Chapter Three
Poly- Phase Induction Motors

An AC electric motor . Induction motor can therefore be made without electrical connections to the rotor. Poly-Phase I.M. is extensively used for industrial drives. It has the following advantages and disadvantages:-

Advantages

1) It has very simple and rugged construction
2) It's cost is low
3) It has high efficiency and good power factor
4) It needs minimum maintenance
5) It has starting torque

Disadvantages

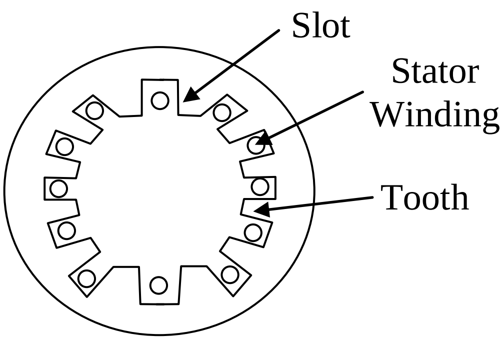
1) It's speed cannot be varied without changing it's efficiency
2) It's speed decreases with increase in load (similar to d.c. shunt motor)
3) It's starting torque is not so high

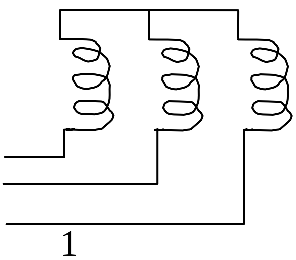
3-1 Construction:-

As in any motor an I.M. consists mainly from two parts: a) Stator, and b) Rotor.

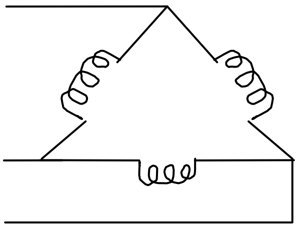
a) Stator:-

The stator of an I.M. is the same as that of a synchronous machine. It is made from laminated steel with slots in the inner periphery. The stator carries a poly-phase winding in these slots. For a 3-ph I.M. the winding is connected in star or delta connection. The stator winding of a poly-phase I.M. is almost similar to the armature winding of a poly-phase alternator.





Star



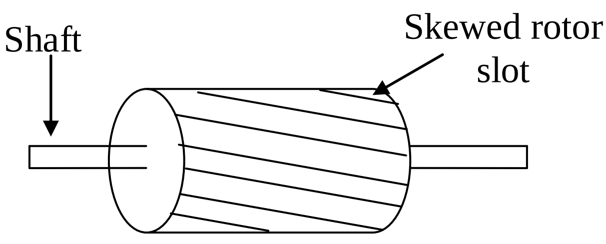
Delta

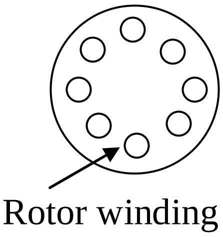
b) Rotor:-

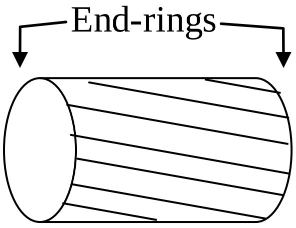
The rotor in an I.M. has one of the following constructions:

1) Squirrel-Cage rotor, and 2) Wound rotor.

1- Squirrel-Cage Rotor:-







The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor bars. These bars are short-circuited by two end-rings. The rotor slots are not quite parallel to the shaft but are given slight skew.

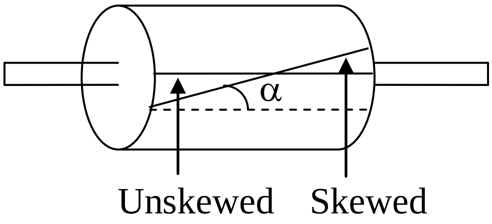
The advantages of skewing are:

1. It makes the motor run quietly by reducing the magnetic hum.
2. It reduces the locking tendency of the rotor. The tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between them.

The magnetic hum is reduced because the air gap in a skewed rotor is more constant reluctance resulting in a more uniform torque and a quieter motor.

The skewing factor = K_S = The voltage induced in the skewed inductor / The voltage induced in the unskewed inductor

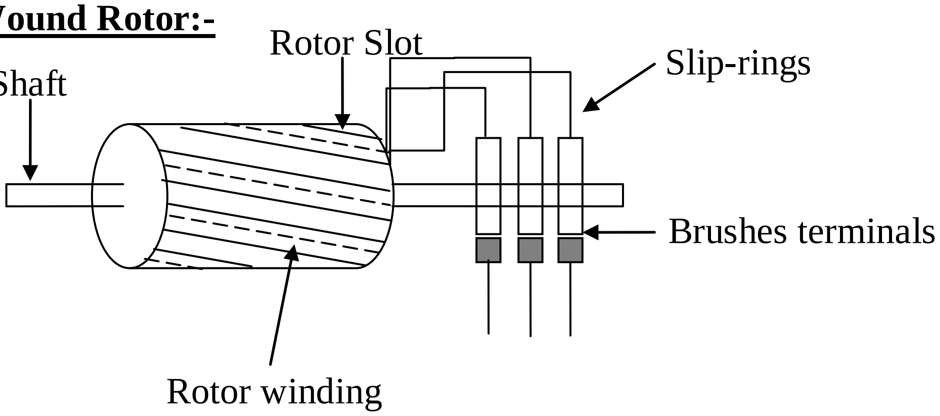
$$K_S = \frac{2E_m \sin\left(\frac{\alpha}{2}\right)}{E_m \alpha} = \frac{\sin\left(\frac{\alpha}{2}\right)}{\frac{\alpha}{2}}$$



Where: E_m is the max. voltage / unit angle of the skewed inductor (V/rad.)

α is the angle of skew.

2-Wound Rotor:-



The rotor core is laminated with skewed slots on its outer periphery. The rotor is provided with 3-ph, double-layer, distributed windings. The rotor is wound to have the same number of poles as for the stator. The 3-ph windings are connected in star formation. The terminals of the rotor star-winding are connected to slip-rings mounted on the shaft.

3-2 Production of Rotating Field:-

It can be shown that symmetrical 3-ph windings when supplied from a balance 3-ph power supply produce a rotating field. The figure below showed a 3-ph, 2-pole I.M.

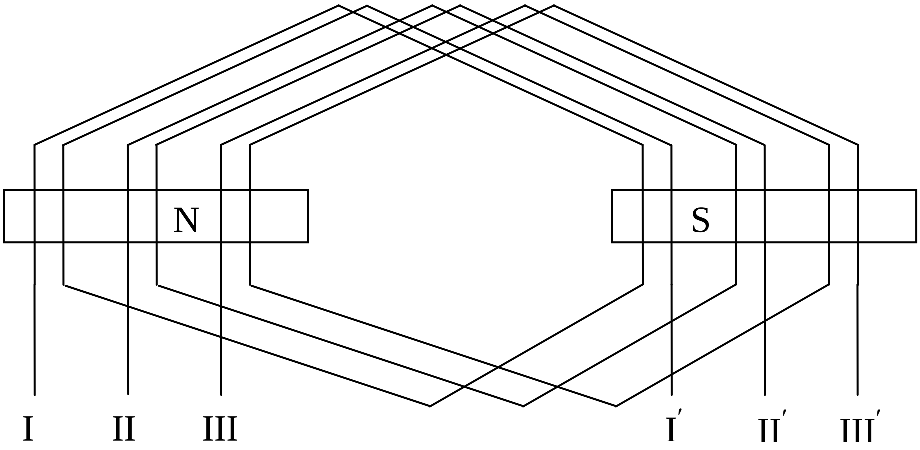


Fig-1-

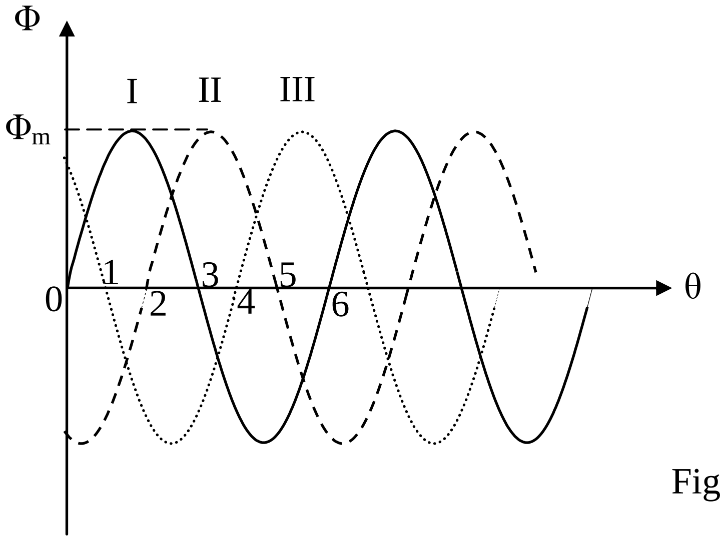


Fig-2- The flux due to the 3-phase

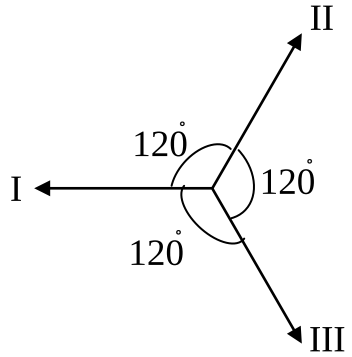
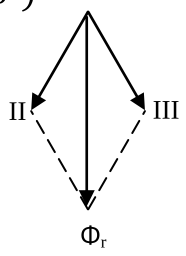


Fig-3- The +ve direction of the fluxes

$$\emptyset_1 = \emptyset_m \sin\theta,\ \emptyset_2 = \emptyset_m \sin(\theta - 120^\circ),\ \emptyset_3 = \emptyset_m \sin(\theta - 240^\circ)$$

