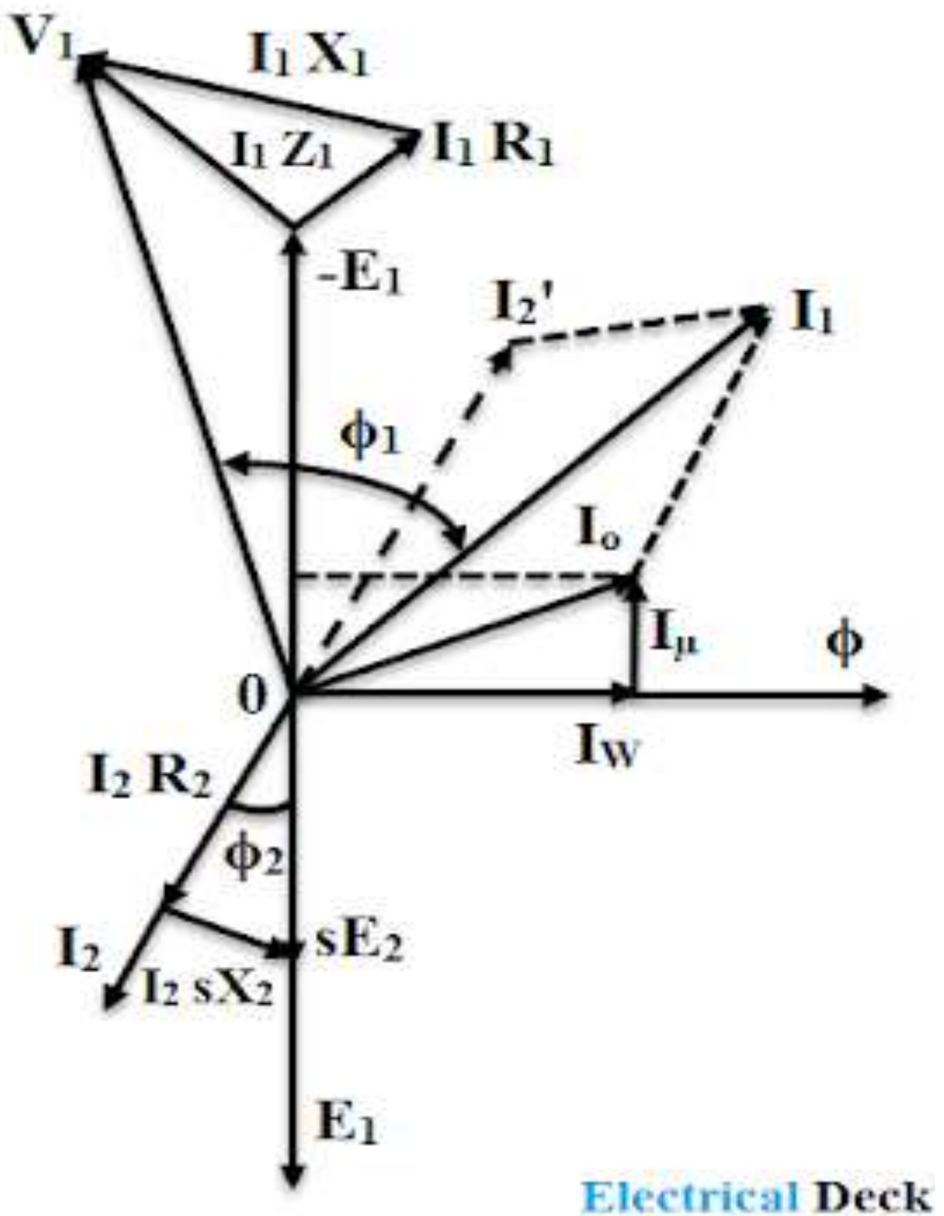
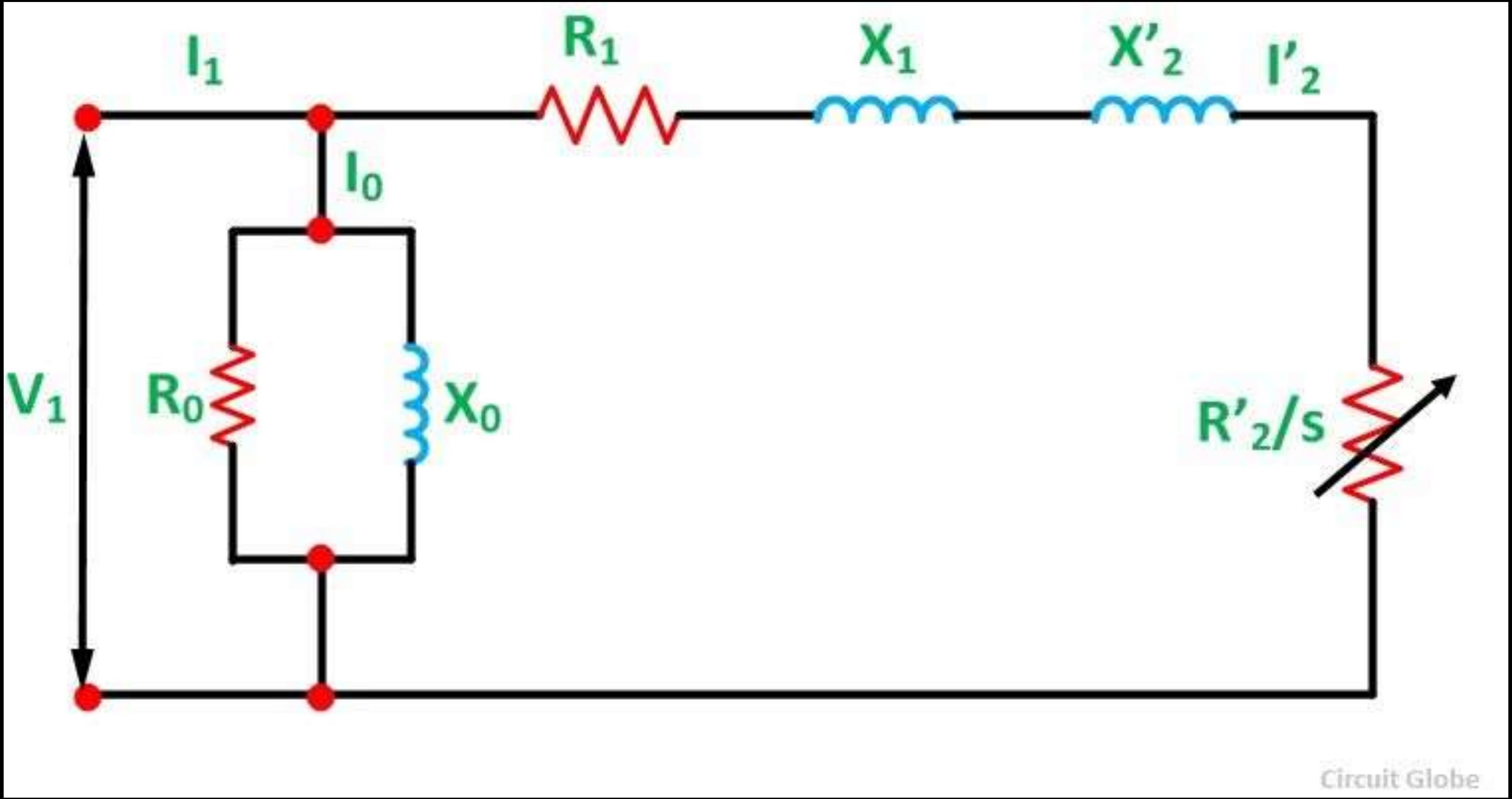
Module-3

Performance of Three-Phase Induction Motor:

- Phasor diagram of induction motor on no-load and on load,
- equivalent circuit, losses, efficiency,
- No-load and blocked rotor tests.
- Performance of the motor from the circle diagram and equivalent circuit.
- Cogging and crawling.
- High torque rotors-double cage and deep rotor bars.
- Equivalent circuit and performance evaluation of double cage induction motor.
- Induction motor working as induction generator.

