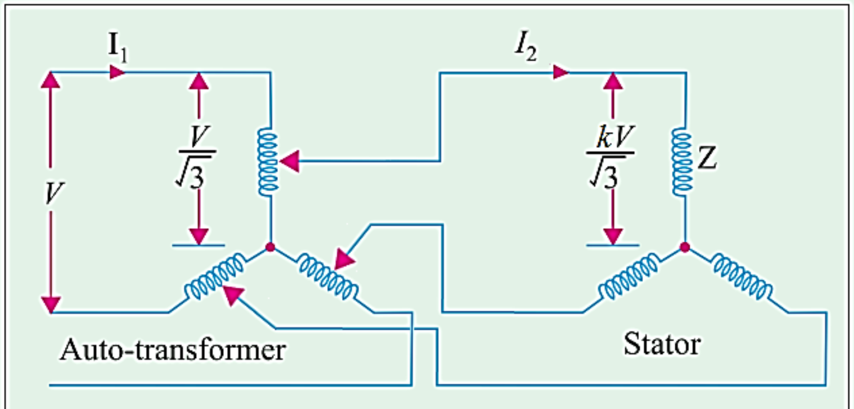
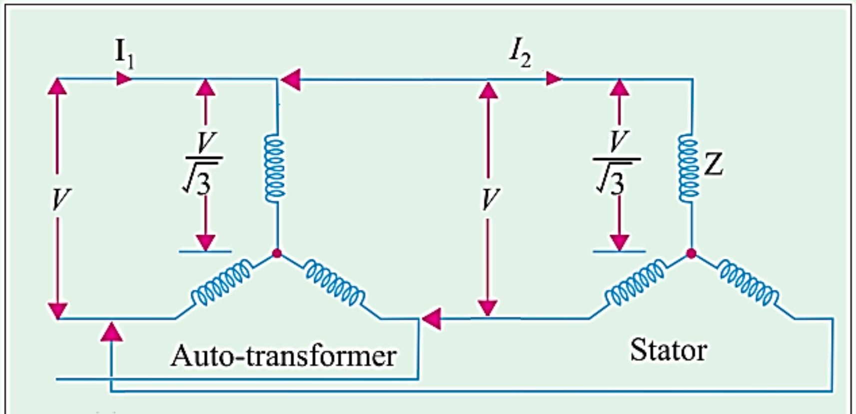
# Autotransformer Starting Method

- This method is known: Reactors or Auto-starter or Compensators
- In this method: in Fig. (a) [Start position] the induction motor connected to a reduced supply voltage (also reduced stator current) at starting and then in Fig. (b) [Run position] the transformer cut out from the circuit and connecting the stator to the full voltage as the motor picks up sufficient speed (about 80% of normal speed).
- The tapping is set 50%:80% of line voltage is applied to the motor.
- $k$ is the transformation ratio of the transformer, $Z$ is the stator impedance per phase, $V$ is the supply rated voltage.



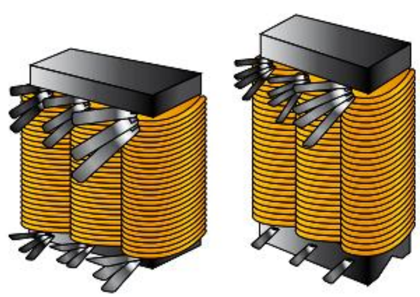
(a) connecting autotransformer in the circuit



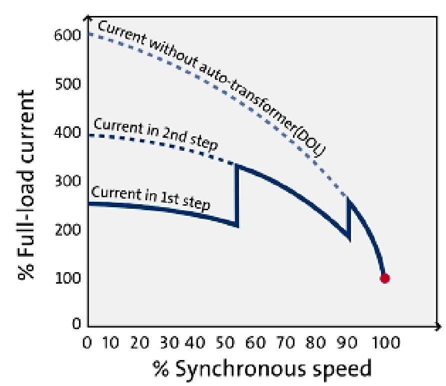
(b) disconnecting autotransformer from the circuit