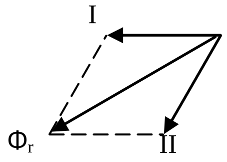
<u>At point 0, θ=0</u>

$$\emptyset_1 = 0, \emptyset_2 = \tfrac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \tfrac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore\ \emptyset_r = \tfrac{3}{2}\emptyset_m$$



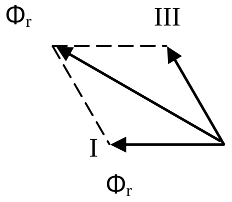
<u>At point 1, θ=60˚</u>

$$\emptyset_1 = \tfrac{\sqrt{3}}{2}\emptyset_m, \emptyset_2 = \tfrac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = 0, \rightarrow \therefore\ \emptyset_r = \tfrac{3}{2}\emptyset_m$$



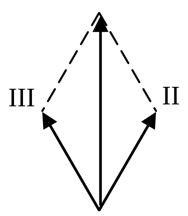
<u>At point 2, θ=120˚</u>

$$\emptyset_1 = \tfrac{\sqrt{3}}{2}\emptyset_m, \emptyset_2 = 0, \emptyset_3 = \tfrac{-\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore\ \emptyset_r = \tfrac{3}{2}\emptyset_m$$



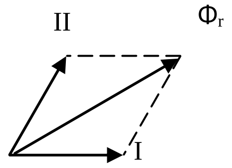
<u>At point 3, θ=180˚</u>

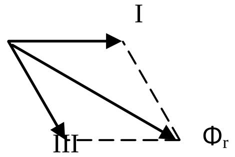
$$\emptyset_1 = 0, \emptyset_2 = \tfrac{\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \tfrac{-\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore\ \emptyset_r = \tfrac{3}{2}\emptyset_m$$



<u>At point 4, θ=240˚</u>

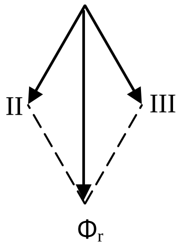
$$\emptyset_1 = \tfrac{-\sqrt{3}}{2}\emptyset_m, \emptyset_2 = \tfrac{\sqrt{3}}{2}\emptyset_m, \emptyset_3 = 0, \rightarrow \therefore\ \emptyset_r = \tfrac{3}{2}\emptyset_m$$





At point 5, θ=300°

$\emptyset_1 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_2 = 0, \emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$



At point 6, θ=360°

$\emptyset_1 = 0, \emptyset_2 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$

From this, it is clear that the resultant flux is constant and is rotating with synchronous speed.

For one current (or flux) cycle → 360° elec. Angle

$$\propto_e = \propto_m * p \rightarrow \propto_m = \frac{\propto_e}{p} \rightarrow \frac{360^\circ}{p} \text{ mech. Angle} \rightarrow \frac{1}{p} \text{ revolution}$$

For f cycles of current (or flux) → $\frac{f}{p}$ revolution/sec

$$\rightarrow \frac{2f}{2p} \text{ revolution/sec}$$

The synchronous speed → $N_S = \frac{120f}{2p}$ r.p.m

3-3 Why does the Rotor Rotate:-

When a 3-ph I.M. is supplied with a 3-ph supply, a rotating field will produce. Such rotating field will cut the rotor conductors with speed equal to the synchronous speed, and as a result of this, a 3-ph emf will be produced with frequency equal to the supply frequency. This emf will send a current through the closed rotor circuit with a direction such as to oppose the very cause producing it, i.e., the rotation of the field. Therefore, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux. This will continue until the speed near the synchronous speed and therefore, the emf and the current will reduce. The difference between these two speeds is called slip.

$N_r = N_S - N \rightarrow S = \frac{N_S - N}{N_S}$, S is equal to the slip

The frequency of the rotor emf depends upon the relative speed or on slip-speed, i.e.,

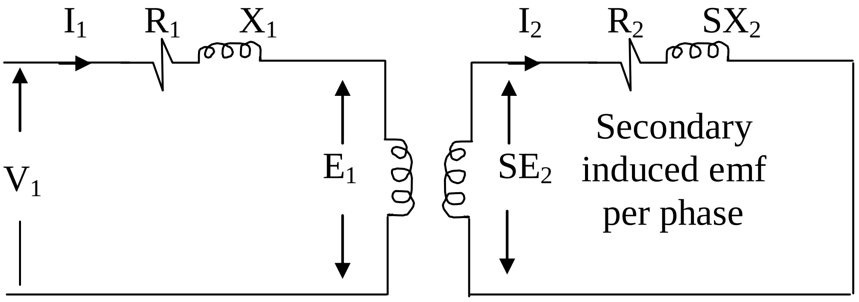
$$N_S - N = \frac{120 f_{rotor}}{2p} \rightarrow SN_S = \frac{120 f_{rotor}}{2p} \rightarrow S * \frac{120f}{2p} = \frac{120 f_{rotor}}{2p}$$

$$\rightarrow f_{rotor} = Sf$$

Speed of the rotor field with respect to stator$= N_{s\cdot rotor} + N = \frac{120Sf}{2p} + N = SN_S + N = \left(\frac{N_S - N}{N_S}\right) N_S + N = N_S - N + N = N_S$

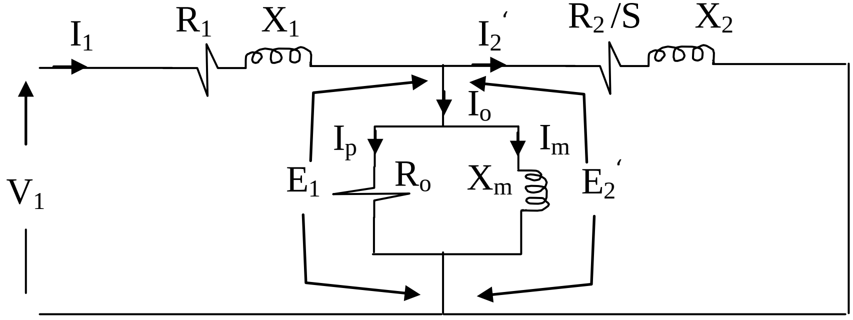
3-4 The Equivalent Circuit:-

The equivalent circuit of a 3-ph I.M. has a certain similarities with the equivalent circuit of 3-ph transformer.

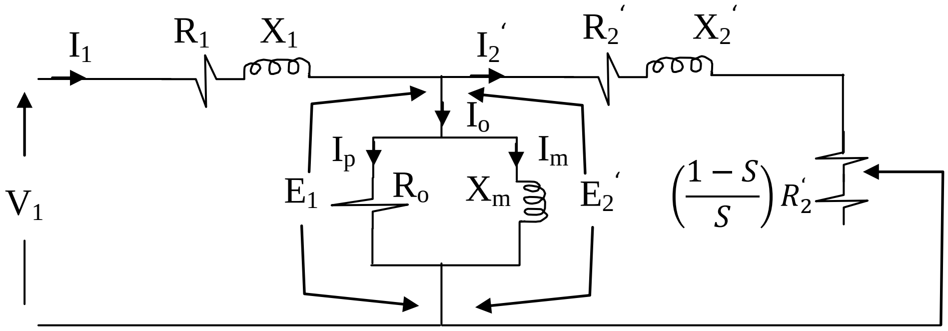


$$f_{rotor} = Sf$$
$$S = \frac{N_S - N}{N_S}$$

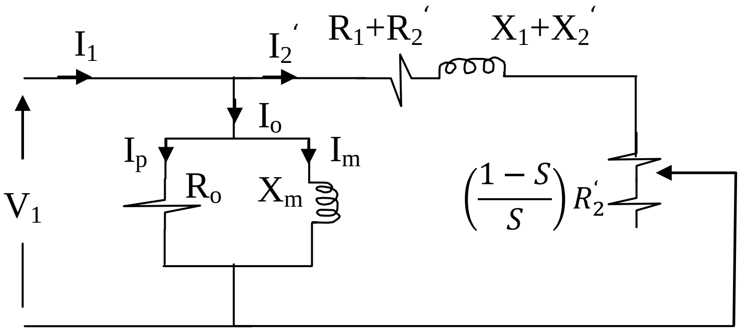
It is possible to reduce this circuit to:-



$$R_2' = R_2\left(\frac{N_1}{N_2}\right)^2, X_2' = X_2\left(\frac{N_1}{N_2}\right)^2, E_2' = E_2\left(\frac{N_1}{N_2}\right), I_2' = I_2\left(\frac{N_2}{N_1}\right)$$



Also, this circuit can be reduced to:-



Equivalent circuit calculations

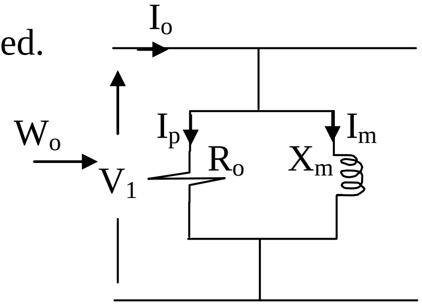
Equivalent circuit parameters can be determined by performing the following two tests on the machine:-

No-load test

The motor should run with no-load at rated voltage, the V_o, I_o, and W_o (the voltage, current, and power per phase) must be noted.

$$\cos \emptyset_o = \frac{W_o}{V_o I_o} \rightarrow I_m = I_o \sin \emptyset_o , I_p = I_o \cos \emptyset_o$$

$$\rightarrow R_o = \frac{V_o}{I_p} , X_m = \frac{V_o}{I_m}$$



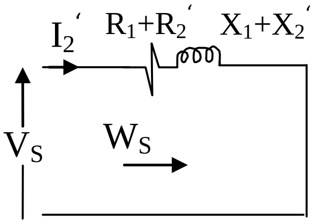
The equivalent circuit of the 3-ph I.M. gets reduced to that shown above since at no-load the slip is very small (normally assumed to be zero).