Phasor diagram of induction motor on load

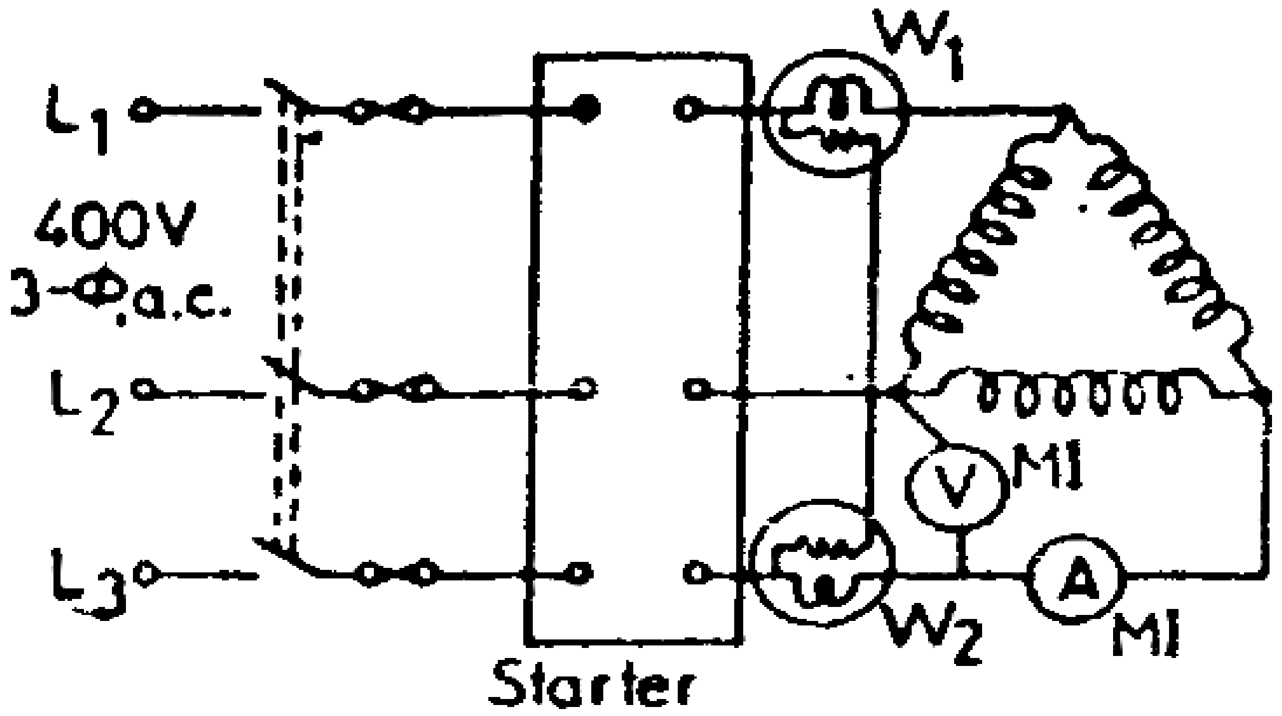



I1
I0
R1
X1
X'2
I'2
V1
R0
X0
R'2/s
Circuit Globe

CIRCUIT DIAGRAM

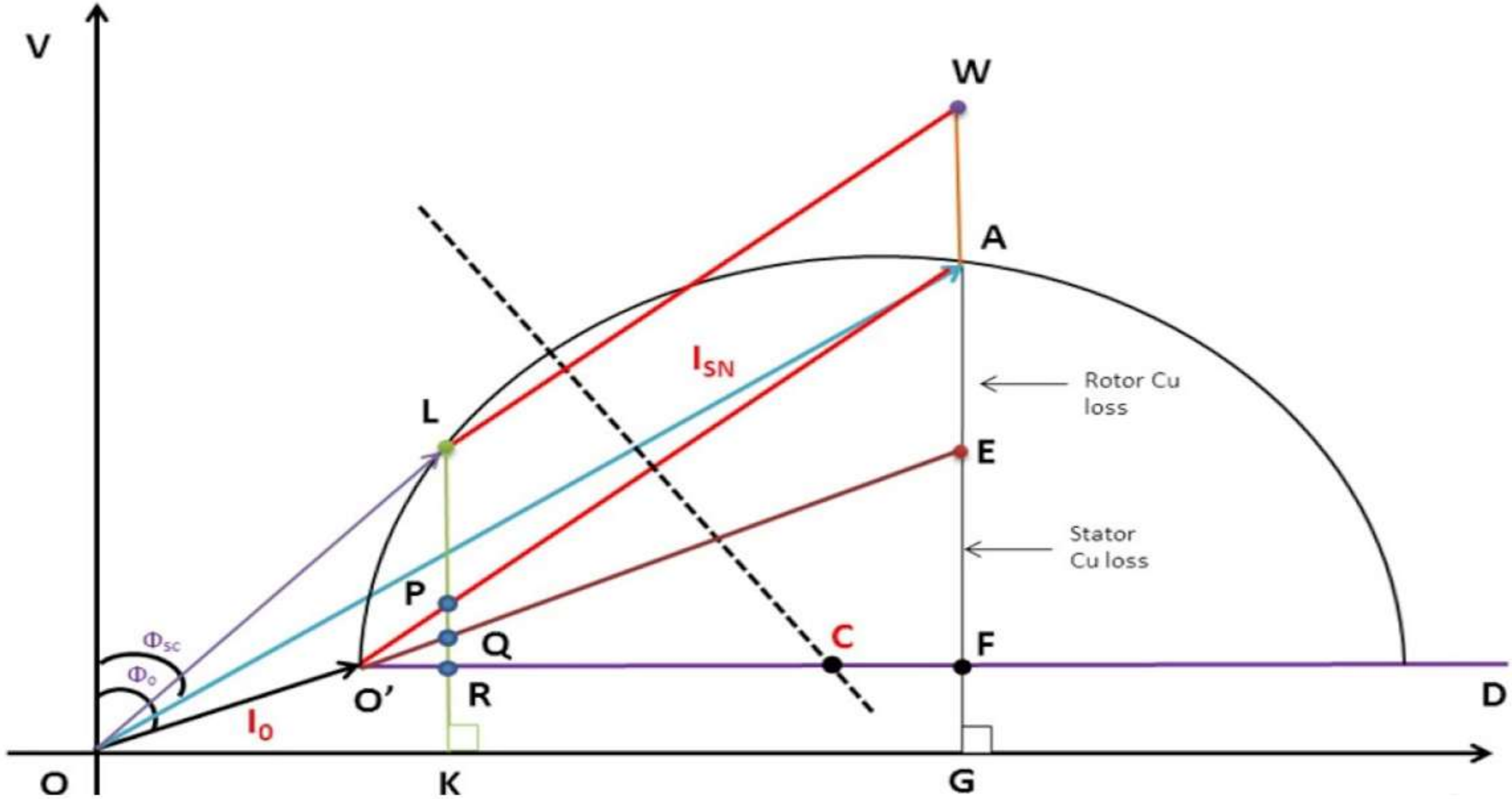
Circuit shown as per attached sheet for NO LOAD & BLOCKED ROTOR Test. To obtain more reliable values range of both the wattmeter should be 2.5 A, 500 V for NO LOAD Test. Where as it should be 5 A, 300 V for BLOCK ROTOR Test. Similarly the range of Ammeter and Voltmeter during No Load Test should be 5 A, 500 V while 10 A, 250 V for Block Rotor Test.

FOR NO-LOAD TEST



STEPS FOR PERFORMING NO LOAD TEST :

1. Connect the circuit as per diagram shown on attached sheet.
2. Ensure Motor is unloaded and the Variac is set at zero position.
3. Switch on the 3 phase A.C. supply and gradually increase the voltage through variac till its rated value. Thus the Motor is running at rated speed under NO LOAD condition.
4. Record the readings of all the meters connected in the circuit and tabulate observation. Calculate the power input and power factor for each reading. Plot characteristic of quantities as indicated in figure ‘A’.



V
W
A
I_{SN}
Rotor Cu loss
L
E
Stator Cu loss
P
Φ_{sc}
C
F
Q
Φ_0
O'
R
D
I_0
O
K
G

SAMPLE CALCULATION

A sample calculation is reproduced here below for drawing a circle diagram of a three phase induction motor on the basis of which circle diagram for any rating of induction machine can be drawn :-

Example : A 400 V, 40 hp, 50 Hz, 4 pole delta-connected induction motor gave the following test data.

No-load test : 400 V, 20 A, 1200 W
Blocked-rotor test : 100 V, 45 A, 2800 W

Draw the circle diagram and determine

(a) the line current and power factor rated output;
(b) the maximum output;
(c) the maximum torque;
(d) the full-load efficiency;
(e) the full-load rotor speed;

Assume stator and rotor I^2R-losses to be equal at standstill.

The test data given are assumed to be of line values.

$$\text{No-load power factor, } \cos \phi_0 = \frac{W_O}{\sqrt{3}\ V_1 I_O}$$

$$= \frac{1200}{1.732 \times 400 \times 200}$$

$$\cos \phi_0 = 0.0866$$

$$\phi_0 = 85^{O}$$

Similarly, power factor under blocked-rotor condition,

$$\cos \phi_S = \frac{2800}{1.732 \times 100 \times 45} \qquad = 0.359$$

$$\phi_S = 69^{O}$$

Input current and input power at blocked rotor condition are at a reduced voltage of 100 V. these quantities are to be converted into rated voltage of 400 V.
Thus,

Input current at blocked-rotor condition at 400 V

$$= 45 \times \frac{400}{100} = 180 \text{ A}$$

$$= 45 \times \frac{400}{100} = 180 \text{ A}$$

Input power at blocked-rotor condition at 400 V

$$= 2800\left[\frac{400}{100}\right]^2 = 44800 \text{ W}$$

Input power at no-load at 400 V = 1200 W

Let us now choose a convenient current scale of

1 cm = 10 A

The circle diagram shown in Fig. 'F' is constructed through the following steps:

Represent voltage V on the vertical axis. Draw a horizontal line OE from O. Since current scale is 1 cm = 10 A, no-load current of 20 A is equivalent to 2 cm. No-load power factor angle is 85°. Thus, represent no-load current by the vector OC whose length is 2 cm and is lagging the vertical voltage axis by 85°.

Similarly, represent the input current of 180 A under blocked rotor condition by a vector CD of 18 cm length and lagging voltage vector by 69°.

Draw a horizontal line CF from C parallel to the line OE. Join OD. Draw a perpendicular bisector from CD to cut the horizontal line CF at Q. With Q as centre and QC as redius draw a semicircle. From D on the semicircle draw a vertical line DM on the horizontal axis. DM cuts CF at N such that NM = CL. Since stator and rotor I^2R-losses are assumed to be equal, divide DN at R and join CR. Now CD represents the output line and CR represents the torque line.

In the circle diagram, length DM represents input at blocked-rotor condition, such that

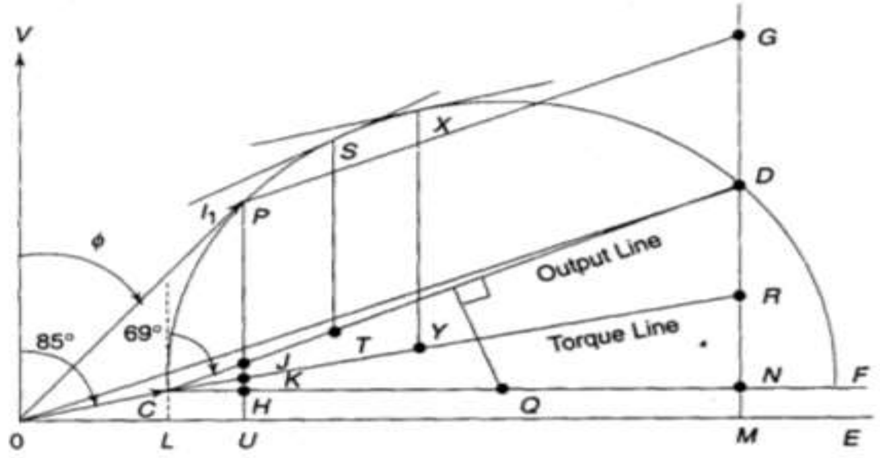
$$DM = 44800 \text{ W}$$

$$DM = 6.8 \text{ cm}$$

From this,

$$1 \text{ cm} = \frac{44800}{6.8} = 6588 \text{ W}$$

which is the power scale for the circle diagram.



Now, full load output of the motor $= 40$ hp

$$= 40 \times 735.5$$

$$= 29420 \text{ W}$$

On the power scale 29420 W represent $= \dfrac{29420}{6588}$ 4.46 cm

JP represent 4.46 cm above the output line. To locate the position of JP we may raise the vertical line MD and cut 4.46 cm from it. DG is 4.46 cm in the figure. Now draw a line from G parallel to the output line CD to cut the circle at P. From P drop a vertical line PJ onto the output line. OP represents the full load input current.

Full load current, $OP = 6.1 \text{ cm} \times 10 \text{ A}$

Input line current at full load $= 61$ A

Power factor all full load

$$\cos\phi = \cos 34^{\circ}$$

$$= 0.829$$

Input power, W_S under blocked rotor condition is wasted as I^2 R-loss in the stator and rotor. The stator circuit resistance can be measured as follows :

$$\text{Stator Cu-loss} = 3\, I^2_1 R_1$$

$$\text{Rotor } I^2 \text{ R-loss} = W_S - 3\, I^2_1 R_1$$

Therefore, for squirrel-cage motors,

$$\frac{RN}{RD} = \frac{3\, I^2_1 R_1}{W_S - 3\, I^2_1 R_1}$$

For slip ring motors, resistance R_1 and R_2 can be determined and the ratio

$$\frac{RN}{RD} = \frac{I^2_1 R_1}{I^2_2 R_2} = \frac{R_1}{R_2}\left[\frac{I_1}{I_2}\right]^2$$

$$\text{Input} = \text{PU in cm x power scale}$$
$$= 5.1 \times 6488 \text{ W}$$

$$\text{Output} = \text{PJ in cm x power scale}$$
$$= 4.46 \times 6488 \text{ W}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{PJ}}{\text{PU}} = \frac{4.46}{5.1}$$
$$= 0.874 = 87.4\ \%$$

To determine the maximum output, draw a line parallel to the output line, tangent to the semicircle at point S. the vertical distance ST represents the maximum output.

In this case ST measures 6.7 cm
Using power scale of 1 cm = 6588 W

$$\text{Maximum output} = 6.7 \times 6588 \text{ W}$$

$$= 60 \text{ hp}$$

To determine the maximum torque, draw a line parallel to the torque line, tangent to the circle at point X. the vertical distance XY represents the maximum torque. In this case XY is 8.1 cm. Using power scale, maximum torque = 6588 x 8.1 Syn. W = 53363 Syn. W.

To determine full load rotor speed we can use the relation

$$\text{Rotor } I^2R\text{-loss} = \text{Slip} \times \text{Rotor input}$$

To determine full load rotor speed we can use the relation

$$\text{Rotor } I^2R\text{-loss} = \text{Slip x Rotor input}$$

At full-load rotor I^2R-loss is represented by the distance JK which is equal to 0,3 cm. Rotor input is represented by PK and is equal to 4.65 cm.