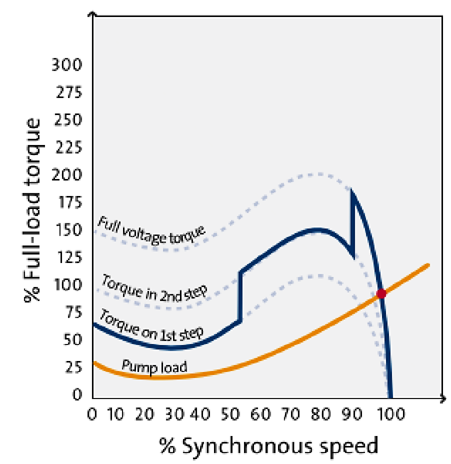
## Autotransformer Starting Method …

- The switching from Start to Run position may be made airbreak circuit breaker (as in small motors) or may be oil-immersed circuit breaker (as in large motors) to reduce sparking.
- Most of the autotransformers are provided with 3-sets of taps, to reduce the voltage to 80, 65, 50% of the line voltage.
- <u>This method has:</u> advantages (low power loss, less radiated heat), disadvantages (low starting current and torque). For large machines (over 25hp) this method is often used. It can be used for both Y and Δ connected motors.



Auto-transformers and Reactors




$$\left(\frac{Voltage_2}{Voltage_1}\right)^2 = \frac{Torque_2}{Torque_1}$$

$$\left(\frac{U_2}{U_1}\right)^2 = \frac{T_2}{T_1}$$

## Relation between $T_{st}$ and $T_{fl}$ for Autotransformer Starting Method

Consider a Y-connected squirrel-cage induction motor.

- If $V$ is the line voltage, then voltage across motor phase on direct switching is ($V/\sqrt{3}$) and starting current is ($I_{st} = I_{sc}$).
- In case of autotransformer, if a tapping of transformation ratio $k$ (a fraction of transformer winding) is used, then the phase voltage across the motor is ($kV/\sqrt{3}$) and ($I_{st} = kI_{sc}$).

$\because I_{st} = k\,I_{sc}$ Then,

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} = k^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}$$

So, we can say that when Autotransformer method is used:

- $Supply\ Line\ Current = k^2 * Short\ Circuit\ Current$
- $[Starting\ Motor\ Line\ Current : I_{st}]_{Autotrans} = k[Starting\ Motor\ Line\ Current : I_{st}]_{DOL}$

  Why? … from. Fig. (a) $I_1 = kI_2 = k^2 I_{sc}$
- $[T_{st}]_{Autotrans} = k^2 [T_{st}]_{DOL}$

**Example 35.10.** *Find the percentage tapping required on an auto-transformer required for a squirrel-cage motor to start the motor against 1/4 of full-load torque. The short-circuit current on normal voltage is 4 times the full-load current and the full-load slip is 3%.*

[answer:

$$\frac{T_{st}}{T_{fl}} = k^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \rightarrow \frac{1}{4} = k^2 \left(\frac{4I_{fl}}{I_{fl}}\right)^2 0.03 \rightarrow k^2 = 0.521 \rightarrow k = 72.2\%$$

**Example 35.12.** *Determine the suitable auto-transformation ratio for starting a 3-phase induction motor with line current not exceeding three times the full-load current. The short-circuit current is 5 times the full-load current and full-load slip is 5%.*

*Estimate also the starting torque in terms of the full-load torque.*

[answer]:

$$Supply\ Line\ Current = k^2.I_{sc} \rightarrow 3I_{fl} = k^2.5I_{sc} \rightarrow k^2 = 0.6 \rightarrow k = 77.5\%$$

$$\frac{T_{st}}{T_{fl}} = k^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} = 0.6 \left(\frac{5I_{fl}}{I_{fl}}\right)^2 0.05 = 75\% \rightarrow T_{st} = 75\% T_{fl}$$

**Example 35.13.** *The full-load slip of a 400-V, 3-phase cage induction motor is 3.5% and with locked rotor, full-load current is circulated when 92 volt is applied between lines. Find necessary tapping on an auto-transformer to limit the starting current to twice the full-load current of the motor. Determine also the starting torque in terms of the full-load torque.*

