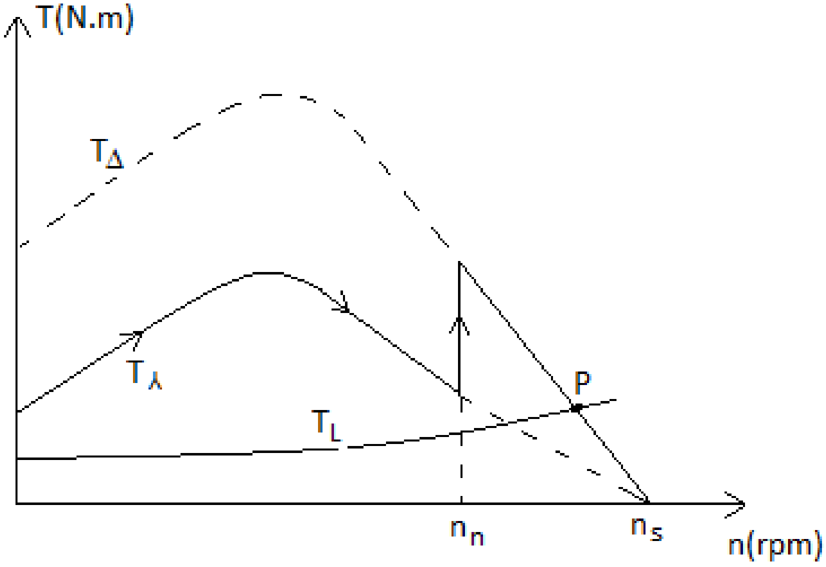



Figure (a) Torque-speed curves for star-delta starting

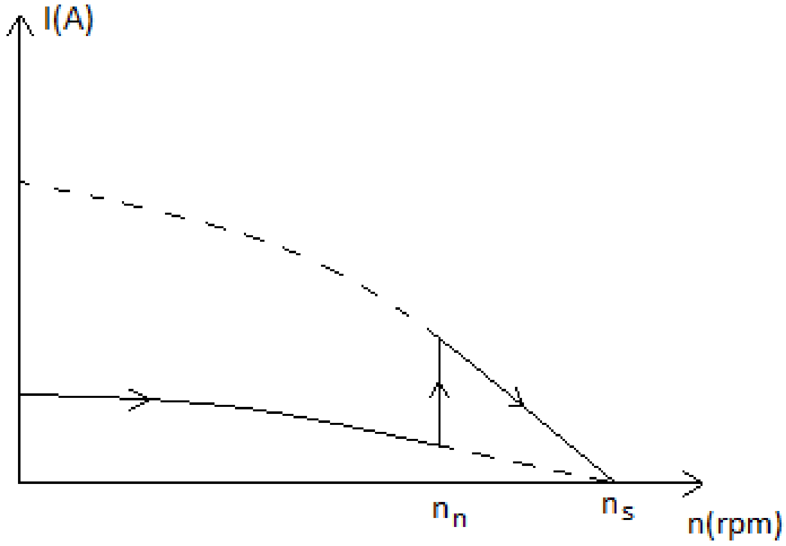



Figure (b) Current-speed curves for star-delta starting

# 5) Starting the motor by connecting either resistors or thyristors in series to the rotor windings

This technique is only applied to the wound rotor induction motors. Wound rotors are complete three-phase rotor windings, with the phases brought out of the rotor through slip rings and brushes. Wound-rotor induction motors therefore have their rotor currents accessible at the rotor brushes, where extra resistance can be inserted into the rotor circuit. It is possible to take advantage of this feature to modify the torque–speed characteristic of the motor.

To start up the wound rotor induction motor with high torque and low current, extra resistances are inserted into the rotor circuit (3-5 resistances connected in series) and then they are extracted step by step during the acceleration. Before the machine speed reaches its rated value all extra resistances are made short-circuit allowing the machine to operate at normal condition. The value of extra resistances ($R_1+R_2+R_3+R_4=R_{start}$) is determined by considering the starting conditions depending on the current and torque of the machine.

