EE240: Power Engineering LAB

Induction Motor

Instructor

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Classification of Machines:

DC machine
- → stator → DC
- → rotor → 'I' flowing in the load or from external source is DC

AC machine

- Synchronous machine
  - Stator → AC/DC
  - Rotor → DC/AC
- Asynchronous machine
  - Stator, Rotor → AC

Asynchronous machine:

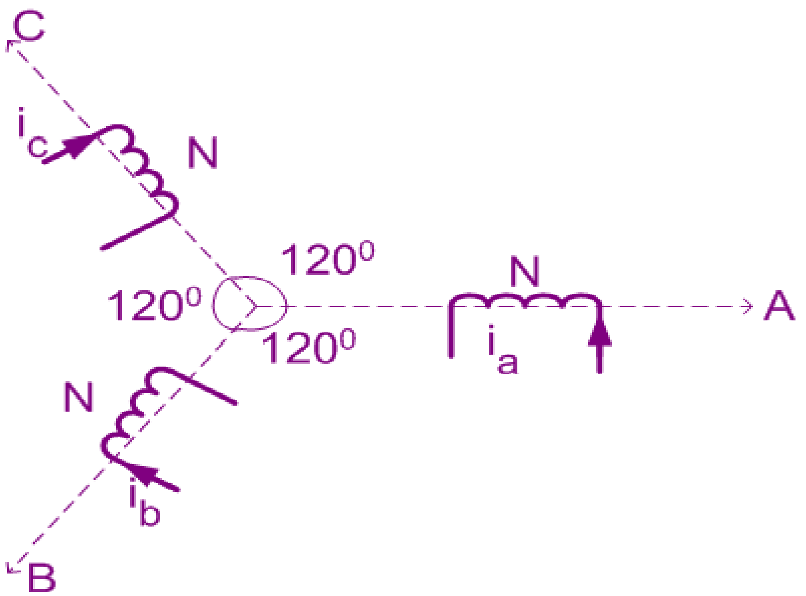
consider 3 coils of ‘N’ turns,
displaced in space by 120°,

let $$i_a = I_m \sin(\omega_s t)$$

$$i_b = I_m \sin\left(\omega_s t - \frac{2\pi}{3}\right)$$

$$i_c = I_m \sin\left(\omega_s t + \frac{2\pi}{3}\right)$$

where $\omega_s = 2\pi f_1$



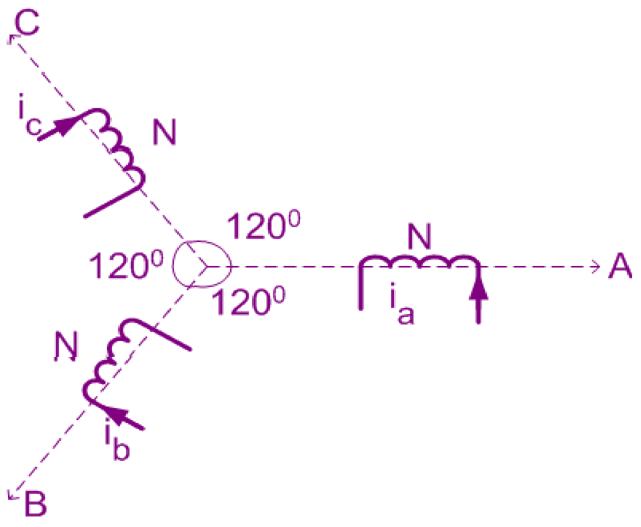
$\Rightarrow$ current in each coil produces a pulsating magnetic field.

$\Rightarrow$ amplitude & direction depend on the instantaneous value of ‘I’ flowing through it.

$\Rightarrow$ each phase winding produces a similar magnetic field displaced by 120^0 in space from each other.