thus, $$\text{slip } S = \frac{0.3}{4.65} = 0.0646$$

Synchronous speed,

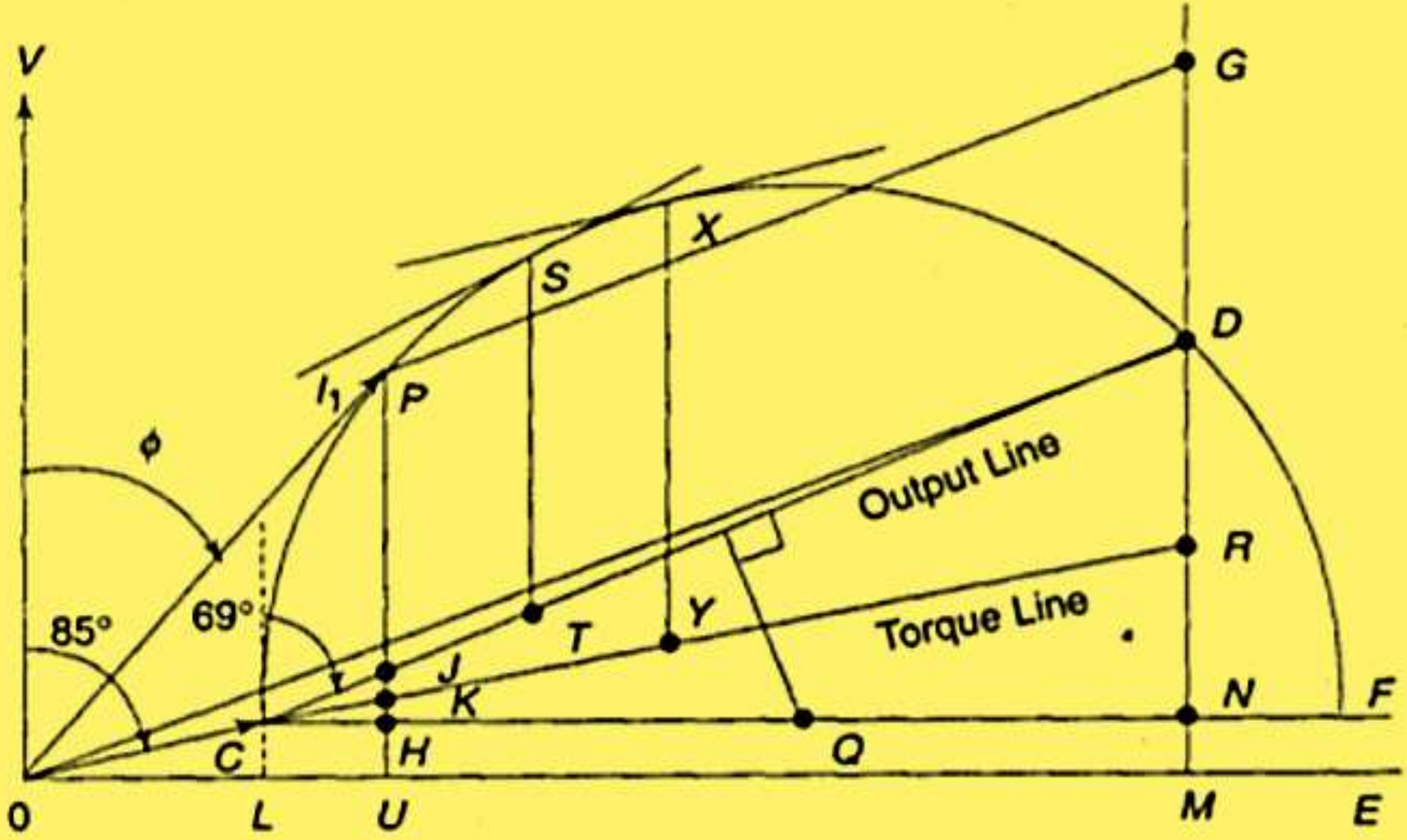
$$N_S = \frac{120f}{P} = \frac{120 \text{ x } 50}{4}$$
$$= 1500 \text{ rpm}$$

Slip, $$S = \frac{N_S - N_r}{N_S}$$

or $$0.0646 = \frac{1500 - N_r}{1500}$$

Therefore, rotor speed at full-load

$$N_r = 1403 \text{ rpm}$$


V
G
X
S
D
I_1
P
ϕ
Output Line
R
69°
Y
85°
T
Torque Line
J
K
N
F
C
H
Q
0
L
U
M
E

Example 4.9.6 A 15 HP, 400 V, 50 Hz, 3-phase, 4 pole delta connected induction motor gave the following test results.

No load test : 400 V, 8 A, 1000 watts ; blocked rotor test : 100 V, 25 A, 1750 watts

Construct the circle diagram and estimate i) Full load current and power factor ii) Maximum possible power output iii) Best possible operating power factor.

VTU : Sept.-2000, June-10, Dec.-10, July-14, Marks 12

Solution : From no load test, $V_0 = 400$ V, $I_0 = 8$ A, $W_0 = 1000$ W

$$\therefore \quad \cos\phi_0 = \frac{W_0}{\sqrt{3}\, V_0\, I_0} = 0.1804 \quad \text{i.e. } \phi_0 = 79.6^\circ$$

From blocked rotor test, $V_{sc} = 100$ V, $I_{sc} = 25$ A, $W_{sc} = 1750$ W

$$\therefore \quad \cos\phi_{sc} = \frac{W_{sc}}{\sqrt{3}\, V_{sc}\, I_{sc}} = 0.4041 \quad \text{i.e. } \phi_{sc} = 66.1^\circ$$

$$I_{SN} = \left(\frac{I_{sc}}{\sqrt{3}}\right) \times \left(\frac{V_L}{V_{sc}}\right) = \frac{25}{\sqrt{3}} \times \frac{400}{100} = 57.735 \text{ A (per phase)}$$

Note that as motor is delta connected, $I_{ph} = \dfrac{I_L}{\sqrt{3}}$.

$$W_{SN} = W_{sc}\left(\frac{I_{SN}}{I_{sc}}\right)^2 = 1750 \times \left(\frac{57.735}{25/\sqrt{3}}\right)^2 = 28000 \text{ W}$$

Example 4.9.7 A 415 V, 29.84 kW, 50 Hz, delta connected motor gave the following test data

No-load test : 415 V, 21 A, 1250 W

Blocked rotor test : 100 V, 45 A, 2730 W

Construct the circle diagram and determine i) Line current and power factor for rated output ii) The maximum torque. Assume stator and rotor copper losses are equal at standstill.

VTU : July-07, 11, Jan.-14, Marks 12

Solution : From no load test,

$$\cos\phi_0 = \frac{W_0}{\sqrt{3}\,V_0 I_0} = \frac{1250}{\sqrt{3}\times 415\times 21} = 0.082 \quad \text{i.e.} \quad \phi_0 = 85.25^\circ$$

From blocked rotor test,

$$\cos\phi_{sc} = \frac{W_{sc}}{\sqrt{3}\,V_{sc} I_{sc}} = \frac{2730}{\sqrt{3}\times 100\times 45} = 0.3502 \quad \text{i.e.} \quad \phi_{sc} = 69.49^\circ$$

$$I_{SN} = I_{sc}\left(\frac{V_L}{V_{sc}}\right) = \frac{45}{\sqrt{3}}\left(\frac{415}{100}\right) = 107.82 \text{ A}$$

Note that for delta connected motor,

$$I_{ph} = \frac{I_L}{\sqrt{3}}$$

$$W_{SN} = W_{sc}\left(\frac{I_{SN}}{I_{sc}}\right)^2 = 2730\left(\frac{107.82}{45/\sqrt{3}}\right)^2 = 47017.425 \text{ W}$$

Choose current scale as 1 cm = 8 A hence $I_0 = \frac{21}{\sqrt{3}}$ A is 1.515 cm and I_{SN} is 13.478 cm

Draw the circle diagram using normal steps as shown in the Fig. 8.36. From the circle diagram,

$$l\,(AD) = 4.703 \text{ cm}$$

$$\therefore \quad \text{Power scale} = \frac{W_{SN}}{l\,(AD)} = \frac{47017.425}{4.703} = 9997.3261 \text{ W/cm}$$

As stator and rotor copper losses are equal, E is midpoint of AF.

According to the power scale, for rated output,

$$l\,(AA') = \frac{29.84 \times 10^3}{9997.3261} = 2.985 \text{ cm}$$

Draw parallel to the output line O'A from A to meet the circle at P. P is full load point.

i) Line current = l (OP) × current scale × $\sqrt{3}$ = 4.29 cm × 8 × $\sqrt{3}$ = 59.44 A

Power factor = cos (ϕ) = cos (35°) = 0.819 lagging

Problems on circle diagram

Example 4.9.1 Draw the circle diagram for a 20 HP, 50 Hz, 3 phase, star connected induction motor with the following data.

No load test : 400 V, 9 A, 0.2 p.f. lagging

Blocked rotor test : 200 V, 50 A, 0.4 p.f. lagging

Determine the line current, efficiency and slip for full load condition from the circle diagram.

VTU : July-12, Marks 14

Solution : From no load test, $\cos\phi_0 = 0.2$, $\phi_0 = 78.46°$

From S.C. or blocked rotor test, $\cos\phi_{sc} = 0.4$, $\phi_{sc} = 66.42°$ $I_{sc} = 50$ A

$$I_{SN} = I_{sc}\left(\frac{V_L}{V_{sc}}\right) = 50\left(\frac{400}{200}\right) = 100 \text{ A}$$

$$W_{sc} = \sqrt{3}\, V_{sc} I_{sc} \cos\phi_{sc} = \sqrt{3} \times 200 \times 50 \times 0.4 = 6928.203 \text{ W}$$

$$W_{SN} = W_{sc}\left(\frac{I_{SN}}{I_{sc}}\right)^2 = 27712.81 \text{ W}$$

or $$W_{SN} = \sqrt{3}\, V_L I_{SN} \cos\phi_{sc} = \sqrt{3} \times 400 \times 100 \times 0.4 = 27712.81 \text{ W}$$

Choose current scale say 1 cm = 5 A

1. Draw vector $OO' = I_0 = 9$ A i.e. 1.8 cm as per scale at an angle of 78.46° w.r.t voltage axis.
2. Draw horizontal line from O′ parallel to X-axis.
3. Draw vector $OA = I_{SN} = 100$ A i.e. 20 cm as per scale at an angle of 66.4° with respect to voltage axis.
4. Join O′A, this is output line.
5. Draw perpendicular bisector of O′A to meet horizontal line drawn from O′ at point C. This is centre of circle.
6. With C as centre and CO′ as radius draw semicircle to meet horizontal line from O′ at point B.
7. Draw perpendicular from A on the X-axis to meet it at D.

$$l\,(AD) = 8.2 \text{ cm} = W_{SN}$$

$$\therefore \quad \text{Power scale} = \frac{W_{SN}}{l\,(AD)} = \frac{27712.81}{8.2} = \underline{3379.61 \text{ W/cm}}.$$

8. Full load output is 20 HP i.e. $20 \times 735.5 = \underline{14710 \text{ W}}$

As per scale, full load output $= \frac{14710}{3379.61} = 4.35$ cm

Draw AA′ such that AA′ = 4.35 cm to locate full load point.

9. Draw parallel to the output line from A′ to meet circle at point P. This is full load point.

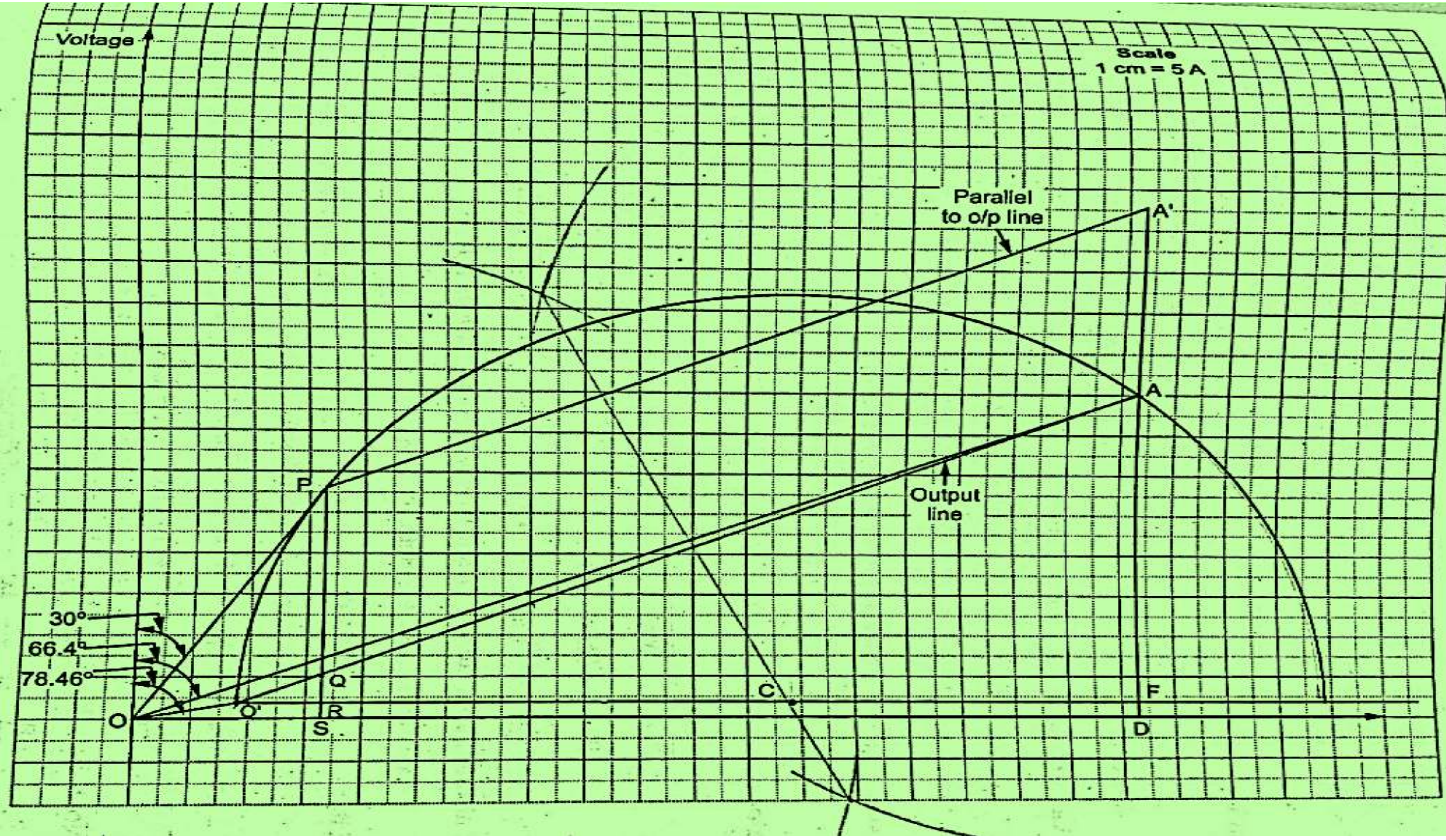
$$\therefore \quad l\,(OP) = \text{Full load line current} = 6 \text{ cm} = 6 \times 5 = 30 \text{ A}$$

$$\text{p.f.} = \cos\,(\text{angle made by OP with voltage axis}) = \cos(30^\circ) = 0.866 \text{ lag}$$