**Table:** Current-torque ratios according to the load during starting

| | Starting at half load | Starting at full load | Starting at heavy load |
|---|---|---|---|
| $\frac{\text{Average starting current (I)}}{\text{Nominal curent (In)}}$ | 0.7 | 1.4 | 2.0 |
| $\frac{\text{Average starting torque (T)}}{\text{Nominal torque (Tn)}}$ | 0.7 | 1.4 | 2.0 |

At the beginning (standstill) all the resistances ($R_{start}$) are connected in series to the rotor circuit through the slip rings and brushes. At full load, the motor accelerates with maximum torgue ($T_{max}$). When the torque reaches a certain $T_{min}$ value, R1 resistor is extracted from the rotor circuit ($R_{start}$-$R_1$=$R_2$+$R_3$+$R_4$). In this case, the torque increases again. Again when the torque reaches to $T_{min}$, this time $R_2$ is extracted from the rotor circuit ($R_{start}$-$R_1$-$R_2$=$R_3$+$R_4$).

- Thus, until the motor reaches its nominal operation conditions, extra resistances are systematically extracted (short-circuited) and finally the rotor windings are short-circuited through the slip rings. In this case, only $R_R$ rotor circuit resistor remains in the rotor circuit. Here, $(T_{min}+T_{max})/2=T$ is the average starting torque. At full load, $T/T_n=1.4$ is taken during starting from the table given above. If $T_{min}=1.2T_n$ is chosen;