Blocked-rotor test

In this test the rotor of the machine is held stationary and a reduced voltage (V_S per phase) is applied to the armature winding such that it will allow rated current (I_S) in the armature winding. In blocked-rotor test the equivalent circuit of the machine gets reduced to that shown below:-

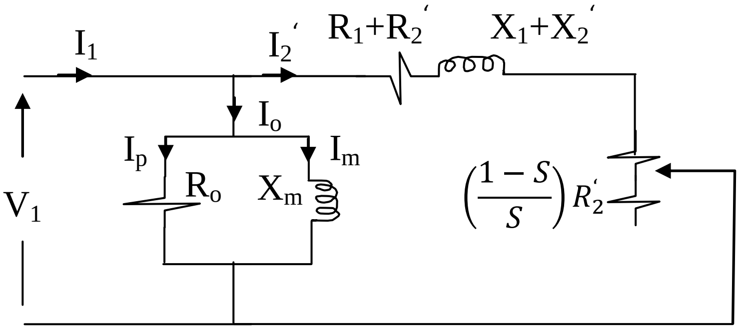
$$R_1 + R_2^{'} = \frac{W_S}{I_S^2} , X_1 + X_2^{'} = \sqrt{\left(\frac{V_S}{I_S}\right)^2 - \left(R_1 + R_2^{'}\right)^2} ,$$

$$X_1 = X_2^{'}$$



The dc value of R_1 can be measured by voltmeter-ammeter method (R_1=R_{1dc}*1.2(skin effect)).

3-5 Relation between Torque and Slip:-



$$I_2' = \frac{V_1}{\sqrt{\left(R_1+\frac{R_2'}{S}\right)^2+\left(X_1+X_2'\right)^2}} \ldots\ldots\langle 1\rangle,\quad P_d = T_d\omega = 3{I_2'}^2\left(\frac{1-S}{S}\right)R_2' \ldots\ldots \langle 2\rangle$$

Where P_d: developed power, T_d: developed torque, ω: angular speed

$$\omega = \frac{2\pi N}{60} \rightarrow T_d * \frac{2\pi N}{60} = P_d \rightarrow T_d = \frac{60}{2\pi N}P_d \ldots\ldots \langle 3\rangle$$

$$S = \frac{N_S-N}{N_S} \rightarrow SN_S = N_S - N \rightarrow N = N_S - SN_S \rightarrow N = (1-S)N_S \ldots\ldots \langle 4\rangle$$

From equations 4 & 2 in 3 give:-

$$T_d = \frac{60}{2\pi(1-S)N_S} * 3{I_2'}^2\left(\frac{1-S}{S}\right)R_2' \rightarrow T_d = \frac{90}{\pi N_S}R_2'\frac{{I_2'}^2}{S} \ldots\ldots \langle 5\rangle$$

From equation 1 in 5 gives:-

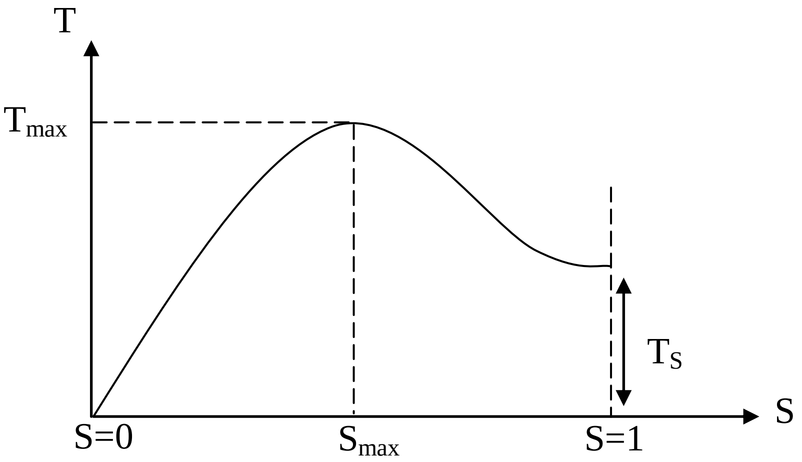
$$T_d = \frac{90}{\pi N_S} * \frac{R_2'}{S} * \frac{{V_1}^2}{\left(R_1+\frac{R_2'}{S}\right)^2+\left(X_1+X_2'\right)^2}$$, let $T = K' T_d$ where T: output torque

$$T_d = K'\frac{90}{\pi N_S} * \frac{R_2'}{S} * \frac{{V_1}^2}{\left(R_1+\frac{R_2'}{S}\right)^2+\left(X_1+X_2'\right)^2} \rightarrow T = K\frac{R_2'\;{V_1}^2/S}{\left(R_1+\frac{R_2'}{S}\right)^2+\left(X_1+X_2'\right)^2} \ldots\ldots \langle 6\rangle$$

Ignoring R_1 & X_1 gives:-

$$T = K\frac{R_2'\;{V_1}^2/S}{\left(\frac{R_2'}{S}\right)^2+\left(X_2'\right)^2} \rightarrow T = K\frac{R_2'S\;{V_1}^2}{{R_2'}^2+\left(SX_2'\right)^2} \ldots\ldots \langle 7\rangle$$

From the last equation the relation between T and S can be determined as follow:-



Torque-Slip characteristics

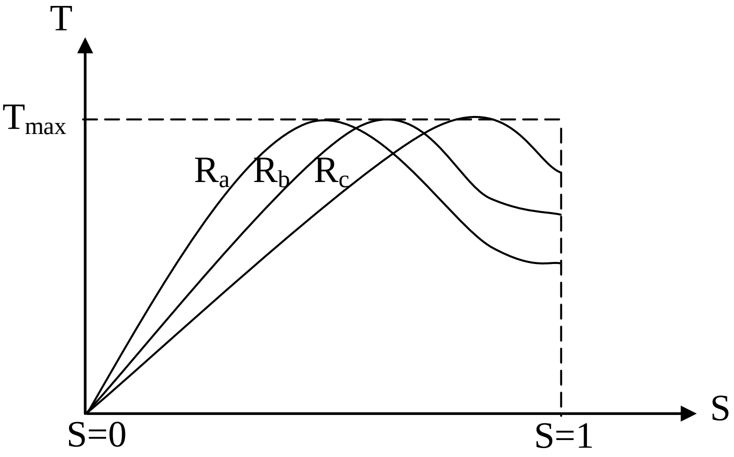
Starting Torque:-

$$T = K\frac{R_2' S\ V_1^2}{R_2'^2 + (SX_2')^2}\ ,at\ starting\ S = 1\ \rightarrow T_S = K\frac{R_2'\ V_1^2}{R_2'^2 + (X_2')^2}$$

Maximum starting torque can be obtained when the following condition is proved:-

$\frac{dT_S}{dR_2'} = 0 \rightarrow R_2' = X_2'$

Maximum starting torque can be obtained by increasing the rotor resistance until it reach X_2'.



Condition for Maximum Torque

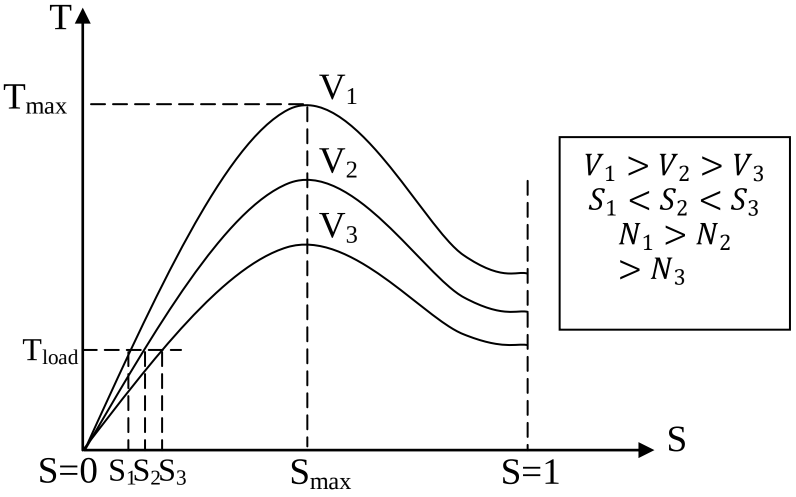
The condition for maximum torque can be obtained by verifying the condition:-

$$\frac{dT}{dS} = 0 \rightarrow S = \frac{R_2'}{X_2'} \rightarrow R_2' = SX_2' \rightarrow T_{max} = \frac{KV_1^2}{2X_2'}$$

3-6 Effect of Supply Voltage on Torque-Slip Characteristics:-

From the slip-torque equation it is clear that any change in the supply voltage V_1 will affect the characteristics in a great manner.

$$T = K\frac{R_2' S\ V_1^2}{R_2'^2 + (SX_2')^2}$$



From this figure it is clear that the supply voltage can be used to control the speed of a 3-ph I.M., but the range of control is not so great.