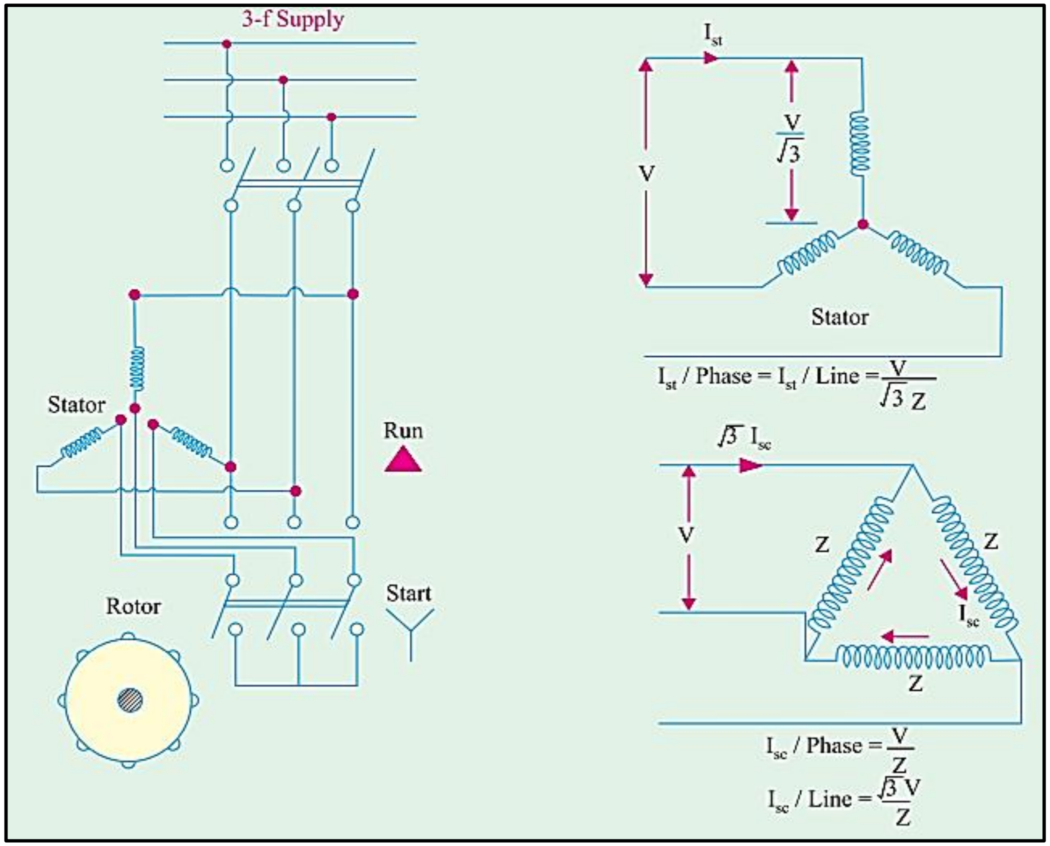
answer:

$$\because I_{sc} = \frac{400}{92} I_{fl}$$

$$I_{st} = k^2 . I_{sc} \rightarrow 2I_{fl} = k^2 . \tfrac{400}{92} I_{fl} \rightarrow k^2 = 0.46 \rightarrow k = 67.8\%$$

$$\frac{T_{st}}{T_{fl}} = k^2 \left( \frac{I_{sc}}{I_{fl}} \right)^2 s_{fl} = 0.46 \left( \frac{400}{92} \right)^2 0.035 = 0.3043 = 30.43 \rightarrow T_{st} = 30.43\% T_{fl}$$