$\Rightarrow$ magnitude and position of the resultant field can be determined as follows

- resolve the field produced by individual coil along x & y axes
- determine $\sum x$ & $\sum y$ components
- resultant 'R'= $\sqrt{\sum x^2 + \sum y^2}$



and $\theta = \tan^{-1}\dfrac{y}{x}$ w.r.t. axis of coil 'A'

$$\Sigma x = Ni_a + Ni_b\cos(120) + Ni_c\cos(240) = Ni_a - \frac{1}{2}Ni_b - \frac{1}{2}Ni_c$$

$\because i_a + i_b + i_c = 0$ $\qquad \Sigma x = \dfrac{3}{2}Ni_a$

$$\Sigma y = 0 + Ni_b\sin(-120) + Ni_c\sin(-240) = \frac{\sqrt{3}}{2}N[i_c - i_b]$$

$\Rightarrow$ i_a, i_b & i_c are sinusoidal varying quantities

$\omega_s t$	i_a	i_b	i_c	$\sum x$	$\sum y$	R	θ
$0°$	0	$-\frac{\sqrt{3}}{2}I_m$	$\frac{\sqrt{3}}{2}I_m$	0	$\frac{3}{2}NI_m$	$\frac{3}{2}NI_m$	$\frac{\pi}{2}$
$30°$	$\frac{I_m}{2}$	$-I_m$	$\frac{I_m}{2}$	$\frac{3}{4}NI_m$	$\frac{3\sqrt{3}}{4}NI_m$	$\frac{3}{2}NI_m$	$\frac{\pi}{3}$
$90°$	I_m	$-\frac{I_m}{2}$	$-\frac{I_m}{2}$	$\frac{3}{2}NI_m$	0	$\frac{3}{2}NI_m$	0
$180°$	0	$\frac{\sqrt{3}}{2}I_m$	$-\frac{\sqrt{3}}{2}I_m$	0	$\frac{3}{2}NI_m$	$\frac{3}{2}NI_m$	$\frac{-\pi}{2}$

Observations:

- magnitude of 'R' is constant, I $\rightarrow$ peak value
- Input 'I' completes $\frac{1}{4}$ cycle

  $\Rightarrow$ 'R' rotates by 90^0
- Input 'I' completes $\frac{1}{2}$ cycle

  $\Rightarrow$ 'R' rotates by 180^0

Conclusion:

$\Rightarrow$ the result of displacing 3 windings by 120^0 in space and displacing the winding 'I' by 120^0 in time phase is a single revolving field of constant magnitude.

$\Rightarrow$ for a given winding arrangements speed of rotation is determined by frequency of input 'V' or 'I' alone.

$\therefore$ the speed of rotating magnetic field is $\omega_m = \omega_s \frac{2}{P}$ rad/sec(mech)

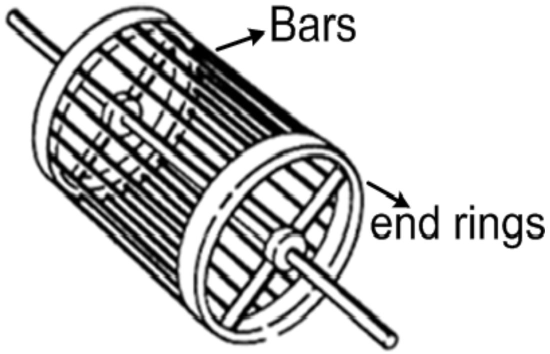
If 'N_s' is speed in rpm, $\frac{2\pi N_s}{60} = \left(\frac{2}{P}\right) 2\pi f_1$

$\therefore N_s = \frac{120 f_1}{P}$ rpm $\qquad P \rightarrow$ no. of poles

In practice stator winding of IM is distributed in large number of slots.

The winding is distributed and number of poles depend on winding arrangement.

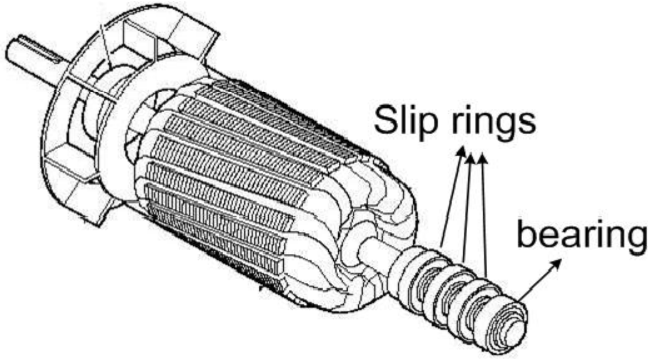
<u>Rotor</u>: Two types of constructions



<u>Squirrel cage</u>: aluminum/ cu bars are embedded in the rotor slots and permanently shorted at both ends by al/cu end rings

$\Rightarrow$ electrically closed circuit

$\Rightarrow$ no additional 'R' can be connected.