$$\frac{T_{min}+T_{max}}{2}=T \rightarrow 1.4T_n=\frac{1.2T_n+T_{max}}{2}$$

- And it is found that $T_{max} = 1.6T_n$

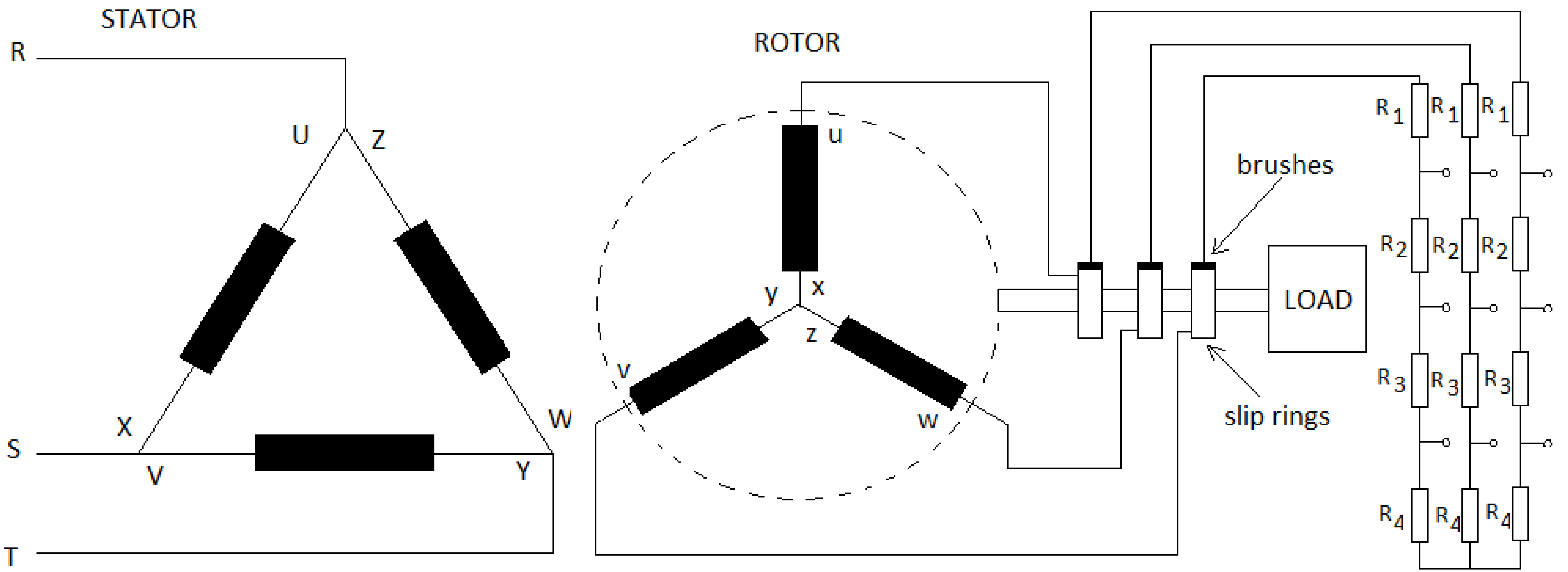
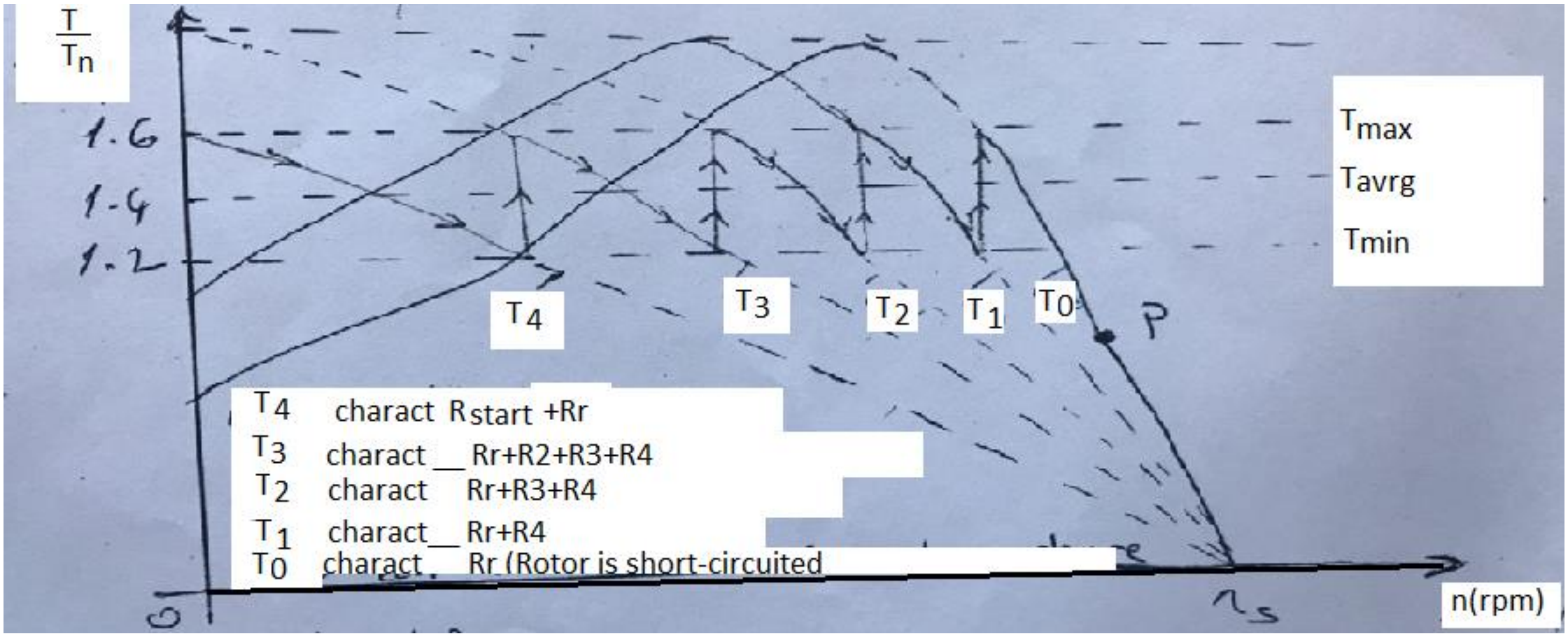



**Figure**: Principle scheme for starting the wound rotor induction motor by introducing extra resistors in series to the rotor windings




- **Figure:** Torque-speed characteristic of the wound rotor induction motor with four-step resistor starting

- The torque at any s slip;

$$T = \frac{R'_R}{s\omega_s} \frac{V_s^2}{[(R_s + R'_R/s)^2 + (X_s + X'_R)^2]}$$

- The torque equation when an extra $R_{start}$ resistor is added to the rotor circuit at starting is;

$$T_{start} = \frac{(R'_R + R'_{start})}{\omega_s} \frac{V_s^2}{[(R_s + R'_R + R'_{start})^2 + (X_s + X'_R)^2]}$$

- If the torque at starting is made equal to the torque with any s slip, $T=T_{start}$. Then,

$$(R'_R + R_{start})^2 > (X_s + X'_R)^2 \; and \; \left(\frac{R'_R}{s}\right)^2 > (X_s + X'_R)^2$$

- is considered. If $R_s$ is taken as zero;

$$\frac{s}{R'_R} = \frac{1}{R'_R + R'_{start}} \rightarrow R'_{start} = \frac{R'_R(1-s)}{s}$$

- Or; $$R_{start} = \frac{R_R(1-s)}{s}$$
- As a result, in order to make the starting torque equal to the torque at any s slip, the above equation must be provided.