10. Draw vertical line from P to intersect output line at Q, base line at R and X-axis at S.

$$\text{Efficiency, } \eta = \frac{\text{Output}}{\text{Input}} \times 100 = \frac{PQ}{PS} \times 100 = \frac{4.20}{5.2} \times 100 = 80.75\ \%$$

$$\text{Slip} = \frac{QR}{PR} = 10.4\ \%$$



Voltage
Scale
1 cm = 5 A
Parallel
to o/p line
A'
A
P
Output
line
30°
66.4°
78.46°
Q
C
F
O
O'
R
S
D

Example 4.9.4 *Draw the circle diagram for a 5.5 kW, 400 V, 3-phase, 50 Hz, 4-pole slip ring induction motor from the test data given below (line values) :*

No load test : 400 V, 6 A, 0.085 p.f. lag

Blocked rotor test : 100 V, 12 A, 700 W

The ratio of primary to secondary turns is 2.6, stator resistance per phase is 0.67 Ω and that of rotor is 0.18 Ω. Calculate;

i) Full load current ii) Full load slip iii) Ratio of maximum torque to full load torque iv) Starting torque.

Solution : From no load test, $I_0 = 6$ A, $\cos\phi_0 = 0.085$, $\phi_0 = 85.12°$

From S.C. test, $I_{sc} = 12$ A, $V_{sc} = 100$ V, $W_{sc} = 700$ W

$$\therefore \quad \cos\phi_{sc} = \frac{W_{sc}}{\sqrt{3}\,V_{sc}I_{sc}} = 0.3367 \qquad \text{i.e.} \quad \phi_{sc} = 70.3^\circ$$

$$I_{SN} = I_{sc}\left(\frac{V_L}{V_{sc}}\right) = 12 \times \left(\frac{400}{100}\right) = 48 \text{ A}$$

and $$W_{SN} = W_{sc}\left(\frac{I_{SN}}{I_{sc}}\right)^2 = 700 \times \left(\frac{48}{12}\right)^2 = 11200 \text{ W}$$

Choose current scale as 1 cm = 3 A

Draw the circle diagram with regular steps as used for the previous problems.

$$\therefore \quad l(AD) = 5.55 \text{ cm} = W_{SN}$$

$$\therefore \quad \text{Power scale} = \frac{W_{SN}}{l(AD)} = \frac{11200}{5.55 \text{ cm}} = 2018.01 \text{ W/cm}$$

The circle diagram is shown in the Fig. 4.9.5 on the next page.

To locate point E to get torque line use,

$$\frac{AE}{EF} = \frac{R_2'}{R_1}$$

Now $$R_2 = 0.18\ \Omega \quad \text{and} \quad R_1 = 0.67\ \Omega \text{ while } K = \frac{1}{2.6}$$

$$\therefore \quad R_2' = \frac{R_2}{K^2} = \frac{0.18}{(1/2.6)^2} = 1.2168\ \Omega$$

$$\therefore \quad \frac{AE}{EF} = \frac{1.2168}{0.67} = 1.8161 = \frac{\text{Rotor copper loss}}{\text{Stator copper loss}}$$

$$\therefore \quad AF = AE + EF = AE + \frac{AE}{1.8161}$$

$$\therefore \quad AF = AE\,(1.5506) \quad \text{i.e.} \quad \frac{AE}{AF} = 0.644 \quad \text{i.e.} \quad AE = 0.644\ AF$$

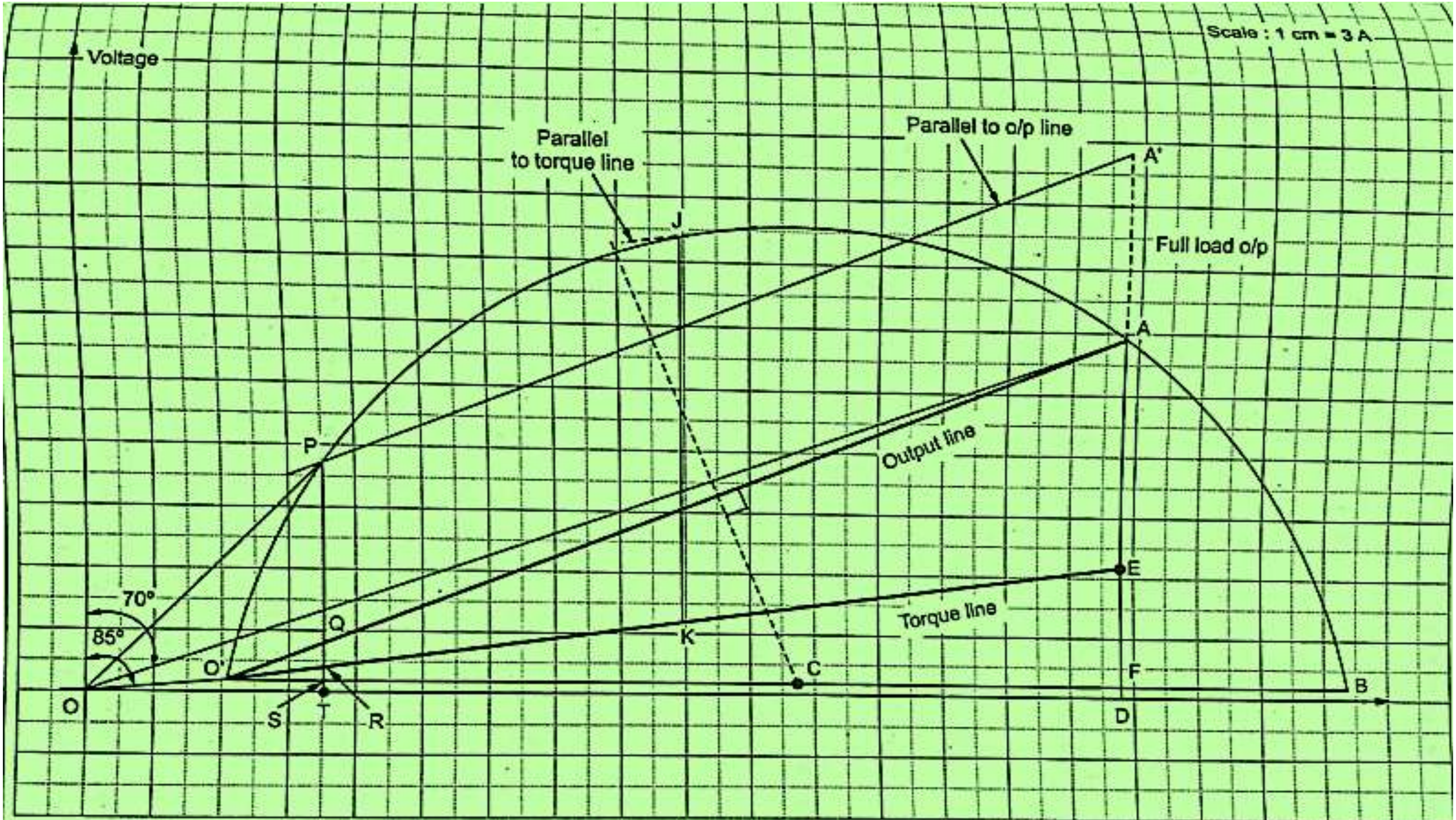
Now $l(AF) = 5.45$ cm hence $l(AE) = 0.644 \times 5.45 = 3.5$ cm

Full load output = 5.5 kW

∴ Draw line AA′ equal to full load output to the scale.

$$\therefore \quad l(AA') = \frac{5.5 \times 10^3}{2018.01} = 2.73 \text{ cm}$$

Draw parallel to the output line from A′ to meet circle at P. This is the required full load point.



Scale : 1 cm = 3 A
Voltage
Parallel
to torque line
Parallel to o/p line
A'
J
Full load o/p
A
P
Output line
E
70°
85°
Q
Torque line
K
O'
C
F
O
S
T
R
D
B

The full load current is,

i) $$l(OP) = 4.5\ \text{cm} \times 3A = \mathbf{13.5\ A}$$

ii) $$\text{Full load slip} = \frac{QR}{PR} = \frac{0.2\text{cm}}{2.9\ \text{cm}} = 0.068 \text{ i.e. } \mathbf{6.8\ \%}$$

iii) For maximum torque, draw line parallel to the torque line and tangential to the circle at point J. l(JK) represents maximum torque while l(PR) represents full load torque

$$\therefore \quad \frac{T_{max}}{T_{F.L.}} = \frac{l(JK)}{l(PR)} = \frac{5.7\text{cm}}{2.9\ \text{cm}} = \mathbf{1.965}$$

iv) $$T_{start} = l(AE) \times \text{power scale} \quad \text{in syn. watts}$$

$$= 3.5 \times 2018.01 = 7063.035 \text{ syn. watts}$$

$$N_s = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$\therefore \quad T_{start} = \frac{T_{start} \text{ in syn. watts}}{\left(\frac{2\pi N_S}{60}\right)} \text{ in N-m} = \frac{7063.035}{\left(\frac{2\pi \times 1500}{60}\right)} = \mathbf{44.96\ N\text{-}m}$$

Crawling of Induction Motor

- It has been observed that squirrel cage type induction motor has a tendency to run at very low speed compared to its synchronous speed, this phenomenon is known as crawling.
- The resultant speed is nearly 1/7th of its synchronous speed.
- Now the question arises why this happens? This action is due to the fact that harmonics fluxes produced in the gap of the stator winding of odd harmonics like 3rd, 5th, 7th etc.
- These harmonics create additional torque fields in addition to the synchronous torque.

- The torque produced by these harmonics rotates in the forward or backward direction at Ns/3, Ns/5, Ns/7 speed respectively.
- Here we consider only 5th and 7th harmonics and rest are neglected.
- The torque produced by the 5th harmonic rotates in the backward direction.
- <u>This torque produced by fifth harmonic which works as a braking action is small in quantity, so it can be neglected</u>.
- Now the seventh harmonic produces a <u>forward rotating torque</u> at synchronous speed Ns/7. Hence, the net forward torque is equal to the sum of the torque produced by 7th

- The torque produced by 7th harmonic reaches its maximum positive value just below 1/7 of Ns and at this point slip is high.
- At this stage motor does not reach up to its normal speed and continue to rotate at a speed which is much lower than its normal speed.
- This causes crawling of the motor at just below 1/7 synchronous speed and creates the racket.
- The other speed at which motor crawls is 1/13 of synchronous speed.

- Torque proportional to the square of the applied voltage

$$(T \propto V_1^2).$$

- Hence synchronous crawling may be observed which absent under rated voltage conditions.
- Thus asynchronous harmonic torques cannot be avoided but can be reduced by proper choice of *coil span and by skewing the stator and rotor slots.*
- The synchronous Harmonic torques can be totally eliminated by proper combination of stator and rotor slots.

noise.