<u>Slip Ring Rotor</u>: three phase winding is placed in rotor slots

$\Rightarrow$ three terminals of the windings are connected to three rings fixed to rotor shaft

$\Rightarrow$ external 'R'/'Z'/'V source' can be connected to these rings.

In both cases, when the rotor is at rest, synchronously rotating stator field induces voltage of stator frequency in rotor.

$\because$ rotor is at rest, relative speed between stator field & rotor is $N_s - 0 = N_s \rightarrow$ is maximum

$\because$ relative speed between field and conductor(rotor) is maximum, induced emf &

$\therefore$ rotor 'I' is maximum.

$\Rightarrow$ similar to transformer, for any current in secondary (rotor) there is an equivalent 'I' in primary(stator)

$\therefore$ if an IM is started at rated V & f, a high 'I' will be drawn from the source

$\Rightarrow$ this 'I' could be $\cong$ (6 - 7) times I_{FL}

$\Rightarrow$ current carrying conductor placed in magnetic field experience a force

$\Rightarrow$ conductor (rotor) starts rotating

$\Rightarrow$ as the speed $\uparrow$, relative speed between stator field & rotor $\downarrow$. As a result:

$\rightarrow$ induced 'V' in the rotor and hence the current $\downarrow$

$\rightarrow$ Frequency of induced 'V' & 'I' in the rotor $\downarrow$

$\Rightarrow$ rotor eventually reach a steady state speed N_r, $N_r < N_s$

$\Rightarrow$ N_r can not be = N_s because at $N_r = N_s$, relative speed between rotor (conductor) and stator field is zero.

$\Rightarrow$ no emf & $\therefore$ no 'I' & no force or torque

$$\text{slip } s = \frac{N_S - N_R}{N_S} \quad \therefore N_R = (1-s)N_S$$

$\Rightarrow$ N_s- N_r $\rightarrow$ slip speed &

slip in terms of frequency, $s = \dfrac{f_1 - f_3}{f_1} = \dfrac{\omega_s - \omega_r}{\omega_s} = \dfrac{f_2}{f_1}$

$f_2 = sf_1$ Hz or $\omega_2 = s\omega_1$

$\Rightarrow$ slip frequency $\Rightarrow$ frequency of rotor 'V' / 'I' $f_3 \rightarrow$ frequency corresponding to rotor speed

assume that if no load (external torque) is applied to the rotor shaft

$\Rightarrow$ developed torque by the motor $\Rightarrow$ overcome friction

$\Rightarrow$ should be very small (if neglected $N_r = N_s$)

$\therefore$ required rotor 'I' should also be small

$\Rightarrow$ $(N_s - N_r)$ is small (how small is this small ?)

$\Rightarrow$ apply external torque(T_L) to the motor shaft

$\Rightarrow$ motor should develop torque > T_L

$\Rightarrow$ 'I' flowing in the conductor(rotor) should $\uparrow$

$\Rightarrow$ $(N_s - N_r)$ should $\uparrow$

$\Rightarrow$ There would be corresponding $\uparrow$ in I_s (stator 'I')

$\therefore$ In IM, N_r is function of load

As TL $\uparrow$ Nr $\downarrow$ & $\therefore$ s$\uparrow$

N_r can never be equal to N_s

$\Rightarrow$ for steady torque, stator field (F_s)

& rotor field(F_r) should be

stationary w.r.t. each other

$\Rightarrow$ speed of $F_s = N_s$

$\Rightarrow$ direction of F_r is the same as that of F_s

$\Rightarrow$ Frequency of rotor 'I' is sf_1

$\Rightarrow$ these currents produce a field which rotates at sN_s rpm

w.r.t. rotor in same direction as that of F_s

$\Rightarrow$ rotor rotates at N_r w.r.t. stator

$\therefore$ speed of F_r w.r.t. stator

$$= N_r + sN_s = (1 - s)N_s + sN_s = N_s$$

$\Rightarrow$ thus both fields are stationary w.r.t. each other

⇒ rotor of IM has no electrically conducting connection with the stator supply (similar to that of a transformer secondary)

⇒ Input power is converted to mechanical output is transferred inductively – by transformer action - from stator to rotor by means of mutual flux

⇒ electrical behavior of IM is similar to that of a transformer.