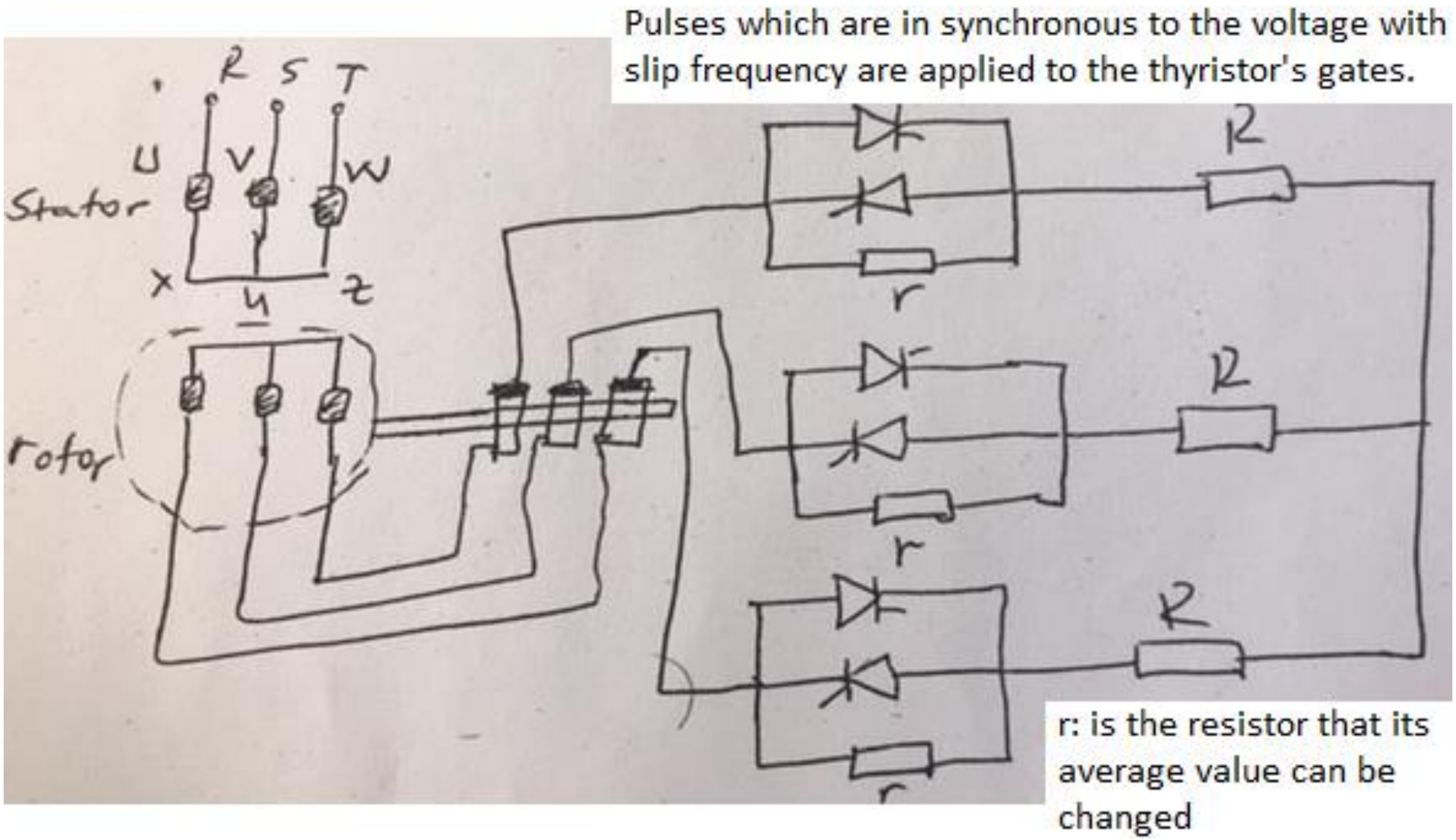
**Example:**

40 HP, wound rotor induction motor has a rotor resistance of $R_R$=0.06 Ω/Phase and its torque at s=0.07 is 1.6 times of the rated torque. Calculate the extra resistance ($R_{start}$) If the starting torque is required to be equal to that at s=0.07.