# Star-Delta Starting Method



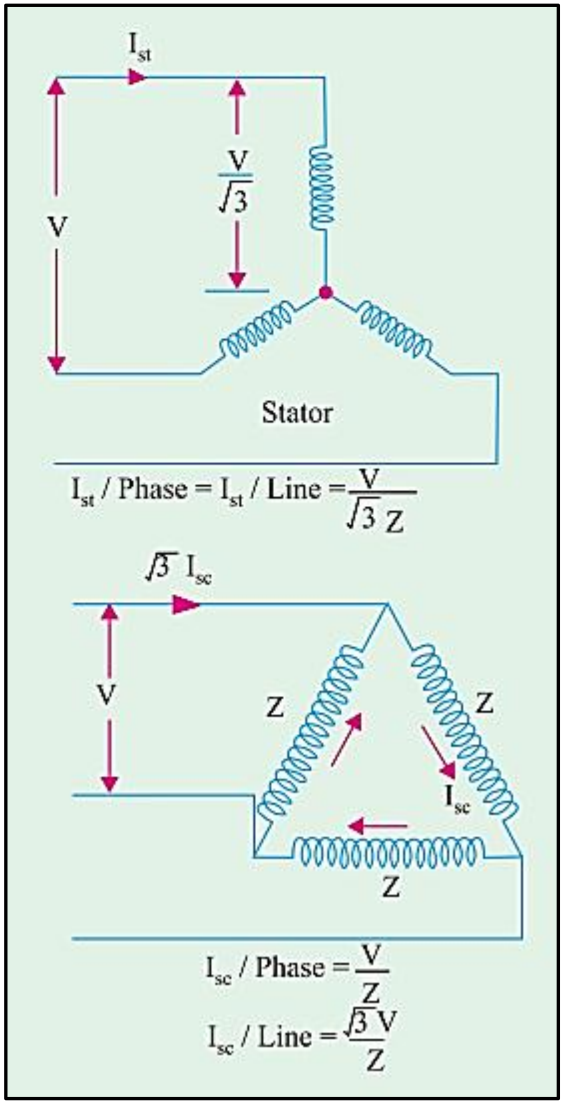

- The stator winding of the motor is designed for Δ operation and is connected in Y during the starting period. When the machine reaches normal speed, the stator connections are changed to Δ. The circuit arrangement for Y-Δ starting is shown in Fig.
- The six leads of the stator windings are connected to the changeover switch as shown. At the instant of starting, the changeover switch is thrown to "Start" position which connects the stator windings in Y. Therefore, each stator phase gets ($V/\sqrt{3}$) where $V$ is the line voltage. This reduces the starting current.
- When the motor picks up speed, the changeover switch is thrown to "Run" position which connects the stator windings in Δ. Now each stator phase gets full line voltage $V$.

# Star-Delta Starting Method …

- Notes:
  - For Y connection: the applied voltage across each motor phase is reduced by ($1/\sqrt{3}$), the line current to ($1/3$) and hence the developed torque reduced by ($1/3$) of that which would have been developed if motor were directly connected as Δ.

$$\text{from equations in figure} : \frac{I_{st(line)_Y}}{I_{st(line)_\Delta}} = \frac{\frac{V}{\sqrt{3}Z}}{\frac{\sqrt{3}V}{Z}} = \frac{1}{3}$$

- Advantages: it is cheap and effective but limited used. (used only when high starting torque is not necessary, e.g. machine tools and pumps up to 25hp).
- Disadvantages: it has less starting torque. The reduction in the voltage is fixed.



# Relation between $T_{st}$ and $T_{fl}$ for Star-Delta Starting Method

- In Δ-connection: From 2nd Figure

  Starting phase current, $I_{sc} = \frac{V}{Z}$

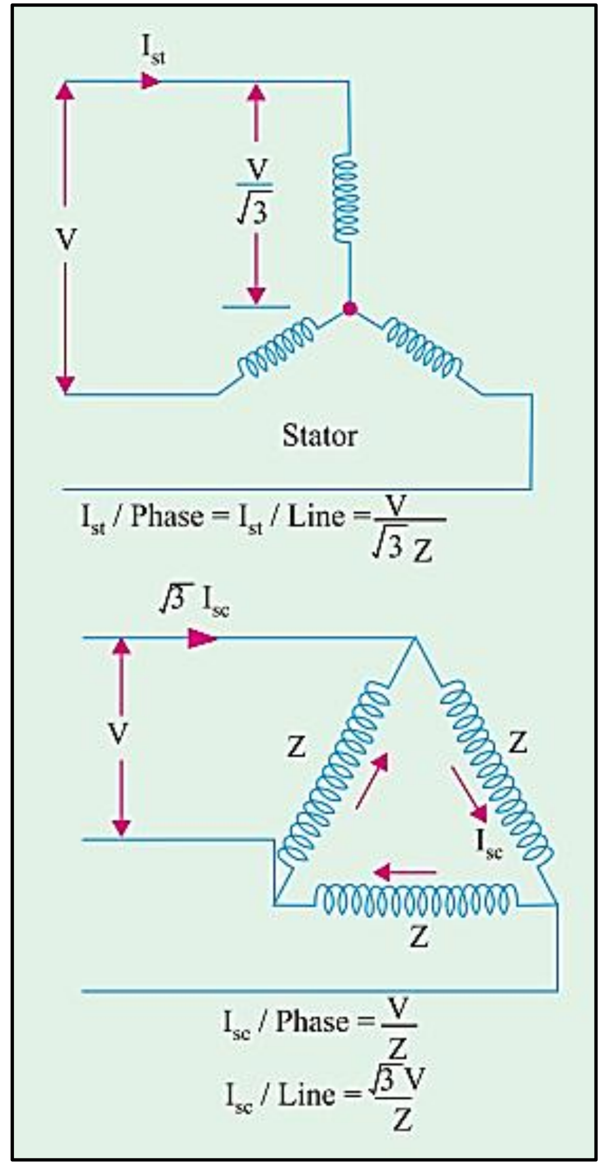
  Starting line current $= \sqrt{3} I_{sc}$