⇒additional feature is frequency transformation (Frequency of rotor current $=sf_1$)

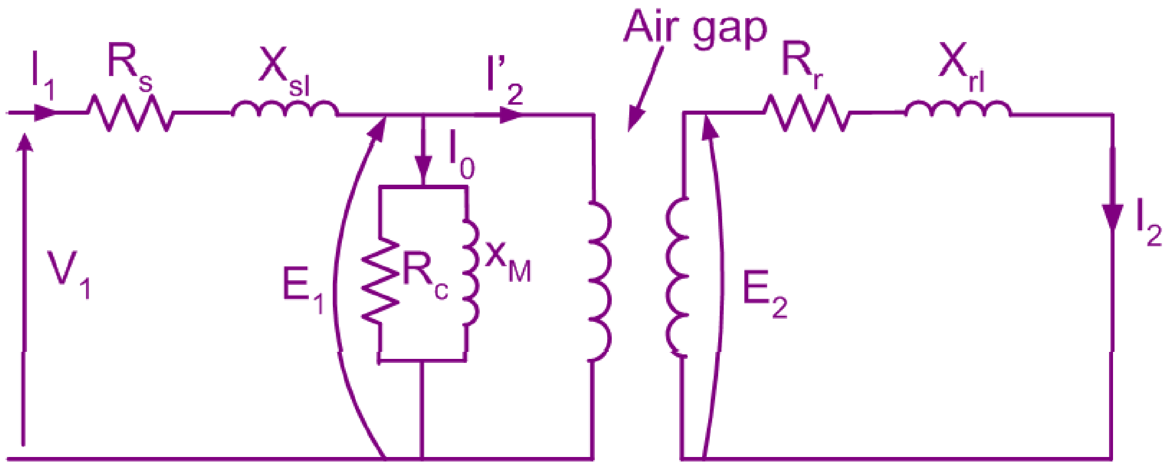
Equivalent circuit:

$x_{rl} = 2\pi f_2 l_{rl}$,

$l_{rl} \rightarrow$ leakage inductance in rotor

$E_2 = 4.44 f_2 \phi_M N_2 k_w$

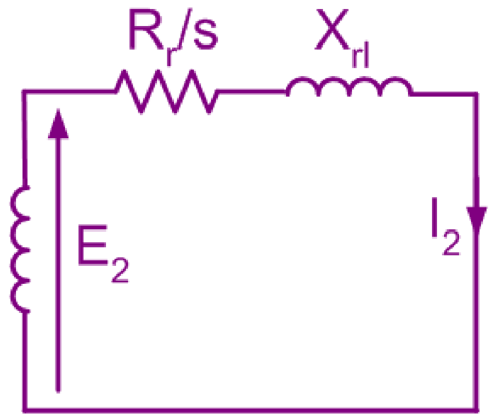
$k_w \rightarrow$ depends on winding, < 1



$$I = \frac{E_2}{R_r + jx_{rl}} = \frac{s(4.44 f_1 \phi_1 N_2 k_w)}{R_r + js(2\pi f_1 l_{rl})} = \frac{E_2}{\frac{R_r}{s} + jx_{rl}}$$