**Solution:**

$$R_{start} = \frac{0.06(1-0.07)}{0.07} = 0.80\,\Omega/Phase$$

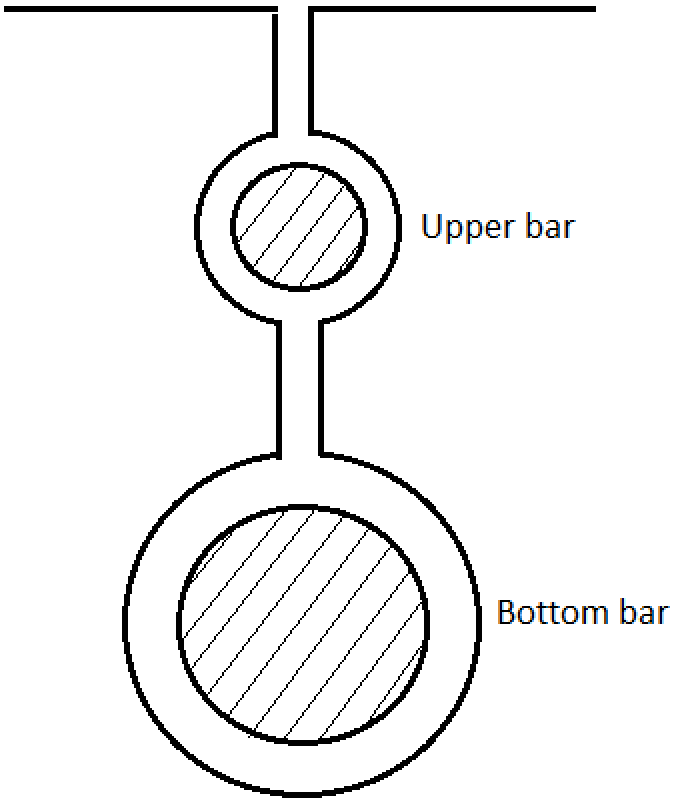
Another technique for starting the wound rotor induction motor is to connect both thyristors and resistors to the rotor circuit.



Here, it is possible to turn-on the thyristors by gate pulses. When the tyristors are off (open circuit), the total resistance connected to the rotor circuit is R+r and when the thyristors are on, the total external resistance is R. Thus, it possible to change the value of resistor connected to the rotor between R and R+r during starting of the motor.

# 6) Starting the motor by using double-cage in the rotor

The starting torque and power factor get bigger with the rotor resistance and the starting current gets smaller. However, increase of the rotor resistance results in low efficiency and it affects the speed control of the motor negatively. In deed, it is desired to have high starting torque and low starting current for induction motors. Double-cage rotor is used to provide these requirements.



As shown above figure, bottom bar is made with big cross-section and upper bar is made with small cross-section. For this reason the bottom cage has low resistance and upper cage has high resistance. At starting, while the bottom cage current is small because of its higher reactance, upper cage current is high because of its lower reactance. Therefore, the resistance of the upper cage is effective during starting providing lower starting current with higher starting torque. At normal operation conditions, since the rotor current frequency is small ($f_R=s*f_{Rstarting}$), the leakage reactance will be small comparing to the $R_R/s$ resistance and the currents flowing through the cages are inversely proportional with resistances. Therefore, after reaching to the normal operation conditions while high currents flow through the bottom cage which has lower resistance, small currents flow through the upper cage.

As can be seen from the figure, the starting torque is high because of the high resistance of the upper cage. The starting torque is low because of the low resistance of the bottom cage. Sum of the torque-speed curves related to the upper and bottom cages gives the torque-speed characteristic of the double-cage induction motor.