3-7 Power Stages in an Induction Machine:-

Input power in stator = $P_{in} = \sqrt{3}V_{1L}I_{1L}\cos\theta_1 = 3V_{1ph}I_{1ph}\cos\theta_1$

$$= P_g + P_c + P_{cu1}$$

P_c: Iron losses, P_{cu1}: Stator copper losses, P_g: Rotor input

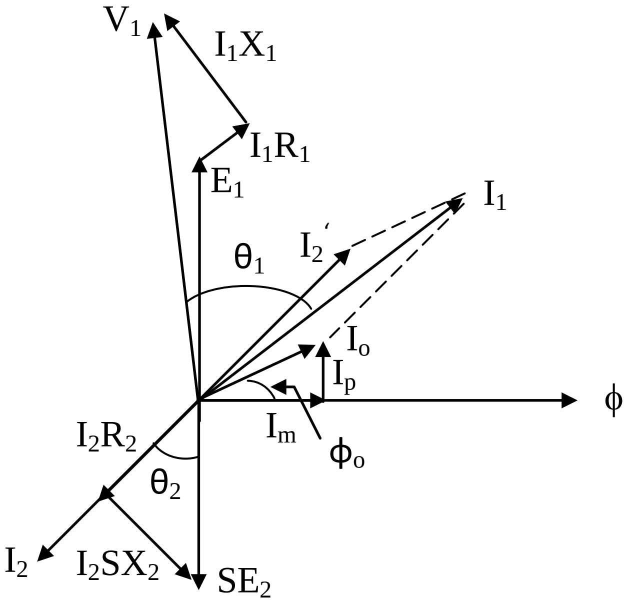
$$P_g = 3I_2'^2\frac{R_2'}{S} = P_d + P_{cu2}, \quad P_{cu1} = 3I_1^2R_1$$

P_d: Mechanical developed power, P_{cu2}: Rotor copper losses

$$P_d = 3I_2'^2\left(\frac{1-S}{S}\right)R_2' = P_o + P_{ml}, \quad P_{cu2} = 3I_2'^2R_2'$$

P_o: Output (shaft) power, P_{ml}: Windage and friction losses

3-8 3-Ph Induction Motor Phasor Diagram:-



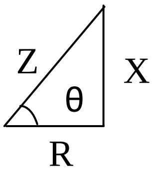
3-9 Circle Diagram:-

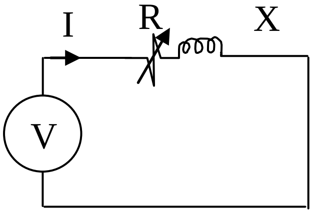
It can be shown that the current vector for a series circuit with constant reactance and voltage but with variable resistance is a circle.

$$I = \frac{V}{\sqrt{R^2 + X^2}} = \frac{V}{Z}$$

$$\sin\theta = \frac{X}{Z} \rightarrow Z = \frac{X}{\sin\theta}$$

$$\therefore I = \frac{V}{X/\sin\theta} = \frac{V}{X}\sin\theta$$





The above equation represents a circle with the polar axis θ (θ is changed between 0 and 180°) and I.

Similarly for 3-ph I.M.:- The vector of current I_2' will lie on a circle and I_1 is the vector sum of I_o (constant) and I_2'.

$$I_2' = \frac{V_1}{\sqrt{\left(R_1 + \frac{R_2'}{S}\right)^2 + \left(X_1 + X_2'\right)^2}}$$

To draw the complete circle diagram we must perform the following two tests:-

a) No-load test b) Blocked-rotor test

From no-load test: I_o, V_o, W_o (per phase) are noted

$$\text{Cos}\,\emptyset_o = \frac{W_o}{V_o I_o} \rightarrow \emptyset_o = \cos^{-1}\frac{W_o}{V_o I_o}$$

From blocked-rotor test: I_S, V_S, W_S (per phase) are noted

$$\emptyset_S = \cos^{-1}\frac{W_S}{V_S I_S} \rightarrow W_S = V_S I_S \cos\emptyset_S$$

$$I_S^{'}(at\ rated\ voltage) = I_S(at\ V_S) * \frac{rated\ voltage}{V_S}$$

The circle diagram should be at least 25 cm in diameter and the scale of current should be chosen accordingly.

K_I: Current scale (A/cm), K_P: Power scale = $\sqrt{3}V_{1L}K_I$

K_T: Torque scale = $K_P/\ \omega_S$

$$\overline{OA} = I_o \lfloor -\emptyset_o\ ,\overline{OP_1} = I_S^{'} \lfloor -\emptyset_S$$

*A and P_1 are two points on the circle diagram and the centre is found by drawing a perpendicular on the midpoint of the sector line AP_1. The intersection between this perpendicular and the horizontal line AD will give the centre of the circle (point C). The radius of the circle is AC.

P_1D = rotor copper loss + stator copper loss at stand still.

$$\frac{P_1F}{FD} = \frac{rotor\ cu\ loss}{stator\ cu\ loss} = \frac{3I_2^{'2}R_2^{'}}{3I_2^{'2}R_1} = \frac{R_2^{'}}{R_1}$$

DE = iron losses in watts, AF = the torque line, AP_1 = the output power line.

The torque is measured in synchronous watts.

P represents any operating point on the circle.

PE = input power, OP = input current, $\eta\% = \frac{PG}{PE} * 100\%$

*From point O the tangent to the circle will give maximum power factor.

$$Torque\ in\ N.m = \frac{synchronous\ watts}{synchronous\ speed\ in \frac{rad}{sec}}$$

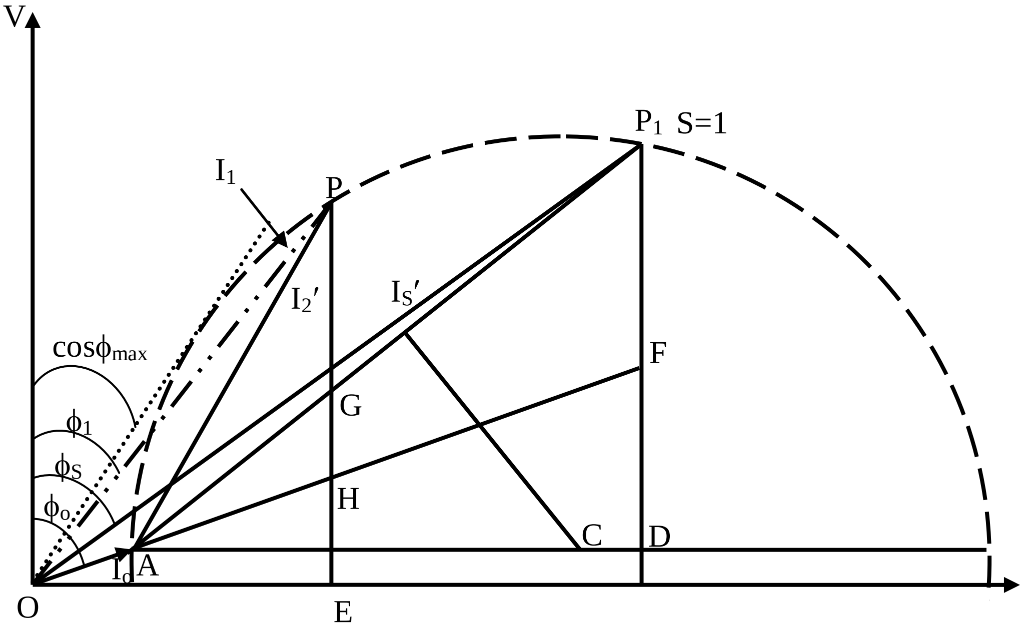
$$Slip = \frac{rotor\ copper\ loss}{rotor\ input} = \frac{GH}{PH}$$

*To obtain the slip line joins IP_1 and produce the line to any convenient point J. From J draw a perpendicular JK on the torque line AF, meeting the line AD at K. With K as zero and J as 100 divide the line JK into 100 equal parts. To find the slip corresponding to the operating point P, join P and I. Let the line PI cut JK at L. The LK will be the slip to the scale of JK as 100, and the slip is equal to

$$Slip = \frac{LK}{JK}$$

*To obtain the efficiency line produce the power line AP_1 backwards to meet the base line OE at A'. Extended the line AP_1 beyond P_1 to a convenient point P_1'. Draw $A'B$ perpendicular to OE. Draw a line from P_1' parallel to OE and meeting $A'B$ at B. Point P_1' represents 0% efficiency and point B 100% efficiency. To obtain the machine efficiency corresponding to the operating point P, the $A'P$ is extended to intersect the line $P_1'B$ at P', and the efficiency is equal to

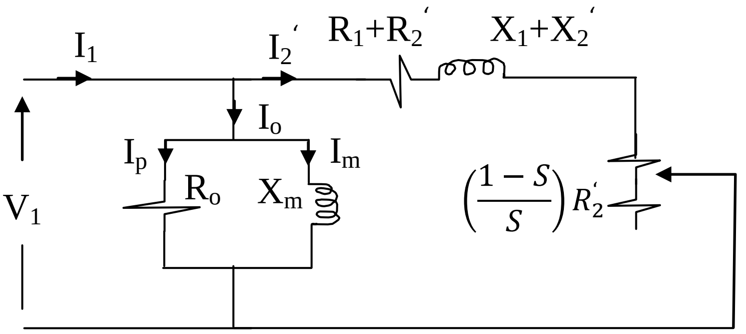
$$\eta\% = \frac{P_1'P'}{P_1'B} * 100\%$$



3-10 Starting of Induction Motors:-

Similarly as in the case of poly phase transformers, a high current will pass through the induction motor when it is switched to the supply.

The reason for that can be explained as follows:



$$I_2' = \frac{E_1}{\sqrt{\left(\frac{R_2'}{S}\right)^2 + (X_2')^2}}$$

From the above equation it is clear that I_2' will reach high value when S=1 (stand still). Thus, I_1 will be high too.

$$P_d = T_d\frac{2\pi N}{60} = 3{I_2'}^2\left(\frac{1-S}{S}\right)R_2' \dots\dots \langle 1\rangle, S = \frac{N_S - N}{N_S} \rightarrow N = (1-S)N_S \dots\dots \langle 2\rangle$$

From 2 in 1:-

$$T_d = \frac{180 R_2' {I_2'}^2/S}{2\pi N_S} = \acute{K}\frac{{I_2'}^2}{S} \rightarrow T = K\,{I_1}^2/_S \dots\dots \langle 3\rangle$$

Where T: output torque, T_d: developed torque, I_1: input current, P_d: developed power, K & K': constants.