4.11.2 Cogging

A special behaviour is shown by squirrel cage induction motor during starting for certain combinations of number of stator and rotor slots. If number of stator slots S_1 are equal to number of rotor slots S_2 or integral multiple of rotor slots S_2 then variation of reluctance as a function of space will have pronounced effect producing strong forces than the accelerating torque. Due to this motor fails to start. This phenomenon is called **cogging**. Such combination of stator and rotor slots should be avoided while designing the motor.

Let the slots of stator and rotor be 24. The stator-slotting produces its tooth harmonics of order $\frac{2S_1}{P} \pm 1$ whereas the rotor-slotting produces its tooth harmonics of order $\frac{2S_1}{P} \pm 1$ where S_1 and S_2 are number of stator and rotor slots. The plus sign refers to the harmonic field rotation in the direction of rotor.

Here $S_1 = S_2$ so stator and rotor slot harmonics are same and given by,

Let $$P = 4$$

$$\frac{2 \times 24}{4} \pm 1 = 11 \text{ or } 13$$

The harmonics of order 11 produce backward rotating field for both stator and rotor. The harmonics of order 13 produce forward rotating field.

Cogging of Induction Motor

- This characteristic of induction motor comes into picture when motor refuses to start at all.
- Sometimes it happens because of low supply voltage.
- But the main reason for starting problem in the motor is because of cogging in which the **slots of the stator get locked up with the rotor slots.**
- As we know that there is series of slots in the stator and rotor of the induction motor.
- When the slots of the rotor are equal in number with slots in the stator, they align themselves in such way that both face to each other and at this stage the reluctance of the magnetic path is minimum and motor refuse to start.
- This characteristic of the induction motor is called cogging.

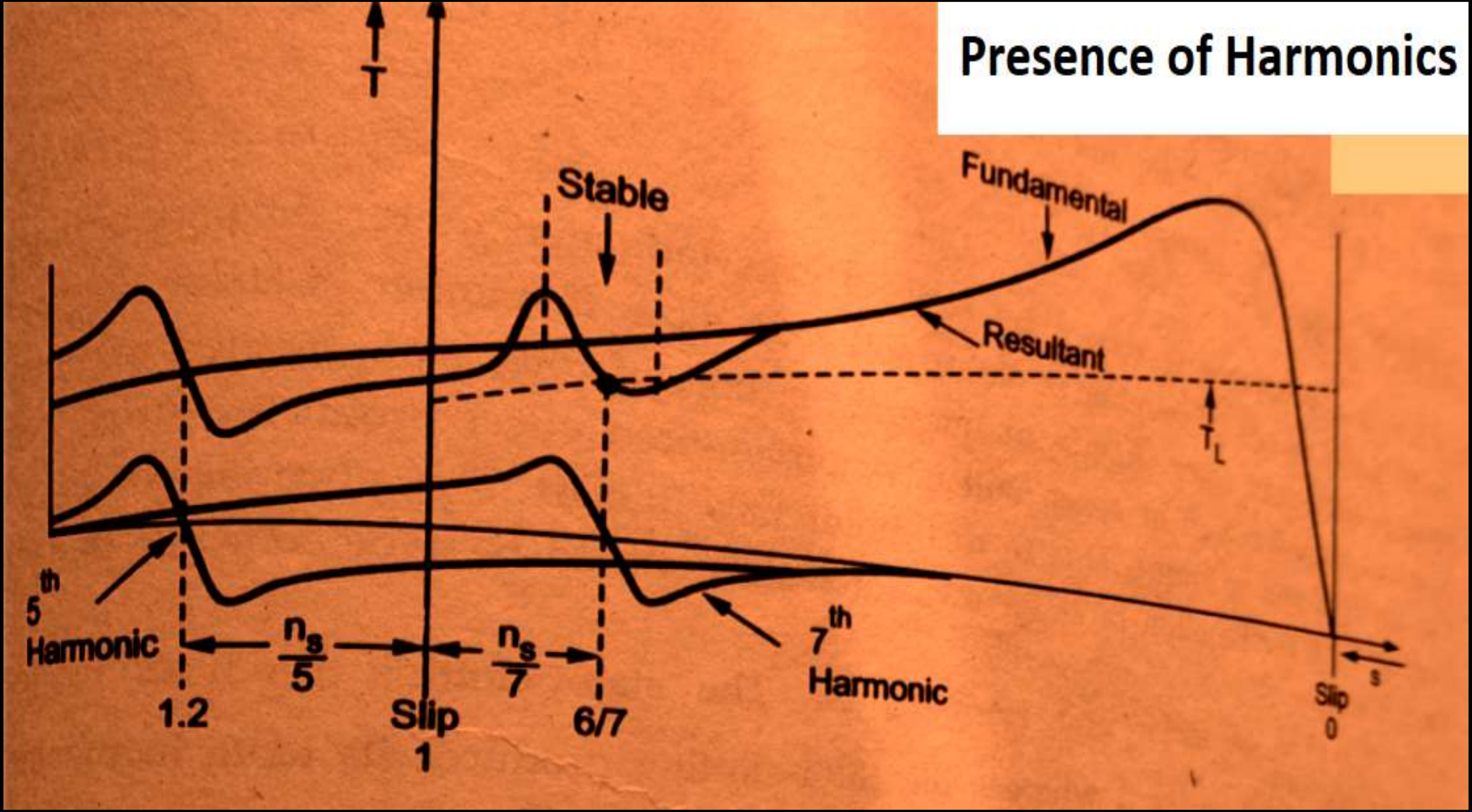
- Apart from this, there is one more reason for cogging.
- If the harmonic frequencies coincide with the slot frequency due to the harmonics present in the supply voltage then it causes torque modulation.
- As a result, of it cogging occurs.
- This characteristic is also known as magnetic teeth locking of the induction motor.

Methods to overcome Cogging

This problem can be easily solved by adopting several measures. These solutions are as follows:

- The number of slots in rotor should not be equal to the number of slots in the stator.
- Skewing of the rotor slots, that means the stack of the rotor is arranged in such a way that it angled with the axis of the rotation.

Presence of Harmonics



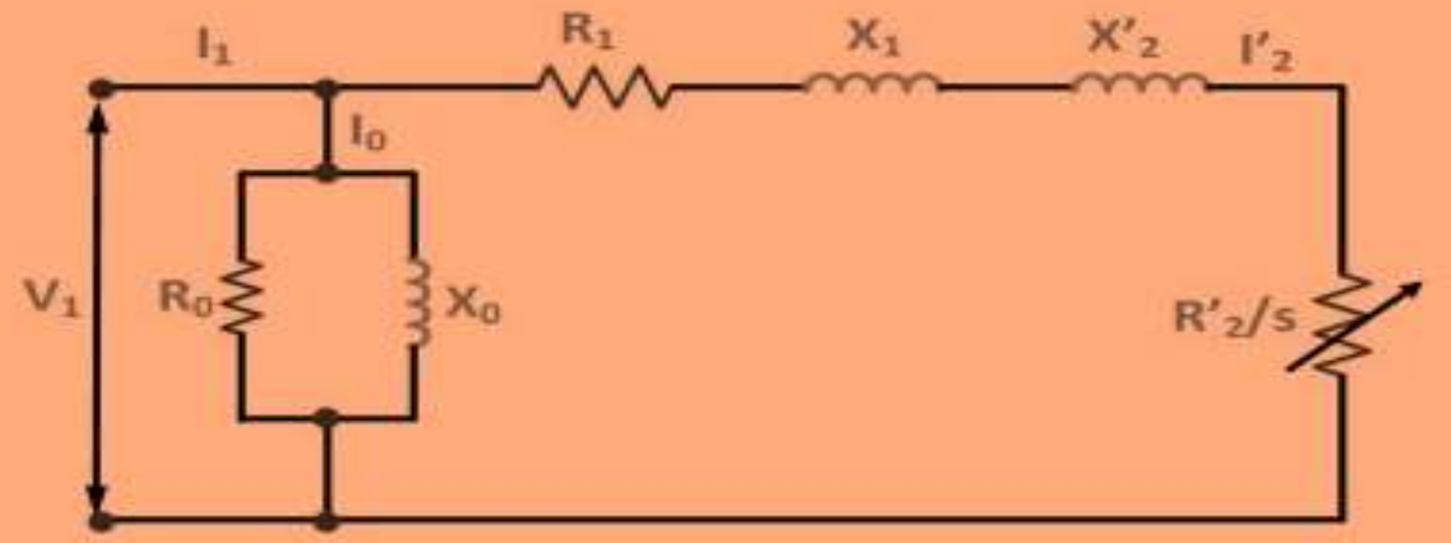
Generally in induction motor related operations, squirrel cage induction motors are widely used. The starting torque equation of an induction motor is given by

$$T_{st} = \frac{k.\, E_2^2 R_2}{R_2^2 + X_2^2} \qquad k = \frac{3}{2\pi N_s}$$

Where, R_2 and X_2 are the rotor resistance and inductive reactance at starting respectively, E_2 is the rotor induced EMF and

N_s is the RPS speed of synchronous stator flux. Here in this equation the starting torque of induction motor T_{sh} is proportional to rotor resistance R_2.

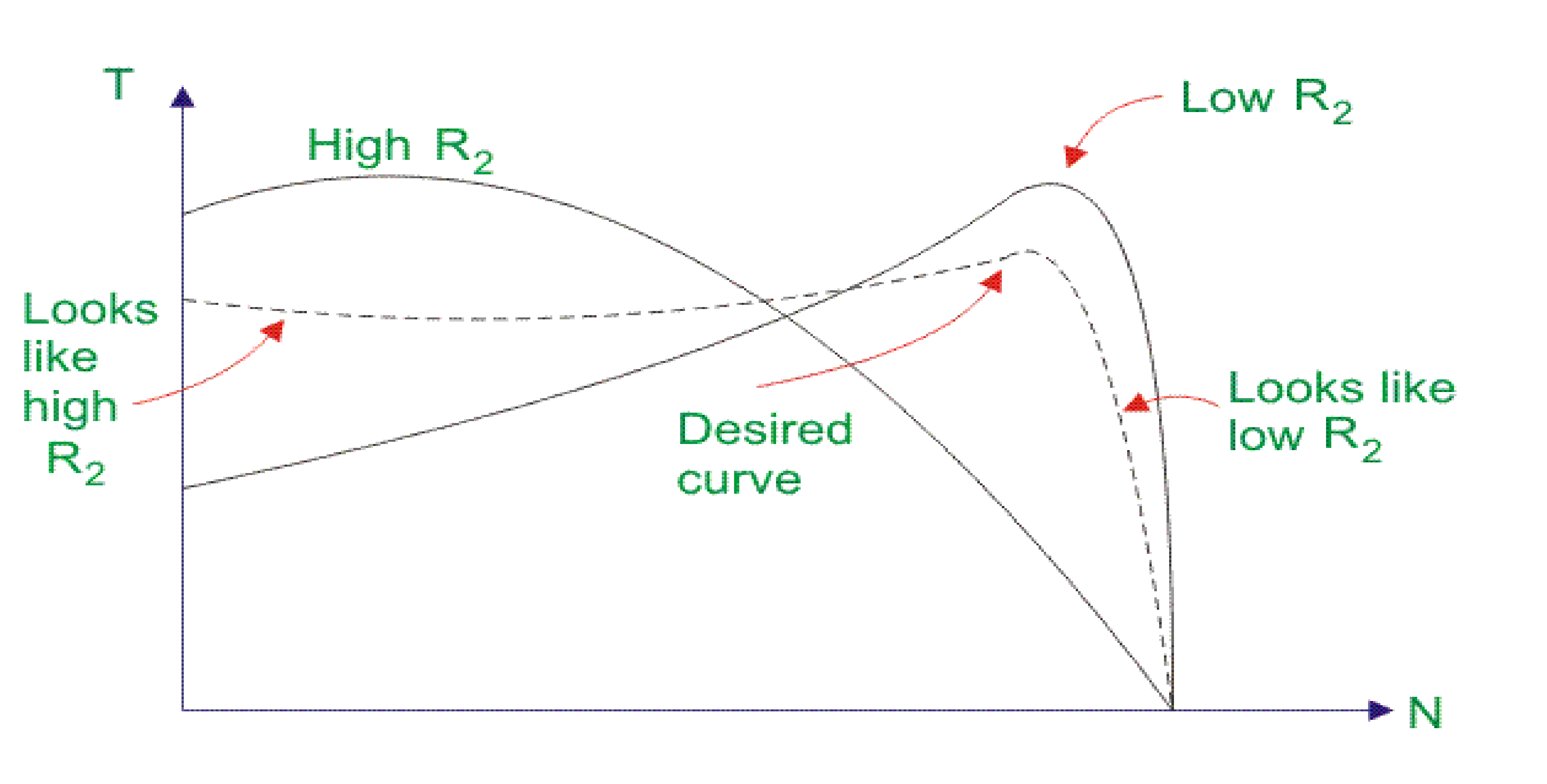
Equivalent circuit of 3 phase Induction motor



High torque rotors:

- Double cage and Deep rotor bars.
- Equivalent circuit and performance evaluation of Double cage induction motor.
- Induction Motor working as induction Generator;
- standalone operation &Grid connected operation.