- In Y-connection: From 1st Figure

  Starting phase current, $I_{st} = \frac{\frac{V}{\sqrt{3}}}{Z} = \frac{1}{\sqrt{3}} \frac{V}{Z} = \frac{1}{\sqrt{3}} I_{sc}$

Now, $$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} = \left(\frac{I_{sc}}{\sqrt{3} I_{fl}}\right)^2 s_{fl} = \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}$$

$I_{sc}$ = the starting phase current (Δ connection).
$I_{fl}$ = the full-load phase current (Δ connection).



***Example:*** A 3-phase, Δ-connected, 6-pole, 50 Hz induction motor takes 60A at full-load speed of 940rpm and develops a torque of 150Nm. The starting current at rated voltage is 300A. What is the starting torque value?. If a star/delta starter is used, determine the starting current and starting torque.

## *Answer*

1st part of the problem is direct switching (DOL):

$$\frac{T_{st}}{T_{fl}}=\left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} \;\rightarrow\; \frac{T_{st}}{150}=\left(\frac{300}{60}\right)^2\left(\frac{N_s-N}{N_s}\right) \;\rightarrow\; T_{st}=150\left(\frac{300}{60}\right)^2\left(\frac{\frac{120\times50}{6}-940}{\frac{120\times50}{6}}\right)=225Nm$$

2nd part of the problem is star/delta starter:

$$statring\ current_Y=\frac{1}{3}statring\ current_\Delta \;\rightarrow\; statring\ current_Y=\frac{1}{3}300=100A$$

$$statring\ torque_Y=\frac{1}{3}statring\ torque_\Delta \;\rightarrow\; statring\ torque_Y=\frac{1}{3}225=75Nm$$

**Example 35.16.** *Determine approximately the starting torque of an induction motor in terms of full-load torque when started by means of* **(a)** *a star-delta switch* **(b)** *an auto-transformer with 70.7 % tapping. The short-circuit current of the motor at normal voltage is 6 times the full-load current and the full-load slip is 4%. Neglect the magnetising current.*

## Answer

(a) Star/delta switch:

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} = \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \quad \rightarrow \frac{T_{st}}{T_{fl}} = \frac{1}{3}\left(\frac{6I_{fl}}{I_{fl}}\right)^2 0.04 = 48\%$$

(b) Auto-transformer:

$$\because k = 70.7\% = 0.707$$

$$\frac{T_{st}}{T_{fl}} = k^2\left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl} = k^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl} \quad \rightarrow \frac{T_{st}}{T_{fl}} = (0.707)^2\left(\frac{6I_{fl}}{I_{fl}}\right)^2 0.04 = 72\%$$

**Example 35.17.** *A 15 h.p. (11.2 kW), 3-φ, 6-pole, 50-HZ, 400-V, Δ-connected induction motor runs at 950 r.p.m. on full-load. If it takes 86.4 A on direct starting, find the ratio of starting torque to full-load torque with a star-delta starter. Full-load efficiency and power factor are 88% and 0.85 respectively.*

## *Answer*

**Star/delta switch:**

$$\because \frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_{fl}$$

- $s_{fl} = \dfrac{N_s - N}{N_s} = \dfrac{\frac{120\times 50}{6} - 950}{\frac{120\times 50}{6}} = 0.05$

- $\%\eta_{fl} = \dfrac{P_o}{P_{in}}\ (\Delta - conn.) \rightarrow 88\% = \dfrac{11.2\times 1000}{\sqrt{3}\times 400\times I_{fl(Line)}\times 0.85} \rightarrow I_{fl(Line)} = 21.6A$