frequency of E_2, $f_2 = sf_1$

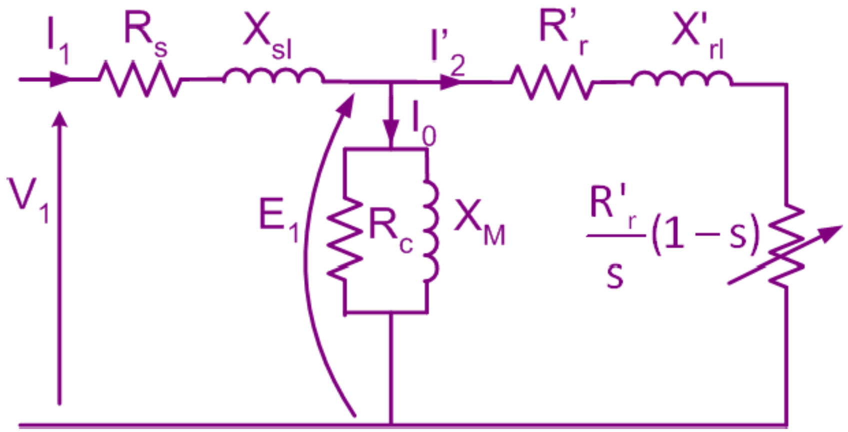
$\rightarrow$ Frequency of rotor 'I' = f_1



Assuming some turns ratio

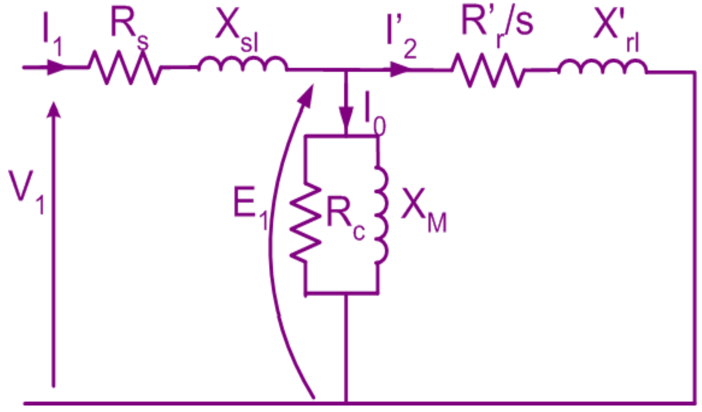
$\Rightarrow$ IM can be thought of as a generator feeding a fictitious 'R'

$\Rightarrow$ it is fictitious because unlike in a transformer, it is not an external 'R' connected at the load terminals



$\Rightarrow$ mech. power developed/phase = ohmic loss in fictitious secondary resistance, $\frac{R'_r}{s}(1-s)$

developed power, $P_d = I'^2_2 \dfrac{R'_r(1-s)}{s}$



rotor cu loss $= (I'_2)^2 R'_r$

$\therefore$ i/p air gap power or i/p power to rotor,

$P_a = (I'_2)^2 \dfrac{R'_r}{s}$ $\quad \therefore\ P_a : I_2'^2 R_r' : P_d = 1 : s : (1-s)$

$\Rightarrow sP_a \,\alpha$ heat $\therefore$'s' should be as small as possible

$\therefore$ developed torque,

$$T_{d/ph} = \frac{P_d}{\omega_r} = \frac{P_a(1-s)}{2\pi n_s(1-s)} = \frac{P_a}{2\pi n_s}$$ $\therefore\ T_d \,\alpha\, P_a$, independent of speed of rotation

$P_a \rightarrow$ air gap input power $\Rightarrow$ Input power/phase = P_a + stator cu. Loss/phase + core loss/phase

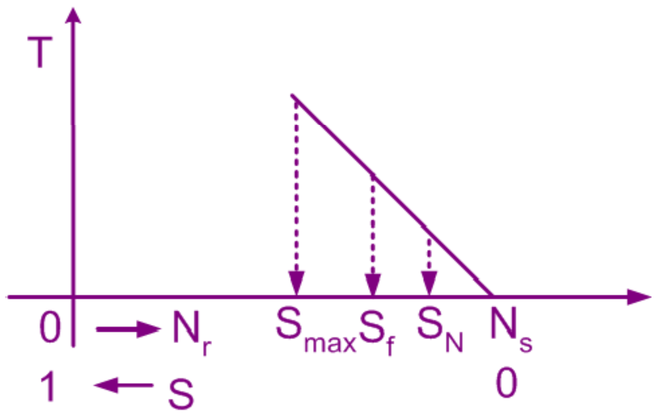
$\sqrt{3} V_L I_L \cos\theta =$ Input power/phase * 3

output power/phase, $P_{out} = P_d -$ frictional loss/phase

$$\therefore \%\eta = \frac{\text{output power}}{\text{input power}} \times 100$$