At starting (S=1) → $T_{St} = K{I_{St}}^2 \dots\dots \langle 4\rangle$

At full load (S=S_{FL}) → $T_{FL} = K\,{I_{FL}}^2\big/_{S_{FL}} \dots\dots \langle 5\rangle$

Dividing 4 by 5 gives:-

$$\frac{T_{St}}{T_{FL}} = \left(\frac{I_{St}}{I_{FL}}\right)^2 S_{FL} \dots\dots \langle 6\rangle$$

Different method of starting will be discussed as follows:-

1. Direct Switching of 3-ph Induction Motor:-

In this method the I.M. is directly switched to a 3-ph supply. The starting current I_{St} is called the short circuit current I_{SC}.

$$\frac{T_{St}}{T_{FL}} = \left(\frac{I_{SC}}{I_{FL}}\right)^2 S_{FL} \dots\dots \langle 7 \rangle$$

2. Primary Resistors:-

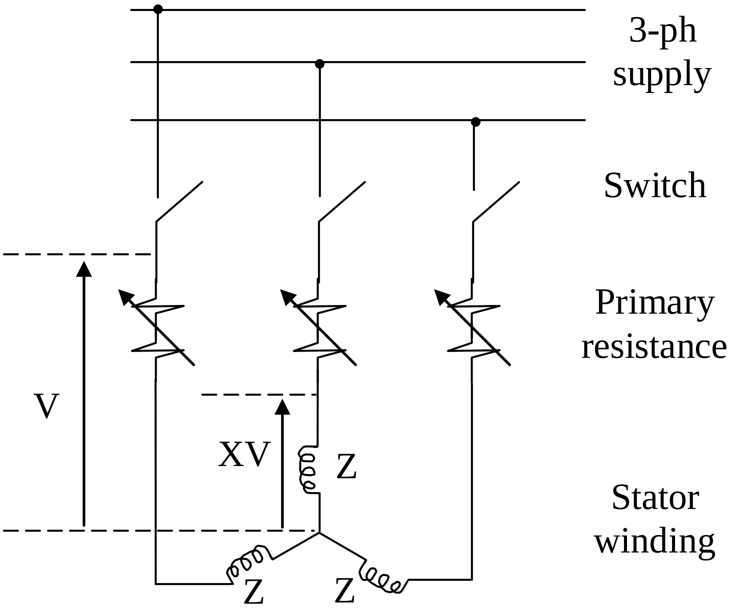
$I_{SC} = \frac{V}{Z}$ *for direct switching*

$I_{St} = \frac{XV}{Z}$ *using resistors*

$I_{St} = XI_{SC}$

Substituting in equ. 6 gives

$$\frac{T_{St}}{T_{FL}} = X^2 \left(\frac{I_{SC}}{I_{FL}}\right)^2 S_{FL} \dots\dots \langle 8 \rangle$$

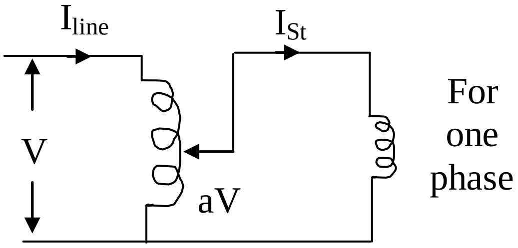


3. Auto Transformer Starting:-

$I_{St} = \frac{aV}{Z} = aI_{SC}$

Substituting in equ. 6 gives

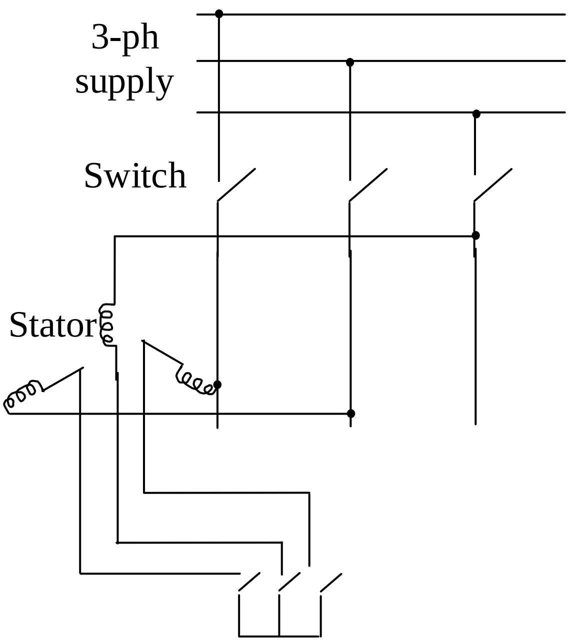
$$\frac{T_{St}}{T_{FL}} = a^2 \left(\frac{I_{SC}}{I_{FL}}\right)^2 S_{FL} \dots\dots \langle 9 \rangle$$



Auto transformer

Where a is the transformation ratio (a<1)

4. Star-Delta Starting:-



$$I_{SC} = \frac{V}{Z}, I_{lst} = \sqrt{3}\, I_{SC} \rightarrow$$

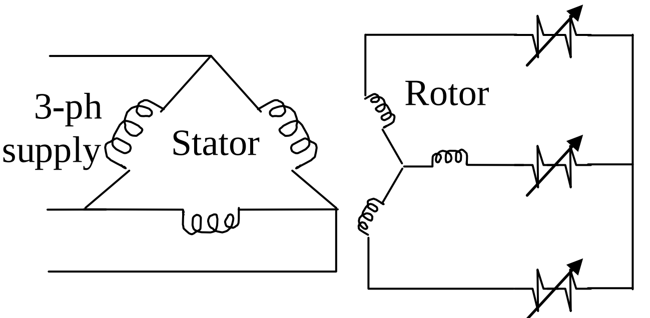
$$I_{SC} = \frac{I_{lst}}{\sqrt{3}}\ delta\ direct\ switching$$

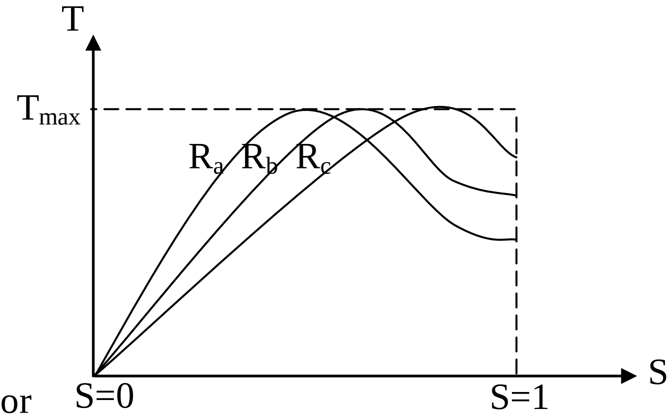
$$I_{St} = \frac{V/\sqrt{3}}{Z} = \frac{I_{SC}}{\sqrt{3}}\ star \rightarrow I_{St} = \frac{I_{lst}}{3}$$

Substituting in equ. 6 gives

$$\frac{T_{St}}{T_{FL}} = \frac{1}{3}\left(\frac{I_{SC}}{I_{FL}}\right)^2 S_{FL} \ldots\ldots \langle 10 \rangle$$

Starting of Slip-Ring I.M.





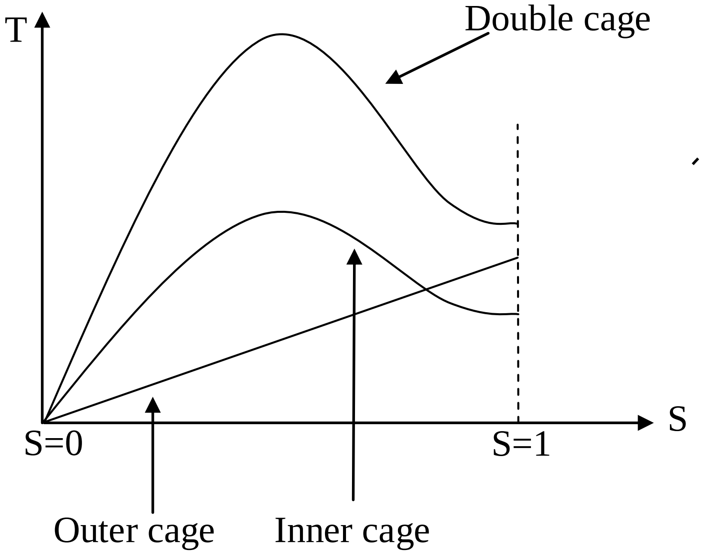
The variable resistor connected to the rotor can control the starting torque of the slip-ring I.M. as shown above. Also the addition of resistance in the rotor circuit will reduce the starting current.

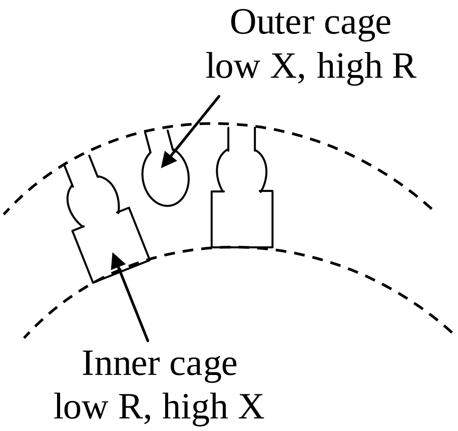
$$I_2 = \frac{E_2}{\sqrt{\left(\frac{R_2}{S}\right)^2 + (X_2)^2}} \rightarrow I_{2st} = \frac{E_2}{\sqrt{{R_2}^2 + {X_2}^2}}$$

Thus, increasing R_2 will reduce I_{2st}

Double Squirrel Cage Motor

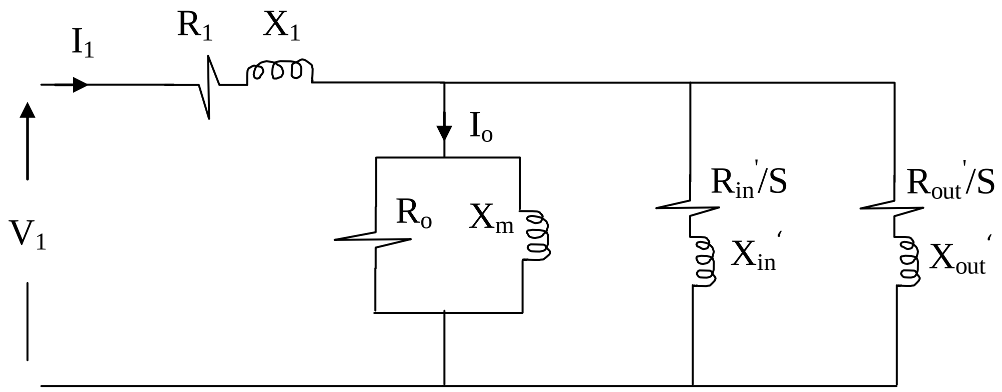
The outer cage will increase the starting torque since it has high resistance, but its running performance is poor due to the same reason. Most of the current passes in the inner cage at running condition since its impedance will be low.