- But the thing is that squirrel cage induction motor has very low starting torque due to its rotor resistance of very low value resistance in squirrel cage induction motor double bar double cage rotor is used in induction motor.
- The motive is to provide higher value of rotor resistance in such a manner that the rotor with its higher valued resistance provides higher torque and more efficiency.


T
High R_2
Low R_2
Looks like high R_2
Desired curve
Looks like low R_2
N

Why Starting Torque is Poor in Squirrel Cage Induction Motor?

The fixed resistance of the resistance cannot be varied in squirrel cage rotor as it is possible in slip ring induction motor.

he rotor of the squirrel cage induction motor is very low.

At the starting moment, the induced voltage in the rotor has same frequency as the frequency of the supply.

Hence the starting inductive reactance gets higher value at stand still condition.

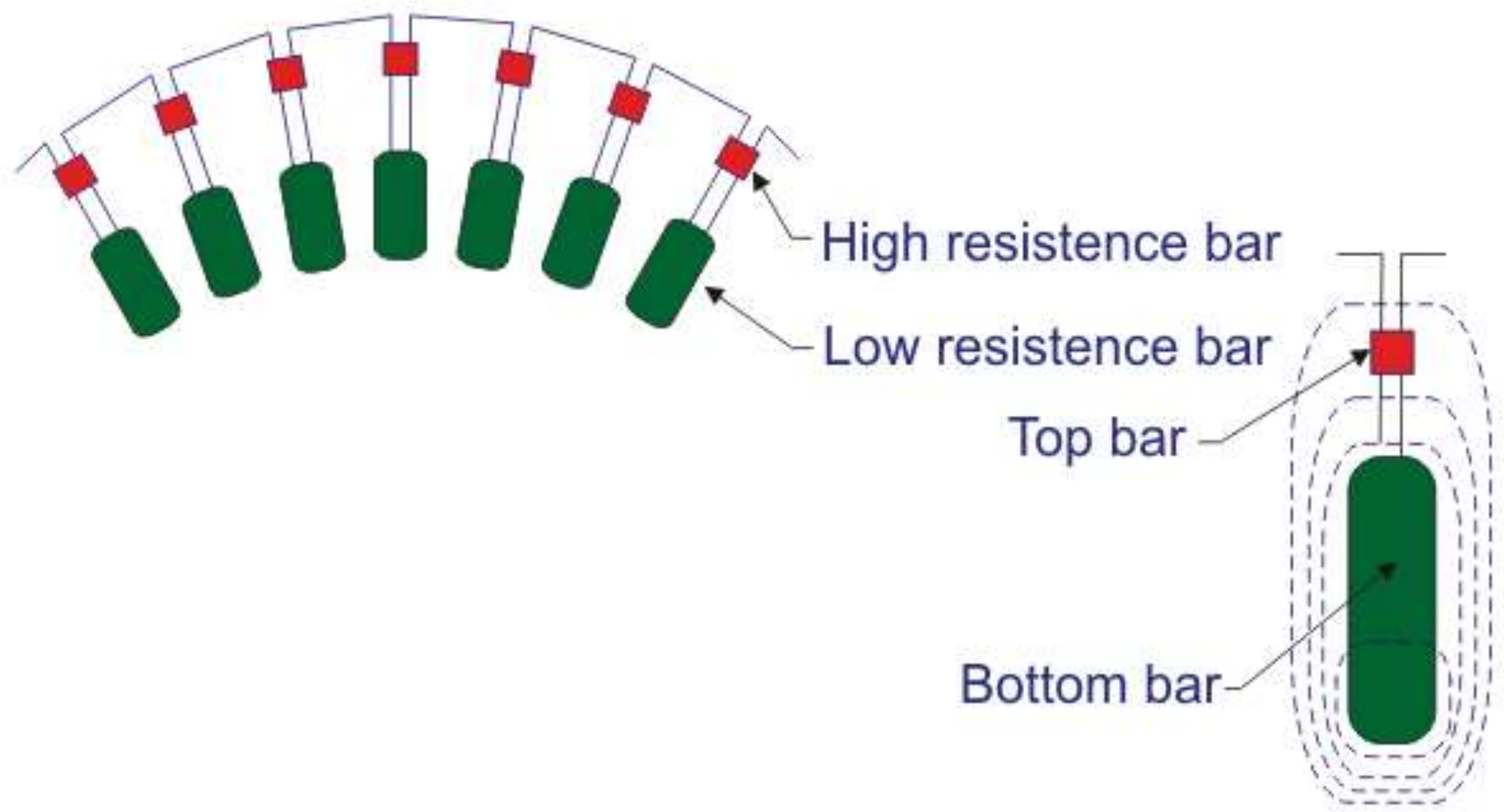
The frequency of the rotor current gets same frequency as the supply frequency at standstill.

- Now the case is that the rotor induced current in spite of having higher value lags the induced voltage at a large angle.
- So this causes poor starting torque at the stand still condition.
- This torque is only 1.5 times of the full load torque though the induced current is 5 to 7 times of the full load current.
- Hence, this squirrel cage single bar single cage rotor is not being able to apply against high load.
- We should go for deep bar double cage induction motor to get higher starting torque.

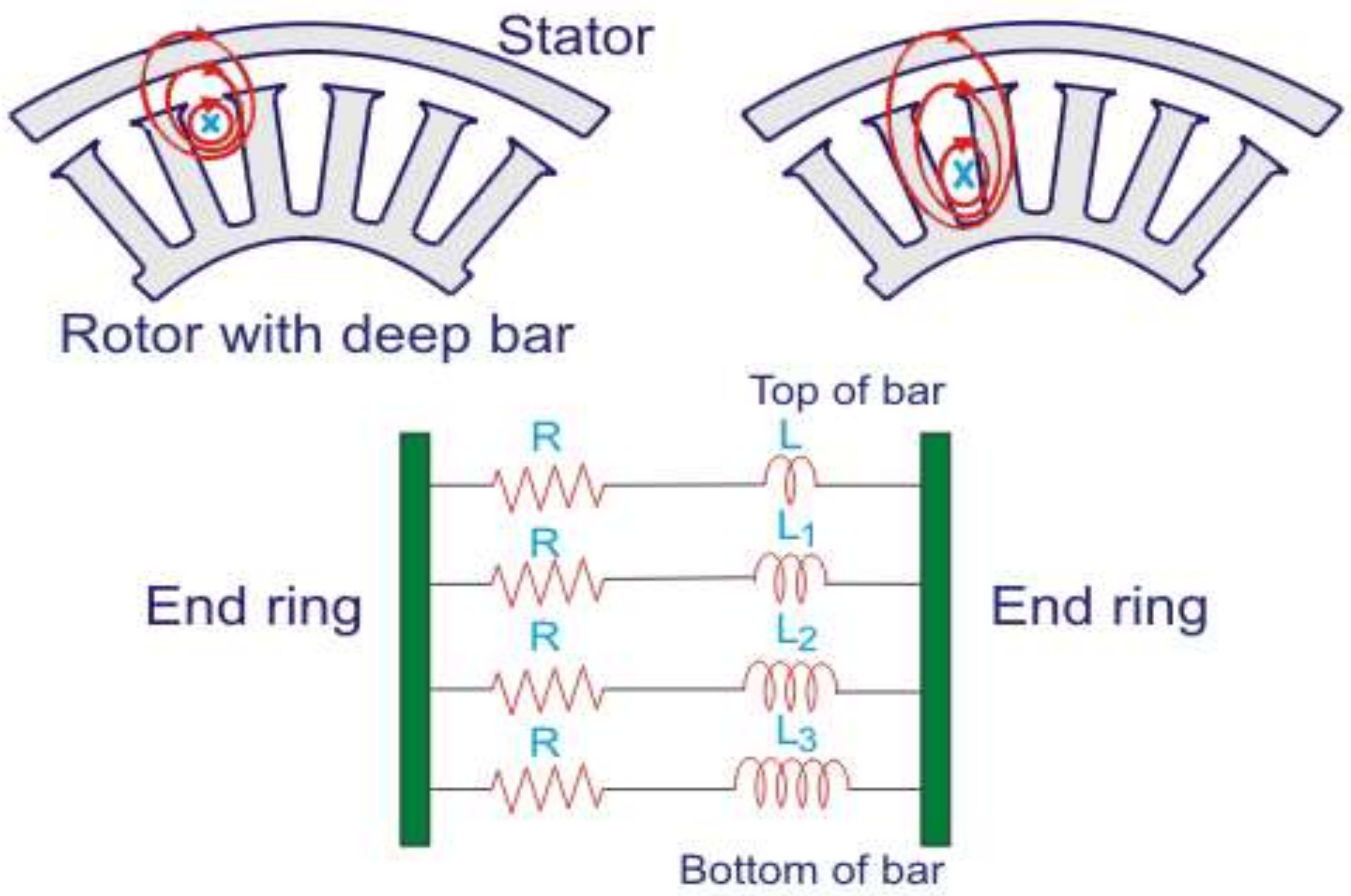
Construction of Deep Bar Double Cage Induction Motor

- In deep bar double cage rotor bars are there in two layers.
- Outer layer has the bars of small cross sections.
- This outer winding has relatively large resistance.
- The bars are shorted at the both ends.
- The flux linkage is thus very less.
- And hence inductance is very low.
- Resistance in outer squirrel cage is relatively high.
- Resistance to inductive reactance ration is high.

- Inner layer has the bars of large cross section comparatively.
- The resistance is very less.
- But flux linkage is very high.
- The bars are thoroughly buried in iron.
- As flux linkage is high the inductance is also very high.
- The resistance to inductive reactance ration is poor.


High resistence bar
Low resistence bar
Top bar
Bottom bar

- Operational Principle Construction of Deep Bar Double Cage Induction Motor
- At the stand still condition the inner and outer side bars get induced with voltage and current with the same frequency of the supply.
- Now the case is that the inductive reactance ($XL = 2\pi fL$) is offered more in the deep bars or inner side bars due to skin effect of the alternating quantity i.e. voltage and current.
- Hence the <u>current tries to flow through the outer side rotor bars</u>.


Stator
Rotor with deep bar
Top of bar
R
L
R
L1
R
L2
R
L3
End ring
End ring
Bottom of bar

- The outer side rotor offers more resistance but poor inductive reactance.
- The ultimate resistance is somewhat higher than the single bar rotor resistance.
- The higher valued rotor resistance results more torque to be developed at the starting.
- When the speed of the rotor (N)of the deep bar double cage induction motor increases, the frequency (f)of the induced EMF and current in the rotor gets gradually decreased.
- Hence the inductive reactance (XL) in the inner side bars or deep bars gets decreased and the current faces less inductive reactance and less resistance as a whole.
- Now no need for more torque because the rotor already has arrived to its full speed with running torque.