T - N characteristics:

$$T_d = \frac{3V_1^2}{2\pi n_s}\frac{R_r'}{s}\frac{1}{\left[\left(R_s + \frac{R_r'}{s}\right)^2 + (X_{sl} + X_{rl}')^2\right]}$$



at normal speeds close to N_s, 's' is very small

$\therefore$ $|R_s + R'_r/s| >> (X_{sl} + X'_{rl})$ and $|R_s| << |R'_r/s|$

$T_d \;\; \alpha \; s$

$\therefore$ T - N_r characteristics is $\cong$ linear

$T_d = 0$ at $N_r = N_s$, corresponding s = 0

$T_d \uparrow$ as s $\uparrow$

$T = T_{max}$ when $\frac{dTd}{ds} = 0$

$$T = \frac{3V_1^2}{2\pi n_s}\frac{R_r'}{s}\frac{1}{\left[\left(R_s + \frac{R_r'}{s}\right)^2 + X^2\right]}$$

$$s_{max} = \frac{R_r'}{\sqrt{R_s^2 + X^2}}$$

$$\therefore T_{max} = \frac{3V_1^2}{2\pi n_s}\frac{R_r'}{\frac{R_r'}{\sqrt{R_s^2 + X^2}}}\frac{1}{\left[\left(R_s + \frac{R_r'}{R_r'}\sqrt{R_s^2 + X^2}\right)^2 + X^2\right]}$$

$$\therefore T_{max} = \frac{3V_1^2}{4\pi n_s} \frac{\sqrt{R_s^2 + X^2}}{\sqrt{R_s^2 + X^2}\left[R_s + \sqrt{R_s^2 + X^2}\right]}$$

$$\left|R_s + \frac{R_r'}{s}\right| \ll |X_{sl} + X_{rl}'| \qquad \therefore T \alpha \frac{1}{s}$$

neglecting R_S

$$\approx \frac{3V_1^2}{4\pi n_s X^2} \Rightarrow \text{Independent of } R'$$

$$s_{\max} = \frac{R_r'}{\sqrt{R_s^2 + X^2}} \qquad X = X_{sl} + X_{rl}'$$

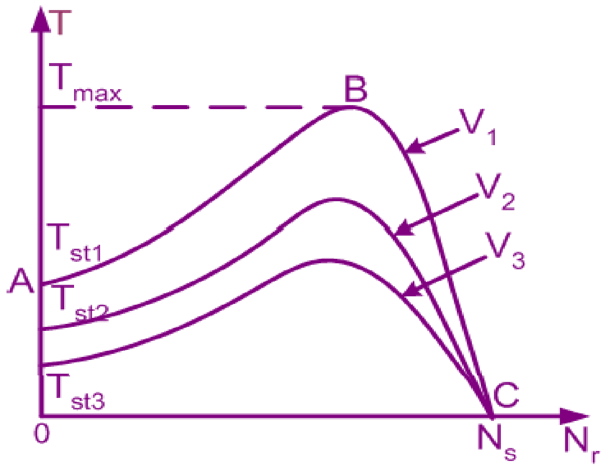
If stator parameters are neglected

$$s_{\max} = \frac{R_r'}{X_{rl}'}$$

at low speeds and at starting, $s \rightarrow 1$

$\Rightarrow$ due to air gap, leakage flux is quite Substantial (generally $R_r/x_{rl} \cong 0.2$)

$\Rightarrow$ T - N_r characteristic is a rectangular hyperbola



Observations:

From (A – B)

$T\uparrow$ as $N_r\uparrow \rightarrow$ unstable

from (B – C)

$T\uparrow$ as $N_r\downarrow \rightarrow$ stable

$\Rightarrow T \quad \alpha \quad V^2$

$\therefore$ If $V\downarrow$ by 10% , T_{st} reduces by 19%.