$Z_{in} = \sqrt{R_{in}^2 + (SX_{in})^2} \approx R_{in}, Z_{out} = \sqrt{R_{out}^2 + (SX_{out})^2} \approx R_{out}$,, since S≅0

The equivalent circuit of the double cage 3-ph I.M. is:-



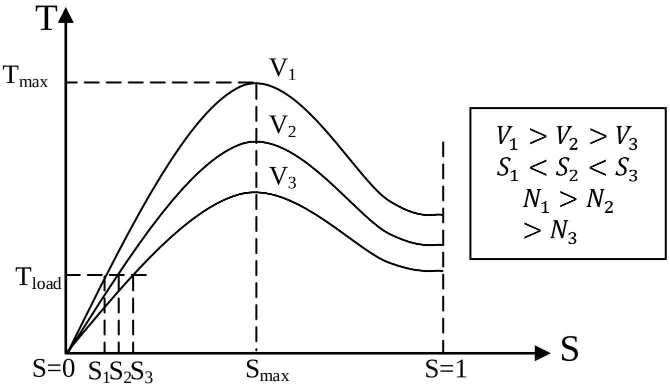
3-11 Speed Control of Induction Motor:-

The speed of 3-ph I.M. can be controlled either from stator or from rotor.

a) Control from Stator Side:-

1) Changing the applied voltage:-

$$T = K\frac{R'_2 S\, V_1^2}{R'^2_2 + (SX'_2)^2}$$



From the above equation it is clear that the applied voltage can affect the torque-slip characteristics as shown in the figure above. For constant load torque, the speed will change with the applied voltage but the control is not so high.

2) Changing the applied frequency:-

The synchronous speed of the I.M. is $N_S = \frac{120f}{2p}$. Therefore, the supply frequency can control the synchronous speed and thus controlling the speed of the motor.

3) Changing the number of stator poles:-

$N_S = \frac{120f}{2p}$, f=50Hz

For 2p=2	4	6	8	----	
N_S= 3000	1500	1000	750	-----	r.p.m.

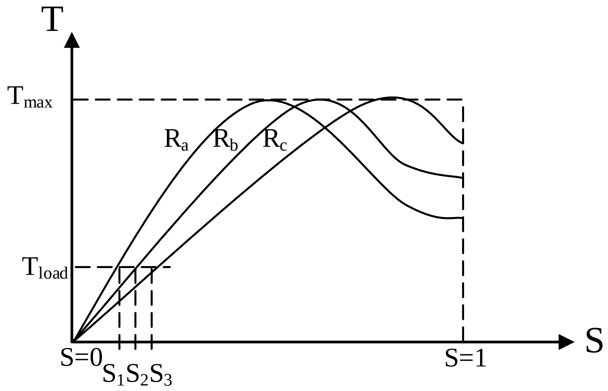
Therefore, the speed of the I.M. can be controlled by changing the number of stator poles but the control is not smooth.

b) Control from Rotor Side:-

1) Rotor rheostat control:-

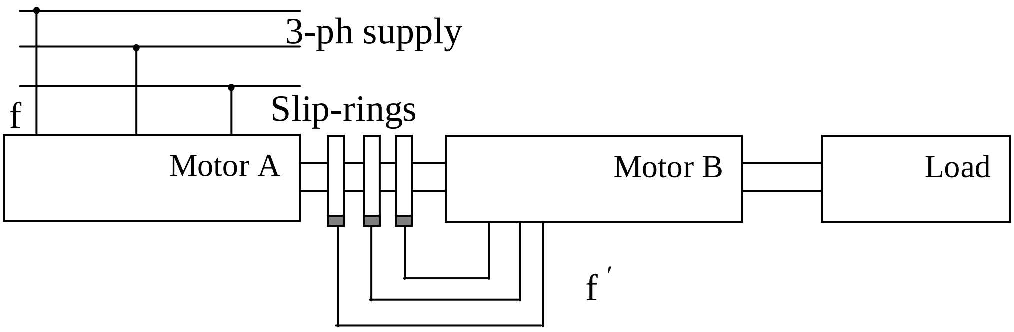
The addition of rheostat in the rotor circuit of the I.M. will greatly affect the speed-torque characteristics as shown:-

$$\boxed{\begin{gathered} R_c > R_b > R_a \\ N_3 < N_2 < N_1 \\ S_3 > S_2 > S_1 \end{gathered}}$$



From this figure it is clear that the speed can be controlled by a great amount by the addition of rotor resistance but this will increase the copper losses in the motor and the efficiency decreased.

2) <u>Cascade operation:-</u>



$$N_{Sa} = \frac{120f}{2p_a} \ldots\ldots < 1 >, \acute{f} = Sf = \frac{N_{Sa}-N}{N_{Sa}} f \ldots\ldots < 2 >$$

Where: f= supply frequency, N= shaft speed, f'= motor A rotor frequency

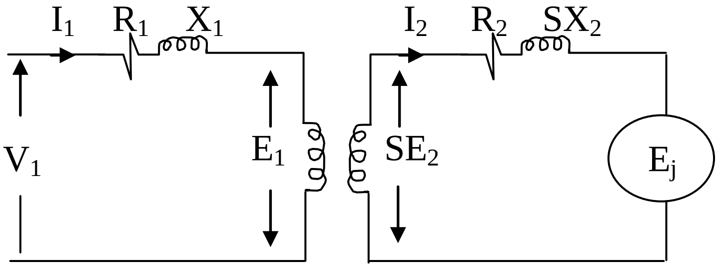
$$N_{Sb} = \frac{120\acute{f}}{2p_b} \ldots\ldots < 3 >$$

On no-load the speed of motor B is almost equal to its synchronous speed, i.e.,

$$N = N_{Sb} \ldots\ldots < 4 > \rightarrow N = \frac{120\acute{f}}{2p_b} = \frac{120f}{2p_a} * \frac{(N_{Sa}-N)}{N_{Sa}} = \frac{120f}{2p_a + 2p_b}$$

3) Injecting an emf in the rotor circuit:-

The speed of an I.M. can be controlled by injecting a voltage with slip frequency in the rotor circuit:-



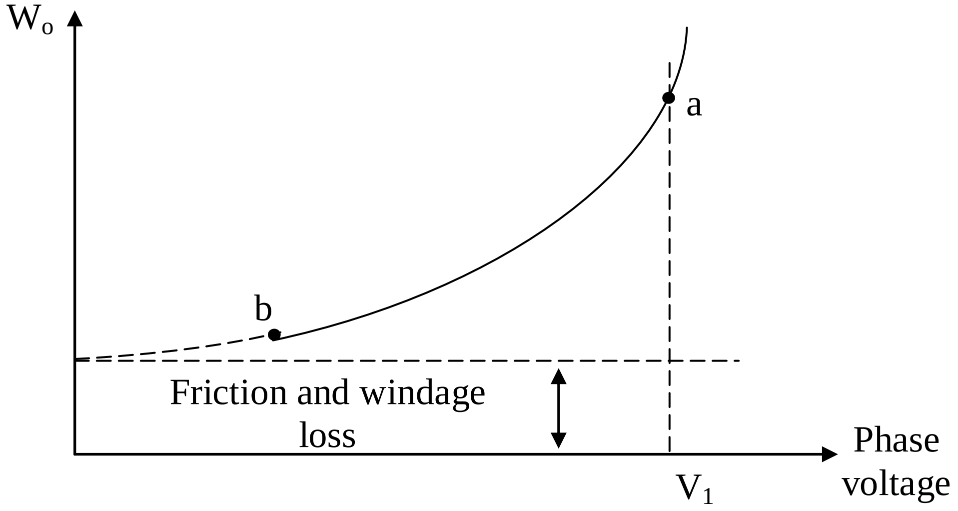
$T = {CI_2^2}/{S}$ where C constant

For constant load torque:

1) The injected voltage is in phase opposition to the induced rotor emf: $I_2 = \frac{SE_2 - E_j}{\sqrt{R_2^2 + (Sx_2)^2}}$, the rotor current will reduce, reducing the torque, reducing the speed and increasing the slip. The slip will continue to increase till sufficient emf (SE_2) is produced to increase the current so that the same torque may be produced. This case is similar to increasing the rotor resistance.
2) The injected voltage is in phase to the induced rotor emf: $I_2 = \frac{SE_2 + E_j}{\sqrt{R_2^2 + (Sx_2)^2}}$, the rotor current will increase, increasing the torque, increasing the speed and reducing the slip. The slip will continue to decrease till sufficient emf (SE_2) is produced to decrease the current so that the same torque may be produced. This case is similar to readucing the rotor resistance. This method can provide a wide range of a speed control.

3-12 Separation of Friction and Windage Losses:-

By performing no-load test with a varying voltage, it is possible to draw the following curve:-



Point (a) corresponds to operation at rated voltage. Experimental points below point (b) are not taken because the speed will no longer be close to synchronous speed. Extrapolation of the curve to the Y-axis gives a good indication of the friction and windage loss at normal speeds.