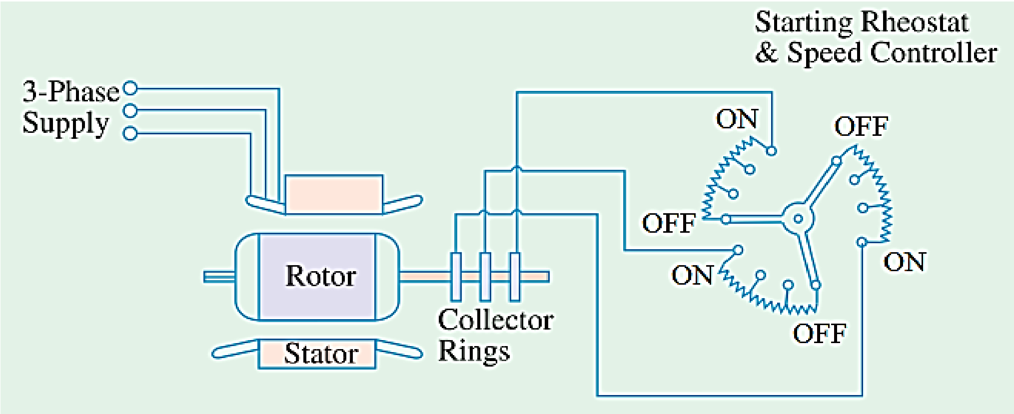
$$\therefore I_{fl(Phase)} = \frac{21.6}{\sqrt{3}} A\ (this\ current\ passes\ in\ \Delta - conn.)$$

- $\because I_{st(Line)_Y} = \frac{1}{3} I_{st(Line)_\Delta} = \frac{1}{3} 86.4 = 28.8A \rightarrow (Y - conn.)\!: I_{st} = I_{st(Phase)_Y} = I_{st(Line)_Y} = 28.8A$

$$\therefore \frac{T_{st}}{T_{fl}} = \left(\frac{28.8}{\frac{21.6}{\sqrt{3}}}\right)^2 0.05 = 26.7\%$$

# Starting in Slip-ring Motor

- Slip-ring motors (wound-rotor type) are started by rotor resistance starting. In this method, a variable star-connected ***rheostat*** is connected in the *rotor* circuit through slip rings and full voltage is applied to the stator winding as shown in Fig.




(i) At starting, the handle of rheostat is set in the OFF position so that maximum resistance is placed in each phase of the rotor circuit. This reduces the starting current, reduces the motor speed and at the same time starting torque (because *pf* is improved) is increased.

(ii) As the motor picks up speed, the handle of rheostat is gradually moved in clockwise direction and cuts out the external (rheostat) resistances in each phase of the rotor circuit. When the motor attains normal speed, the change-over switch is in the ON position and the whole external resistance is cut out from the rotor circuit.

Disadvantages: high losses at starting (due to inserting external resistance to rotor). The motor efficiency is reduced.

# Slip-ring Motors Versus Squirrel-cage Motors

- The slip-ring induction motors have the following advantages over the squirrel cage motors:
  (i) High starting torque with low starting current.
  (ii) Smooth acceleration under heavy loads.
  (iii) No abnormal heating during starting.
  (iv) Good running Ch/s after external rotor resistances are cut out.
  (v) Adjustable speed.

- The disadvantages of slip-ring motors are:
  (i) The initial and maintenance costs are greater than those of squirrel cage motors.
  (ii) The speed regulation is poor when run with resistance in the rotor circuit.

# Induction Motor Rating

- The nameplate of a 3-phase induction motor provides the following information:
    - (i) Horsepower
    - (ii) Line voltage
    - (iii) Line current
    - (iv) Speed
    - (v) Frequency
    - (vi) Temperature rise

- The horsepower rating is the mechanical output of the motor when it is operated at rated line voltage, rated frequency and rated speed. Under these conditions, the line current that on the nameplate will pass, whilst the temperature rise does not exceed that on the nameplate.
- The speed given on the nameplate is the actual speed of the motor at rated full-load; *it is not the synchronous speed*.

# Testing Methods of 3~ph Induction Motor to Determine its Parameters