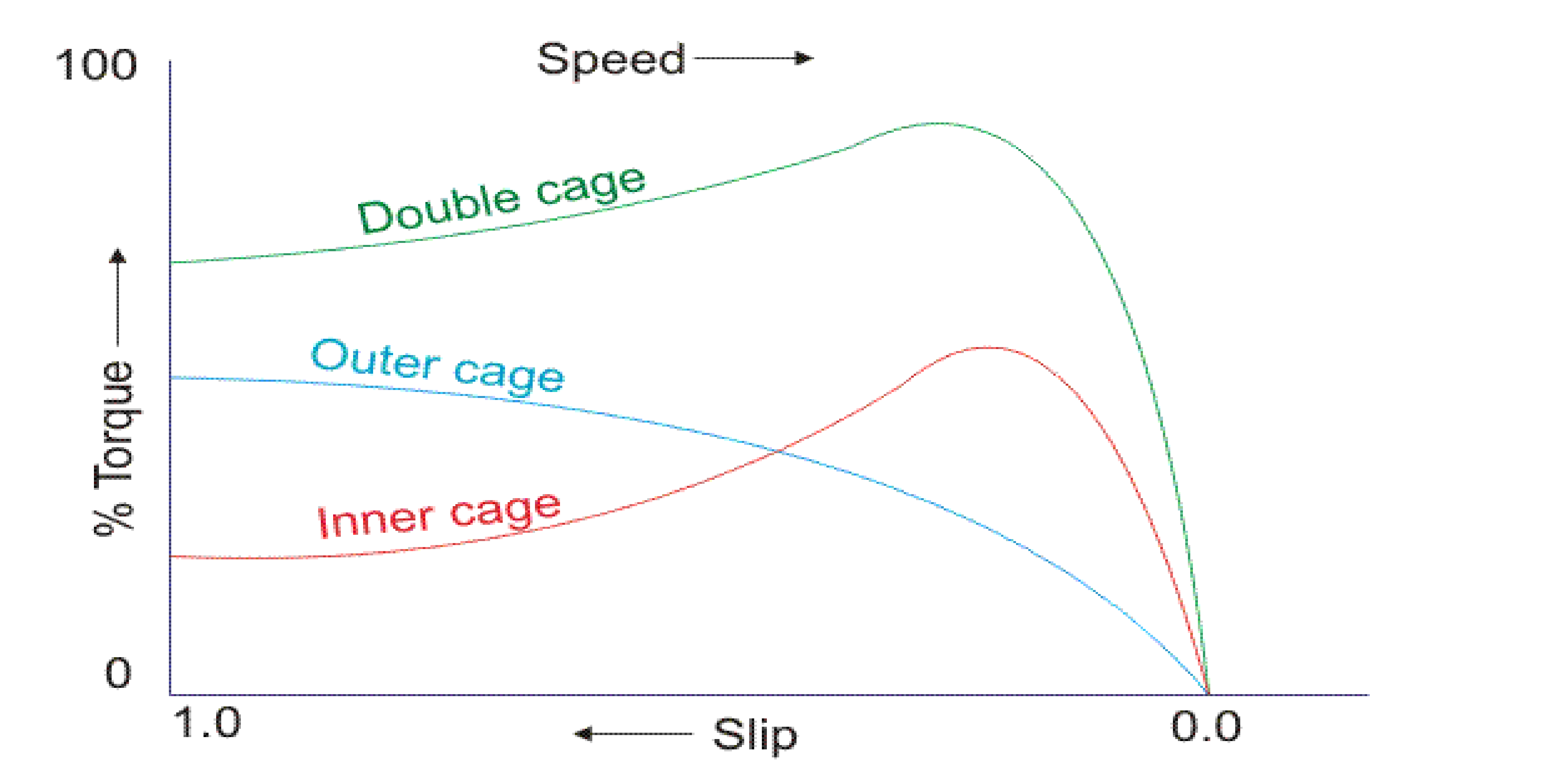
- Where, R2 and X2 are the rotor resistance and inductive reactance at starting respectively, E2 is the rotor induced EMF and

$$k = \frac{3}{2\pi N_s}$$

- Ns is the RPS speed of synchronous stator flux
- S is the slip of the rotor speed.

The above speed-torque graph shows that the higher valued resistance offers higher torque at the stand still condition and the max torque will be achieved at higher valued slip.

Speed Torque Characteristics of Deep Rotor IM



- Each layer is short-circuited by the end rings.

  The outer cage bars have a smaller cross-sectional area than the inner bars and are made of high resistivity materials like brass, aluminium, bronze, etc.

- the bars of the inner cage are made of low resistance copper. Thus, the resistance of the outer cage is greater than the resistance of the inner cage.
- There is a slit between the top and the bottom slots.
- The slit increases linking the inner cage winding is much larger than that of the outer cage winding.
- Thus, the inner winding has a greater self-inductance.

- At starting, the voltage induced in the rotor is same as the supply frequency that is (f2 = f1).
- Hence, the leakage reactance of the inner cage winding as compared to that of the outer cage winding is much larger.

The outer cage winding carries most of the starting current which offer low impedance to the flow of current.

- The high resistance outer cage winding, therefore, develops a high starting torque.

- As the rotor speed increases, the frequency of the rotor EMF (fr =sf) decreases.

At normal operating speed, the leakage reactance of both the windings become negligibly small.

- The current in the rotor divides between the two cages and is governed by their resistances.
- The resistance of the outer cage is about 5 to 6 times that of the inner cage.
- Hence, the torque of the motor developed mainly by the low resistance inner cage and is developed under normal operating speed.

- For the low starting torque requirements, an ordinary cage motor is used.
- For higher torque requirements a deep bar cage motor is used.
- A double cage motor is used for higher torques.
- The slip ring construction is used for large size motors.
- The starting torque and the starting periods is also large.

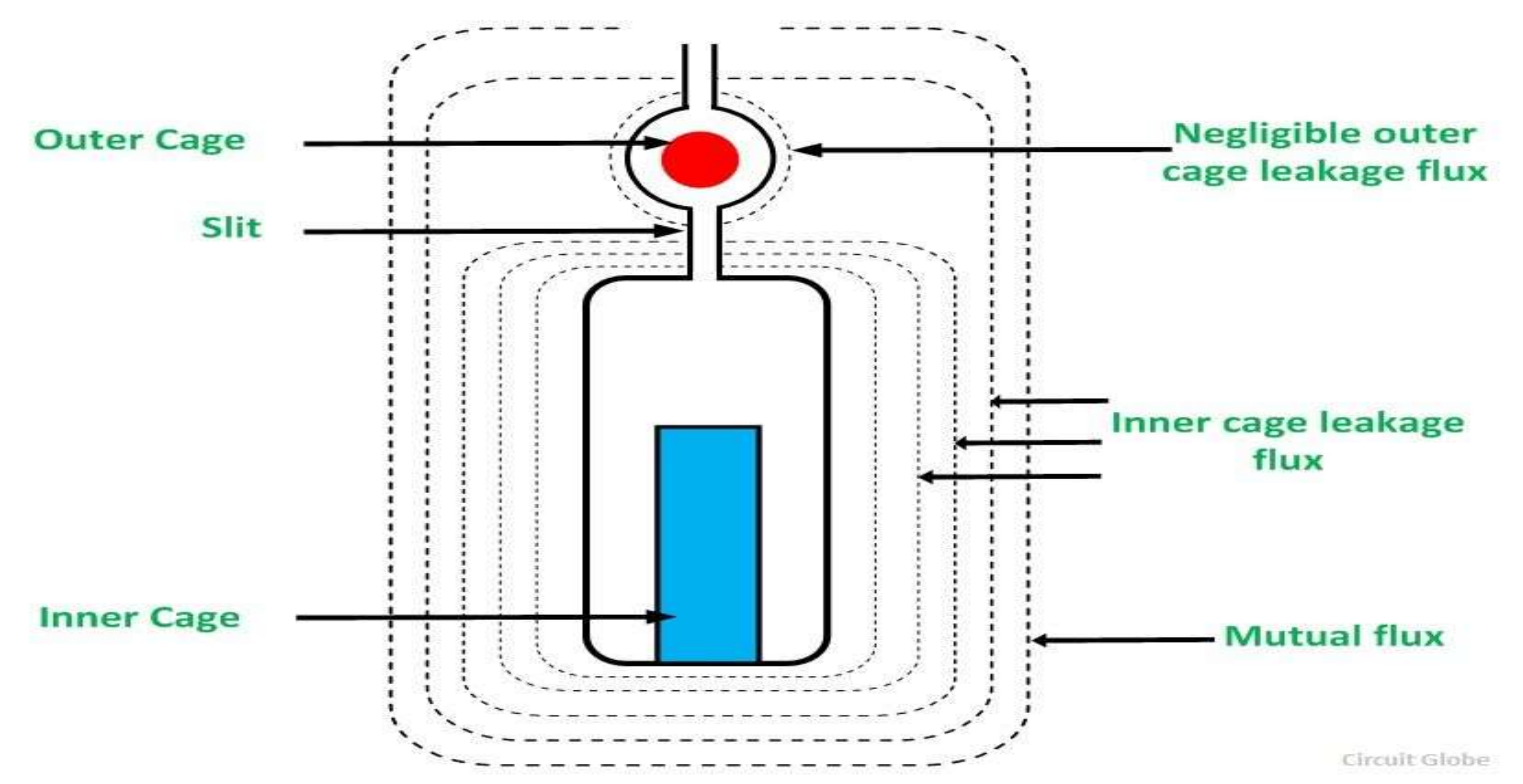
Comparison between Single Cage and Double Cage Motors

- A double cage rotor has low starting current and high starting torque. Therefore, it is more suitable for direct on line starting.
- Since effective rotor resistance of double cage motor is higher, there is larger rotor heating at the time of starting as compared to that of single cage rotor.
- The high resistance of the outer cage increases the resistance of double cage motor. So full load copper losses are increased and efficiency is decreased
- The pull out torque of double cage motor is smaller than single cage motor.
- The cost of double cage motor is about 20-30 % more than that of single cage motor og same rating.

Double Cage Rotor of an Induction Motor

- A Double Cage Induction motor is that type of motor in which a double cage or two rotor windings or cages are used.
- This arrangement is used for obtaining high starting torque at a low value of starting current.
- The stator of a double cage rotor of an induction motor is same as that of a normal induction motor.
- In the double cage rotor of an induction motor, there are two layers of the bars.
- The figure of the Double cage induction motor is shown below