At no-load and rated voltage the input power is used to supply three losses:

$$W_o = P_{cu1} + P_c + P_{ml} = mI_o{}^2R_1 + P_c + P_{ml}$$

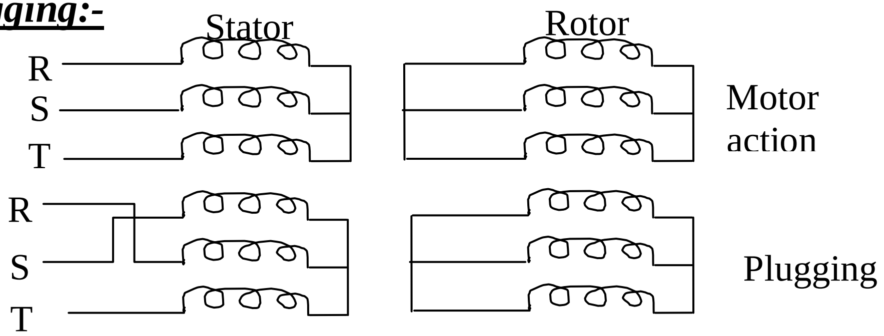
Where m: no. of phases, I_o: no-load current

Note:- When specific information about P_c or P_{ml} is not known, it is often to assume these quantities to be equal.

3-13 Braking of 3-ph I.M.:-

It is generally desirable to employ an electric brake to bring an ac motor to rest quickly because electric braking is smooth, provides accurately timed stops, and is not subject to the problems of friction. It is possible to have electric braking by:-

a) Plugging:-

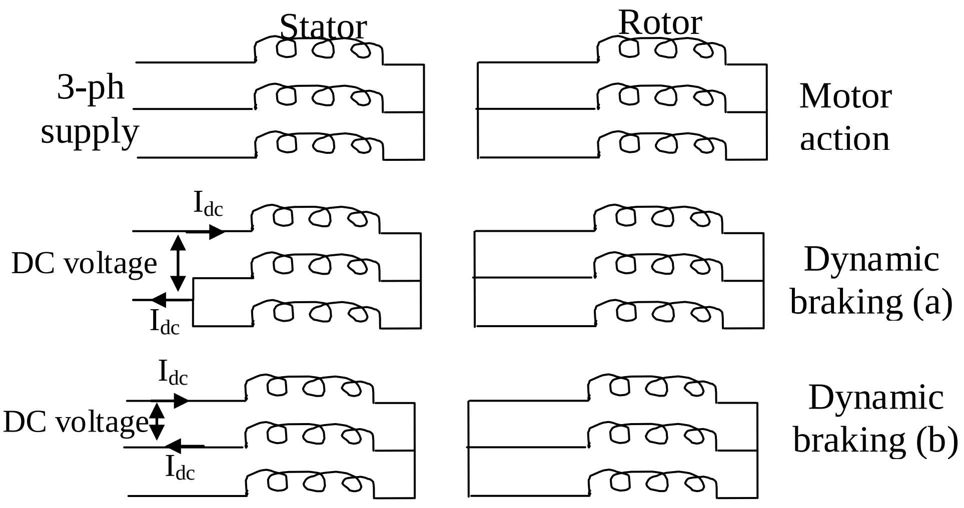


The principle of plugging as applied to I.M. depends upon the fact that the direction of rotation is the same as the direction of the revolving field which depends on the phase sequence of the source. This means that the direction of rotation of a 3-ph I.M. may be reversed by interchanging two leads at the motor because such a change reverses the direction of the revolving field. Under this condition the slip is more than one and the motor develops backward torque. The speed slowdown and the motor will draw very high current. The motor must be disconnected from the supply when reaching zero speed otherwise it will rotate in the reverse direction.

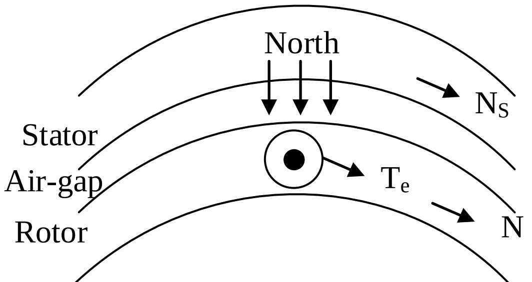
$$I_1 = I_o + I_2' \ , \ I_2' = \frac{V_1}{\sqrt{\left(R_1 + \frac{R_2'}{S}\right)^2 + (X_1 + X_2')^2}} \ , \ S>1 \rightarrow I_2' \text{ is very high}$$

It is possible to reduce the braking current by changing the stator connection to star during braking, thus, reducing the line current to 1/3 or by connecting resistances in series with the stator and with the rotor (for wound-rotor).

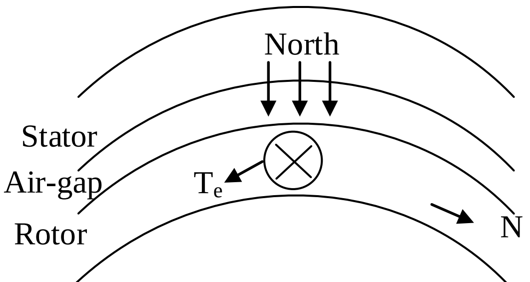
b) <u>Dynamic Braking or Rheostatic Braking:-</u>



The field produced by poly phase current rotates at speed N_S in the same direction, but faster than the rotor conductors. If, when operating with an initial slip S, the primary winding is switched over to dc excitation, the field is now stationary in space, so that the conductors are moving faster than the field at a speed N.

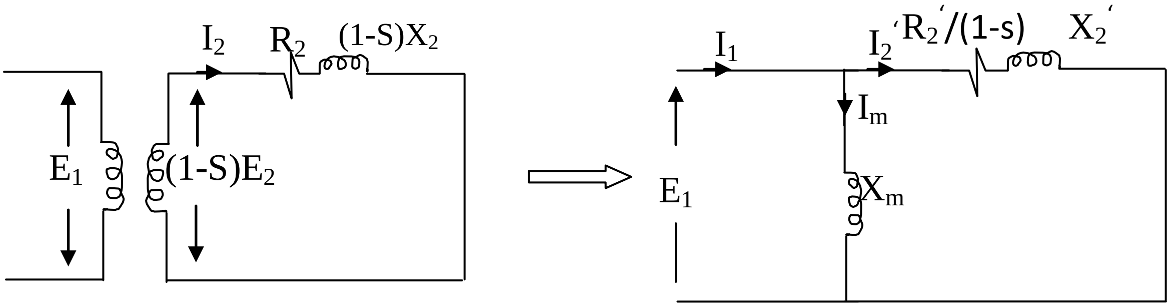


AC excitation
(motor)



DC excitation
(braking)

The induced current is therefore reversed and a generating torque (braking torque) is produced in the opposite direction. Thus, the motor slowdowns and it will stop when reaching zero speed because it is disconnected from the ac supply. The rotor reactance, rotor frequency, and the rotor emf become (1-S)X_2, (1-S)f, and (1-S)E_2 respectively.



The stator circuit no longer carries ac current so that the reactance of the stator in neglected and the resistance is only required to determine the dc excitation voltage. There will be no iron loss on the stator core and the rotor iron loss will cause effective increase in the rotor referred resistance. The magnetizing branch of the equivalent circuit will be just X_m.

$$E_1 = I_m X_m, \acute{I}_2 = \frac{E_1}{\frac{\acute{R}_2}{1-S} + j\acute{X}_2}, T_d = \frac{P_g}{\omega_S} = \frac{3\acute{I}_2 \frac{\acute{R}_2}{1-S}}{\omega_S}$$

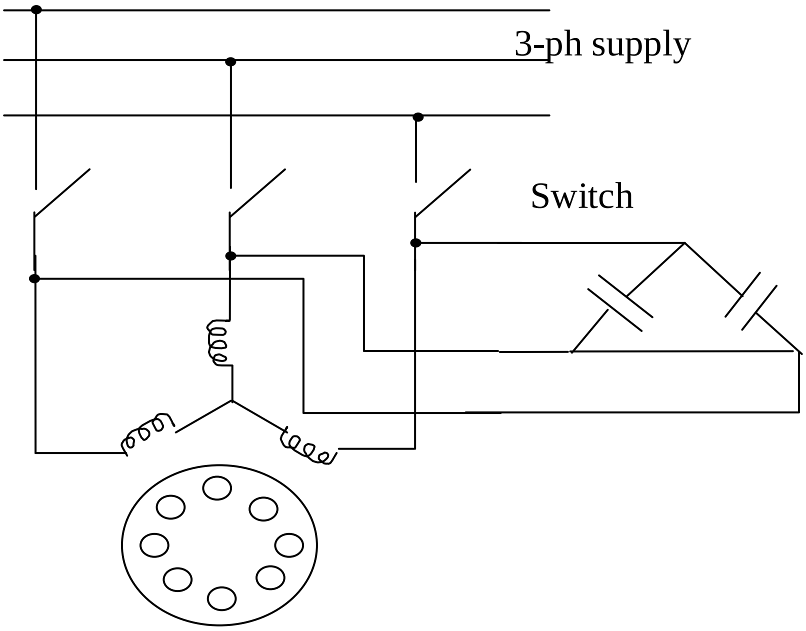
c) ***Regenerative Braking:-***

In this braking, the machine operates as an induction generator feeding the power back to the supply while the power in the previous methods is dissipated as losses. In this method, the slip is made negative (generator action), i.e., the rotor speed is more than the synchronous speed. The slip is made negative by reducing N_S. Hence, by decreasing the frequency or by increasing number of poles, N_S is decreased.

The power is fed back to the supply and the motor speed starts decreasing. Complete braking is not possible in this method because when the machine speed decreases and become less than N_S it will be again in the motor action with the new N_S. In this case use plugging the motor to complete the braking, no high current will flow. Another way to complete the braking is by continuously reducing the frequency as the motor speed decreases.

d) ***A.C. Dynamic Braking:-***

This method is mainly used and is employed for small motors. As shown in the figure below, the stator is connected to capacitors. To brake the motor, the supply is disconnected. The machine will operate as an induction generator and the dynamic power is dissipated in the internal resistors.



3-14 Induction Generator:-

An induction generator does not differ in its construction from an induction motor. An induction machine can act as generator or motor depending upon its slip. Below N_S, it can operate as motor, above N_S it's operate as generator.