N_s remains the same

$\Rightarrow$ at starting 'f' of 'I' in rotor = f_1

$\Rightarrow$ rotor bars are shorted

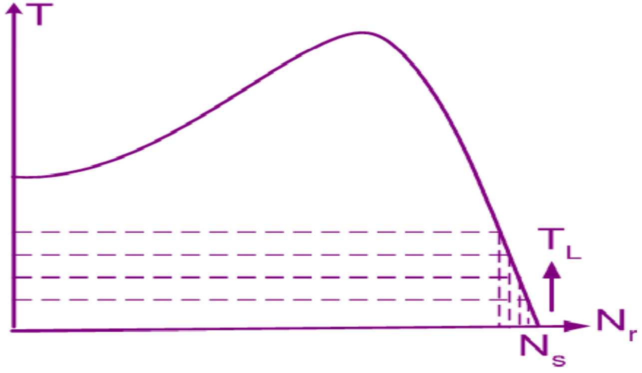
$\Rightarrow$ similar to transformer with shorted secondary

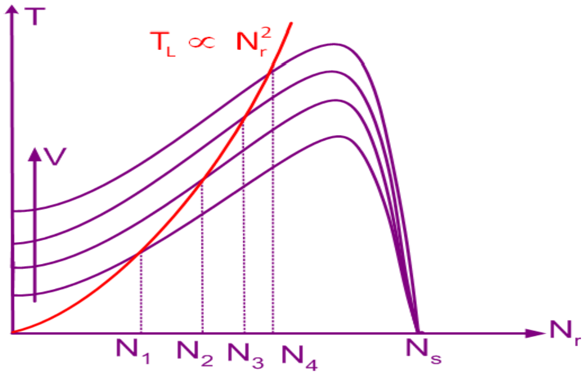
$\Rightarrow$ If rated 'V' is applied $\Rightarrow$ rotor 'I' and $\therefore$ stator 'I' will be high

$\Rightarrow$ one of the ways of reducing this 'I' is applying reduced 'V' to stator (f_1 is unaltered)

$\Rightarrow$ If motor is started with reduced 'V' (rated f_1), $T_{st}\downarrow$ reduces

$\Rightarrow$ In the linear region $T_d\downarrow$ as $N_r\uparrow$





$\Rightarrow$ In case of fan: $T_L \alpha N^2{}_r$

$\Rightarrow$ speed is varied by varying 'V' ('f' is held constant) it can be observed that as $T_L\uparrow$ $N_r\uparrow$

<u>Observations</u> : Even though slip is high, rotor 'I' and $\therefore$ stator 'I' may not be high because rotor 'I' α $(N_s - N_r)\,\phi$; applied V is low, ϕ is low.

frequency of rotor 'I' $\propto$ relative speed $\propto sN_s$ or $\propto sf_1$

for normal operation, 's' varies from 0.01 to 0.03 (HP rating up to 10)

frequency of rotor 'I' $\rightarrow$ 0.5 to 1.5 Hz very low frequency ac $\cong$ dc

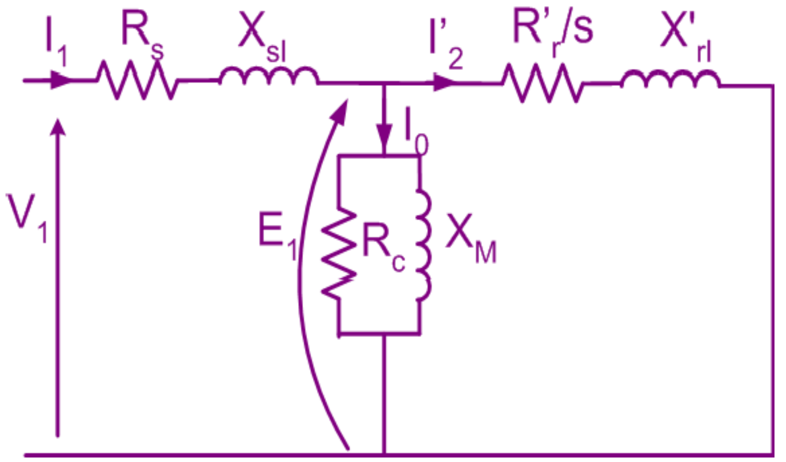
rotor P.F. $\cong$ unity or $\frac{R_r'}{s} \gg X_{rl}'$

$$\therefore \frac{\frac{R'}{s}}{\sqrt{\left(\frac{R_r'}{s}\right)^2 + (X_{rl}')^2}} \approx 1$$