Double cage rotor



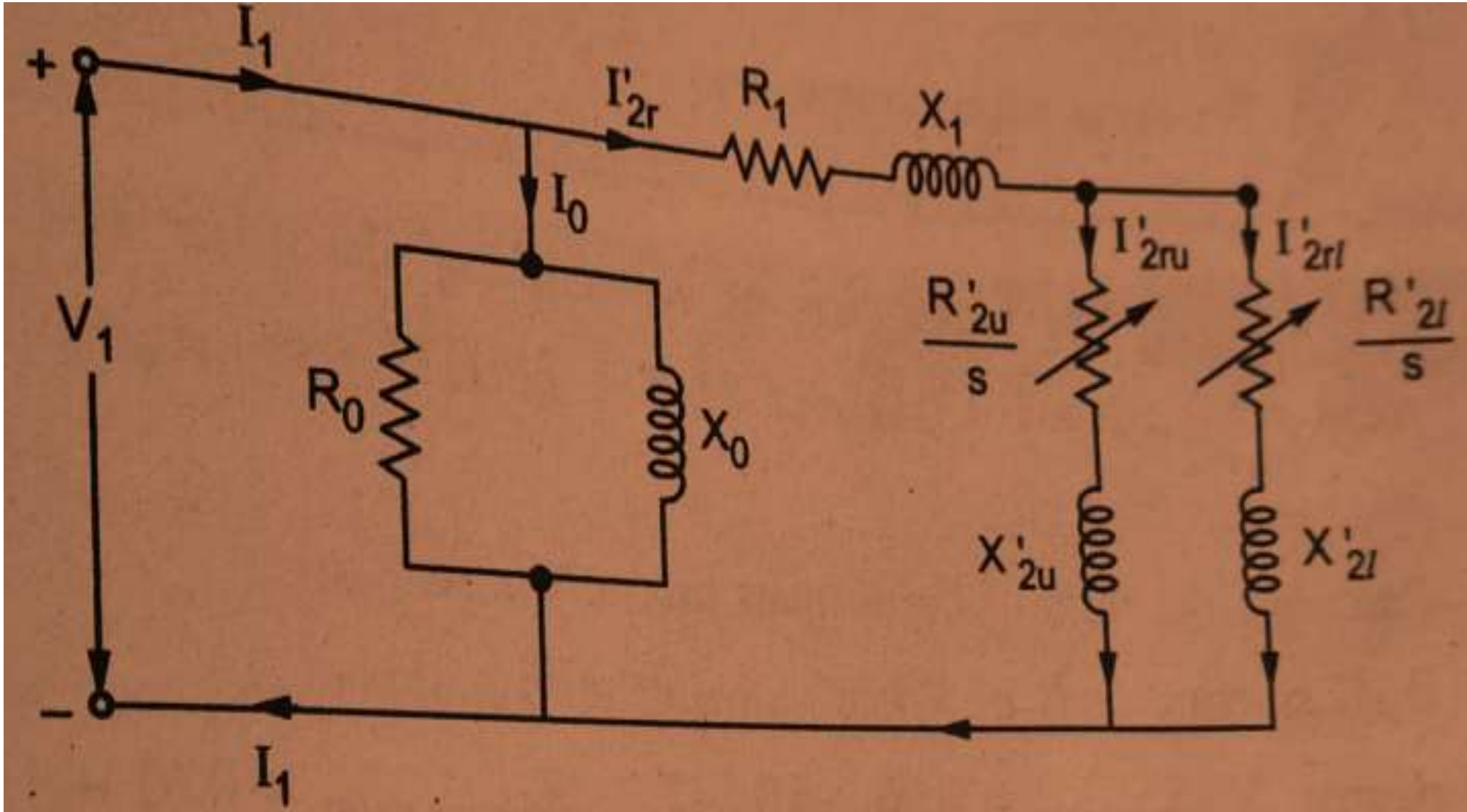


Fig. 4.13.7 Equivalent circuit of double cage induction motor

Grid connected induction Generator

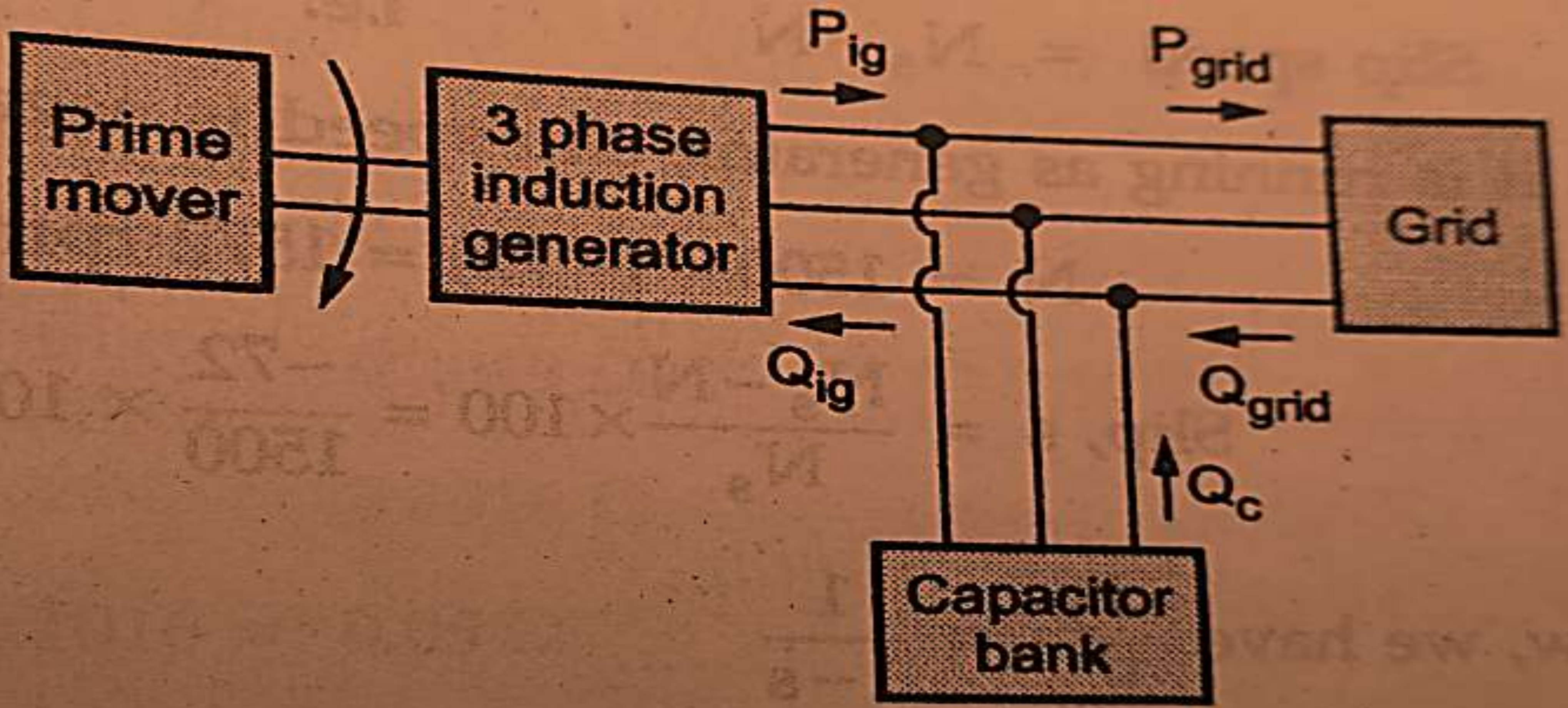


Fig. 4.14.12 Grid connected induction generator

Grid connected induction Generator

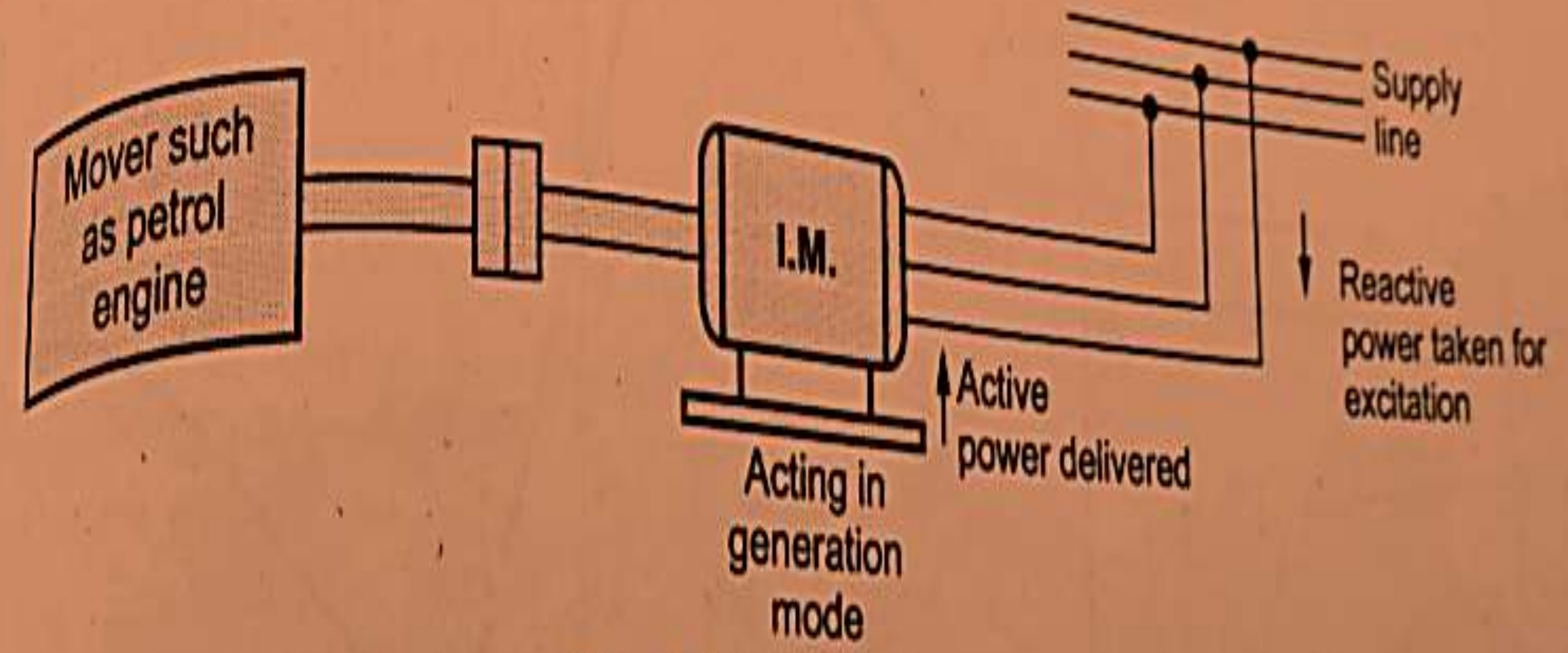


Fig. 4.14.1 Induction generator

4.14.8.1 Importance of Induction Generators in Wind Mill

The induction generator is extremely important in wind power electricity generation system. It is suitable because the stator frequency depends on that of the paralleled synchronous machines and not on the rotor speed.

Induction generator is most commonly used in wind turbines because of low cost, ruggedness, operates with slip (synchronism not required), availability in many sizes and advance technology available.

Induction generators have outstanding operation as either motor or generator. They have robust construction features. It provides natural protection against short circuits. The abrupt changes in speed are easily absorbed by its solid rotor. Also any surge in the current is damped by the magnetization path of the core, avoiding the possibility of demagnetization which is possible in case of permanent magnet generators.

Induction generator-stand alone system

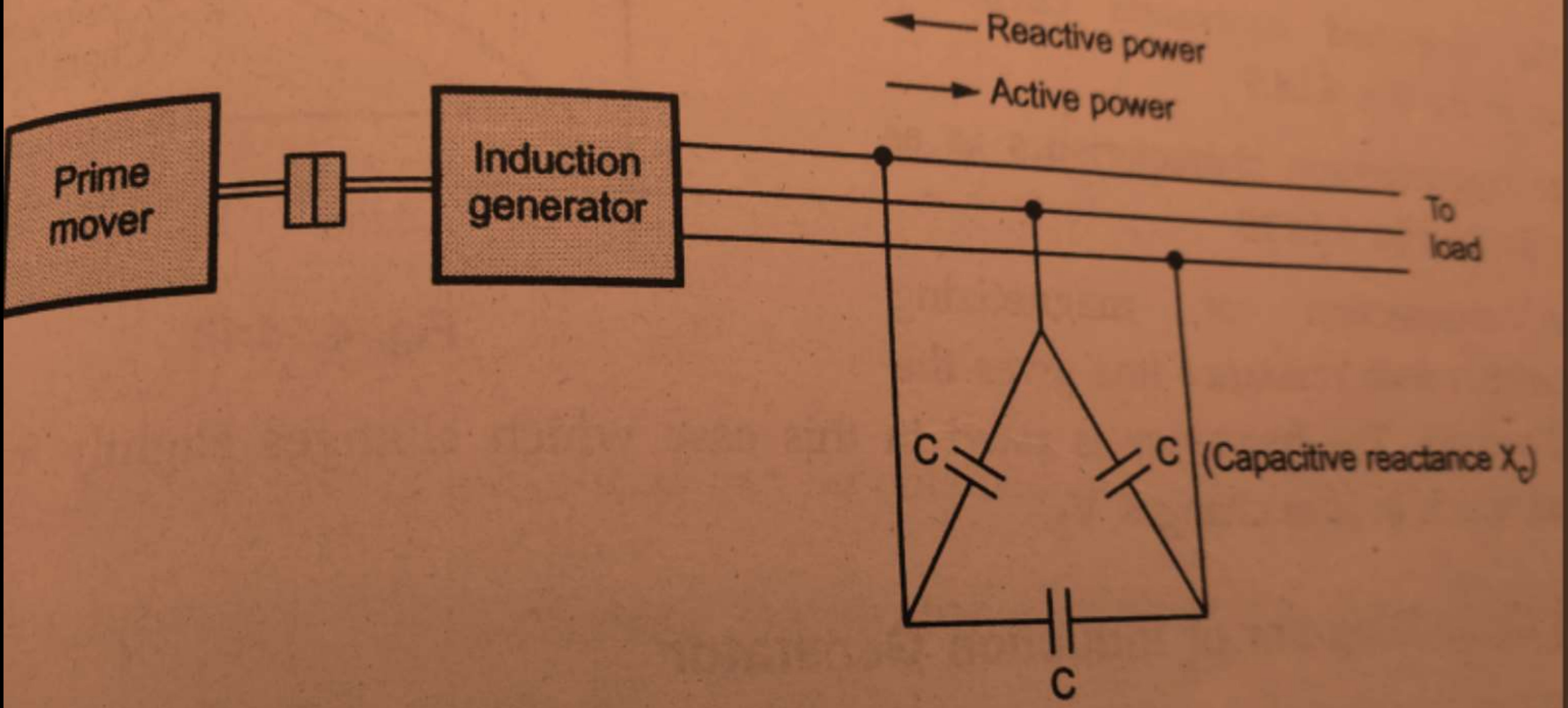


Fig. 4.14.7