The power factor at which an induction generator operates is fixed by its slip and its equivalent circuit constants and not by the load. It is necessary to operate induction generator in parallel with the main supply. The main supply not only supply the lagging current demand by the load but also supply sufficient lagging current to cancel the leading component of the current delivered by the induction generator.

The induction generator depends upon its leading current for excitation, and unless the connected load takes this leading component of current, the induction generator loses its excitation. The frequency and voltage of the induction generator are the same as for the main supply. The induction generator output is fixed by the slip.

3-14-1 Changes in Power Produced by a Change in Slip:-

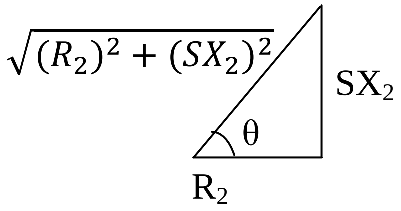
The following changes in power occur as the slip of an induction machine changes:-

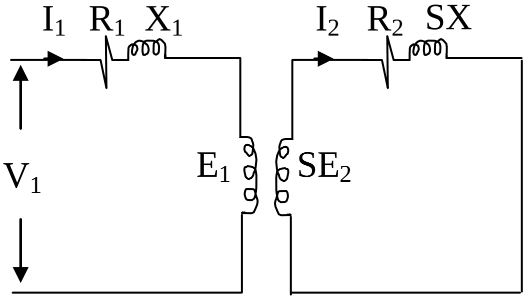
1. Below N_S there is rotor current and the motor action occurs.
2. At N_S the rotor current is zero. The current in the stator comes from the main supply. It consists from the exciting current I_m and the core loss component I_p. The mechanical power (taken from prime mover) required to drive the rotor at N_S is equal to the friction and windage.
3. Above N_S the current in the rotor reverses in the direction as does also the component current in the stator required to balance the demagnetizing action of the rotor current. At a speed above N_S, generator action occurs, but the power is not delivered to the

external circuit until the current in the stator has a component equal and opposite to the current I_p required to supply the core loss. Therefore, the induction generator at this slip will supply its core loss only. Its external output is zero. At larger slip, power is delivered to the load.

3-14-2 Power Factor of the Induction Generator:-

The only current to produce generating power in an induction generator is that component of stator current which is equal and opposite of the referred current. The power factor of this component with respect to the primary induced voltage is fixed by the rotor constants and by the slip. The power factor of an induction generator is leading. The power factor in large machines is over 0.9 at full load, but at no load or small loads it may be very low. $Cos\theta = \frac{R_2}{\sqrt{(R_2)^2+(SX_2)^2}}$



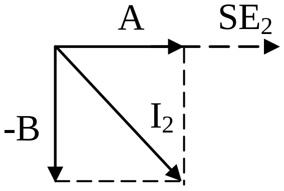


3-14-3 Phase Relation Between Rotor Current Referred to the Stator and Rotor Induced Voltage E_2:-

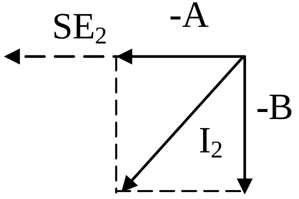
$$I_2 = \frac{SE_2}{R_2 + jSX_2}\left[\frac{R_2 - jSX_2}{R_2 - jSX_2}\right] = E_2\left[\frac{SR_2}{{R_2}^2 + (SX_2)^2} - j\frac{S^2X_2}{{R_2}^2 + (SX_2)^2}\right]$$

$$= A - jB$$

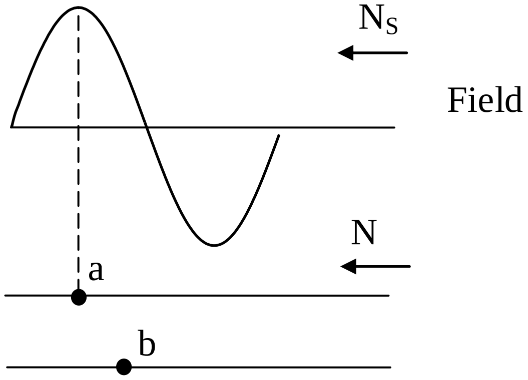
Below N_S, S is +ve and I_2 takes the form $I_2 = A - jB$ (lagging current with respect to SE_2).



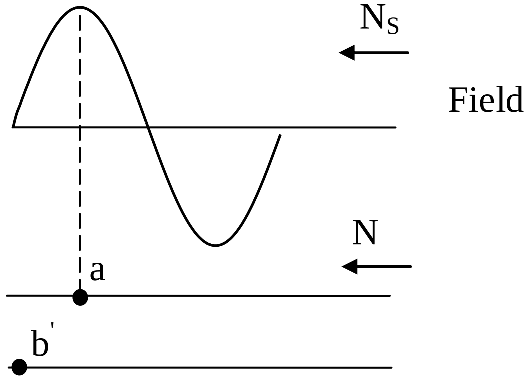
Above N_S, S is -ve and I_2 takes the form $I_2 = -A - jB$ (leading current with respect to SE_2).



The current I_2 in the rotor can not actually lead the rotor voltage which causes it since the rotor circuit is inductive. It is only when this current is considered with respect to the stator. This can be seen from the following figure:-



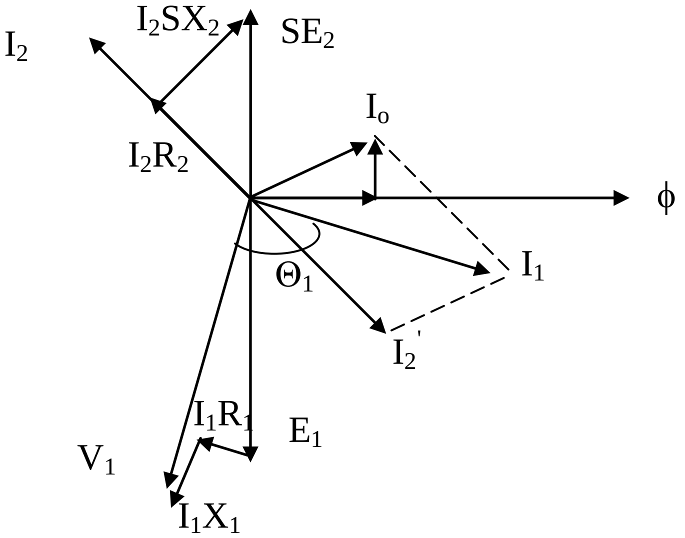
Rotor below N_S



Rotor above N_S

Consider the voltage induced in conductor "a" on the rotor. This voltage has its maximum value when the conductor is at maximum flux density of the stator field, in position "a". Below N_S, the rotor moves to the right relatively to the field, and since the rotor circuit is inductive, the conductor moves to position "b" before the current in it reaches maximum. Above N_S, the rotor moves faster than the field, i.e., it moves to the left with respect to the field. In this case the conductor "a" moves to position "b'" before the current in it reaches its maximum value. In both cases the rotor when considered with respect to the stator moves in the same direction as the field. Therefore, if the voltage and current in the rotor are observed from any fixed point on the stator, the voltage is seen to pass through its maximum (lagging) when the rotor is below N_S and after the current passes through its maximum value (leading) when the rotor is above N_S.

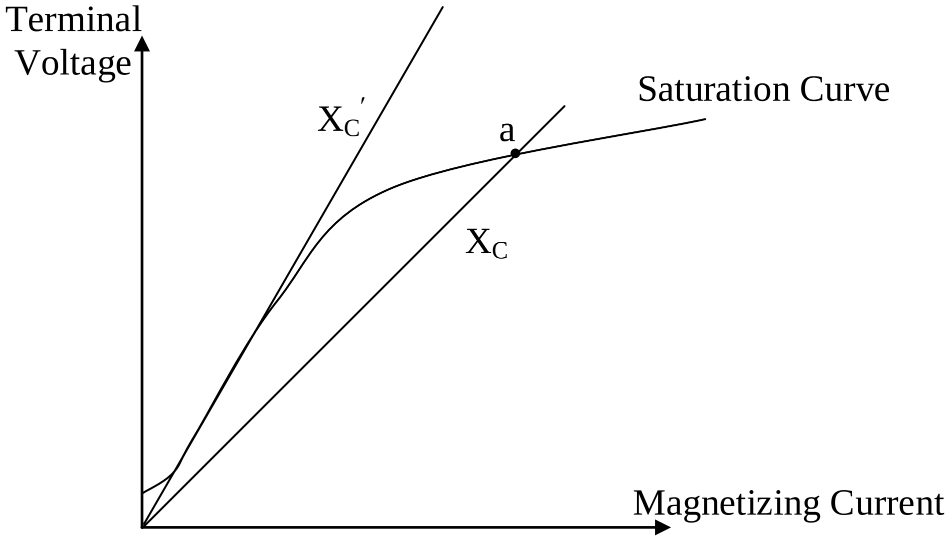
3-14-4 Phasor Diagram of the Induction Generator:-



3-14-5 Use of Capacitors in Parallel with the Induction Generator:-

It is possible to operate an induction generator without connecting it to the main supply by connecting suitable capacitors across its terminals. This method of operation has no practical importance because of the big size and cost of the capacitors and due to the dropping voltage characteristics of such system.

It is often stated that an induction generator is not self-exciting, this statement is not true. If suitable capacitance is placed across the terminals of an induction generator, it generally builds up as a synchronous generator because of the residual magnetism in the rotor from previous operation.



From the figure, "a" is the operating point and X_C is the value of the capacitive reactance. $\acute{X}_C = \frac{1}{\omega \acute{C}}$ is the value of the critical capacitive reactance. This is similar to the magnetizing characteristics of dc shunt generator.

3-14-6 Application of Induction Generator:-

Induction generators are useful when the prime mover does not run at constant speed; for example, hydro-electric power stations, and wind power stations because the frequency depends on that of the main supply. Also, they are used in the braking action of the induction motor.