I_o is pre-dominantly inductive

due to air gap, $|I_0|$ much higher compared to transformer

$\Rightarrow$ could be (25-30)% of I_{FL}

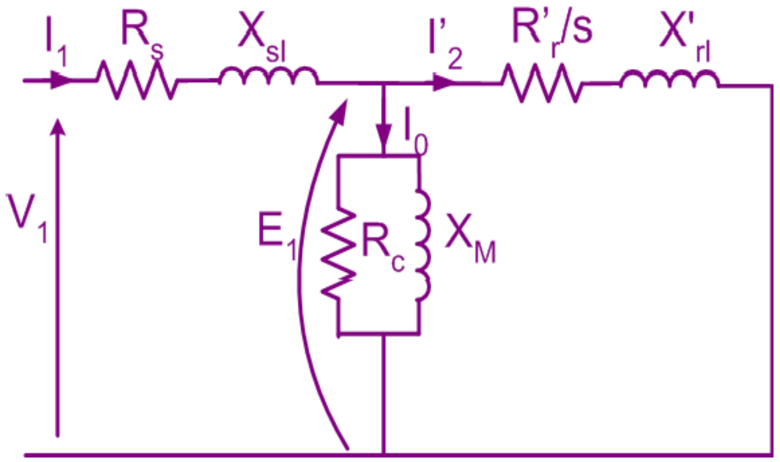


$\therefore \bar{I_1} = \bar{I_o} + \bar{I_2'}$ always lags the input 'V'

$\therefore$ In IM source P.F. is always lagging

(In transformer, source P.F. could be leading/lagging/unity)

Speed Control:



The Torque equation can be written as:

$$T_d = \frac{3P}{2}\frac{1}{\omega_s}\frac{\frac{V_1^2 R_r'}{s}}{\left[\left(R_s + \frac{R_r'}{s}\right)^2 + (X_{sl} + X_{rl}')^2\right]}$$

$$L_m I_m = \phi = \text{Air gap flux} = \frac{V_s}{2\pi F_1}$$

Neglecting stator parameters

$$T_d = \frac{3P}{2}\frac{1}{\omega_s}\frac{V_1^2 s R_r'}{[R_r'^2 + ((s\omega_s)L_{rl}')^2]} \approx \frac{3P}{2}\left(\frac{V_1}{\omega_s}\right)^2\frac{\omega_s}{R_r'}$$

$$\therefore T_d \cong \left(\frac{3P}{2}\right)\frac{\phi^2\omega_s}{R_r'}$$

$$I_m = \frac{E_1}{X_m} = \frac{E_1}{2\pi F_1 L_m} \approx \left[\frac{V_s}{2\pi F_1}\right]\frac{1}{L_m}$$

- In IM starting I can be $\downarrow$ by applying reduced V (f_1=f_{rated})

$\Rightarrow \phi \downarrow \quad \therefore T_d \downarrow$

- For pump & fan type of load ($T_L \propto N_r^2$), Y - Δ starter could be used

$$T_{st} = \frac{1}{3} T_{st\ at\ V_1 = V_{rated}}$$

- Starting 'I' can be $\downarrow$ by keeping $\phi = \phi_{rated}$ & $\downarrow$ (N_s- N_r) N_s can be $\downarrow$ by $\downarrow f_1$
- If V_1= V_{rated} & $f_1 \downarrow$, m/c gets saturated (V_1= $4.44 f_1 \phi_M N_1 k_W$)
- $\therefore$ Keep (V_1/f_1) constant

$\Rightarrow$ Variable Voltage Variable Frequency supply

$\because$ 'ϕ' is constant, T_d can also be controlled (force experienced by conductor $\propto$ B I)

$\Rightarrow$ mmf distribution in space in case of one coil placed in 2 slots is rectangular

$\Rightarrow$ If there are large number of slots then it is a stepped waveform

$\Rightarrow$ field produced by ac current flowing in a coil is pulsating in nature

$\therefore$ 1- ϕ motor is not self starting