Chapter Two

Three Phase Induction Motor Operation

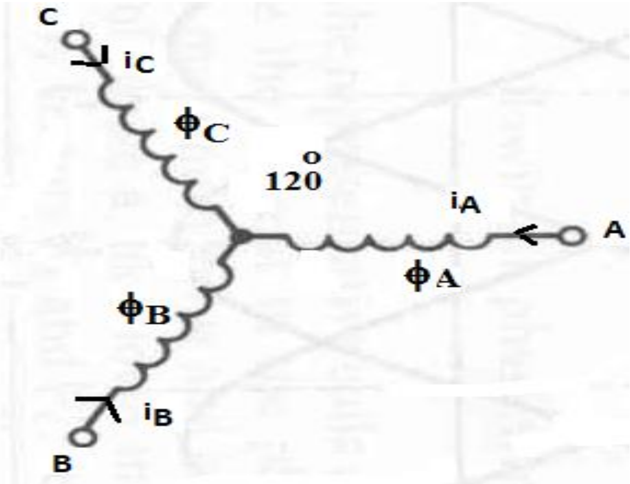
- The principle of IM operation depends on current carrying conductor are present within magnetic field.
- The conductors experience a force which causes them to exert torque on the shaft. In three phases IM, the magnetic field set-up is rotating in nature and hence called the rotating magnetic field.
- The current to the rotor system is supplied by electromagnetic induction. Hence, the motor gets its name, induction motor.

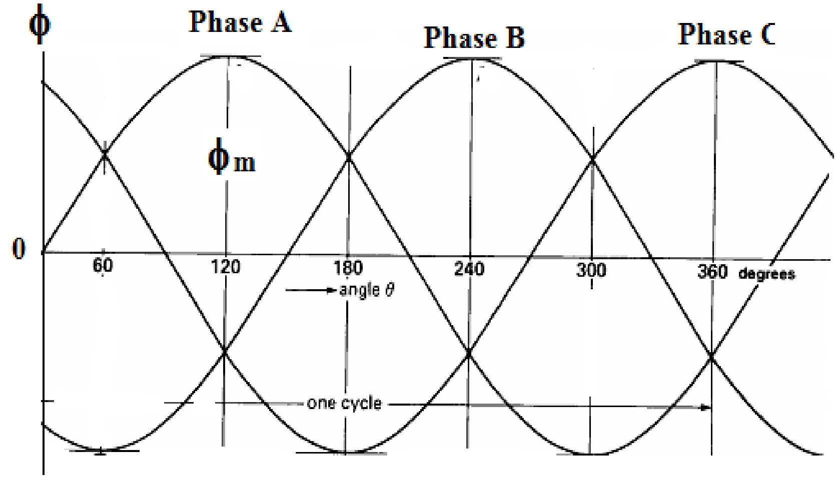
Three Phase Induction Motor Operation

Rotating Magnetic Field

$$n_s = \frac{120f}{P}$$

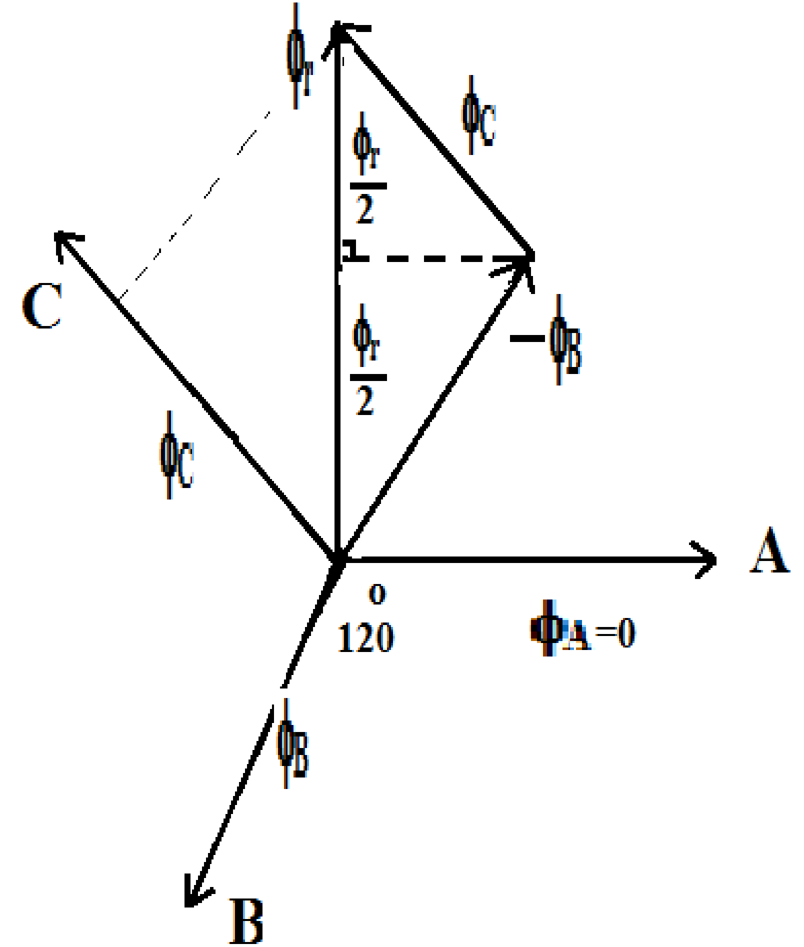
P	2	4	6	8	10	12	16	24
n_s(rpm)	3000	1500	1000	750	600	500	375	250





The resultant flux due to three phases:

$$\phi_A = \phi_m \sin\omega t$$
$$\phi_B = \phi_m \sin(\omega t - 120^0)$$
$$\phi_C = \phi_m \sin(\omega t - 240^0)$$



At wt=0,

$$\phi_A = 0$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_C = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_r = \frac{\sqrt{3}}{2}\phi_m \cos 30 + \frac{\sqrt{3}}{2}\phi_m \cos 30 = \frac{3}{2}\varphi_m$$

<u>H.W:</u>

Show that $\phi_r = 1.5\phi_m$ for the following angles 90^0, 120^0.

Mathematical proof:

When a uniformly distributed windings is excited from the three phase AC supply, the instantaneous mmf wave are according displaced by 120^0 electrical degree in space. But each phase is excited by an alternating current varies in magnitude sinusoidal with time. Under balance three phase condition the instantaneous currents are:

$$i_a = I_{\max} \sin(\omega t)$$

$$i_b = I_{\max} \sin(\omega t - 120^0)$$

$$i_c = I_{\max} \sin(\omega t - 240^0),$$

$$Where I_{\max} \text{ is the maximum value of the current.}$$

$$\phi = \phi_{\max} \sin(\omega t) \sin(\theta)$$

$$\phi_A = \phi_{\max} \sin(\omega t)\sin(\theta) \qquad phase A$$

$$\phi_B = \phi_{\max} \sin(\omega t - 120^0)\sin(\theta - 120^0) \qquad phase B$$

$$\phi_C = \phi_{\max} \sin(\omega t - 240^0)\sin(\theta - 240^0) \qquad phase C$$

$$\phi_r = \phi_A + \phi_B + \varphi_C$$

$$= \phi_{\max}[\sin(\omega t)\sin(\theta) + \sin(\omega t - 120^0)\sin(\theta - 120^0)$$

$$+ \sin(\omega t - 240^0)\sin(\theta - 240^0)\ ]$$

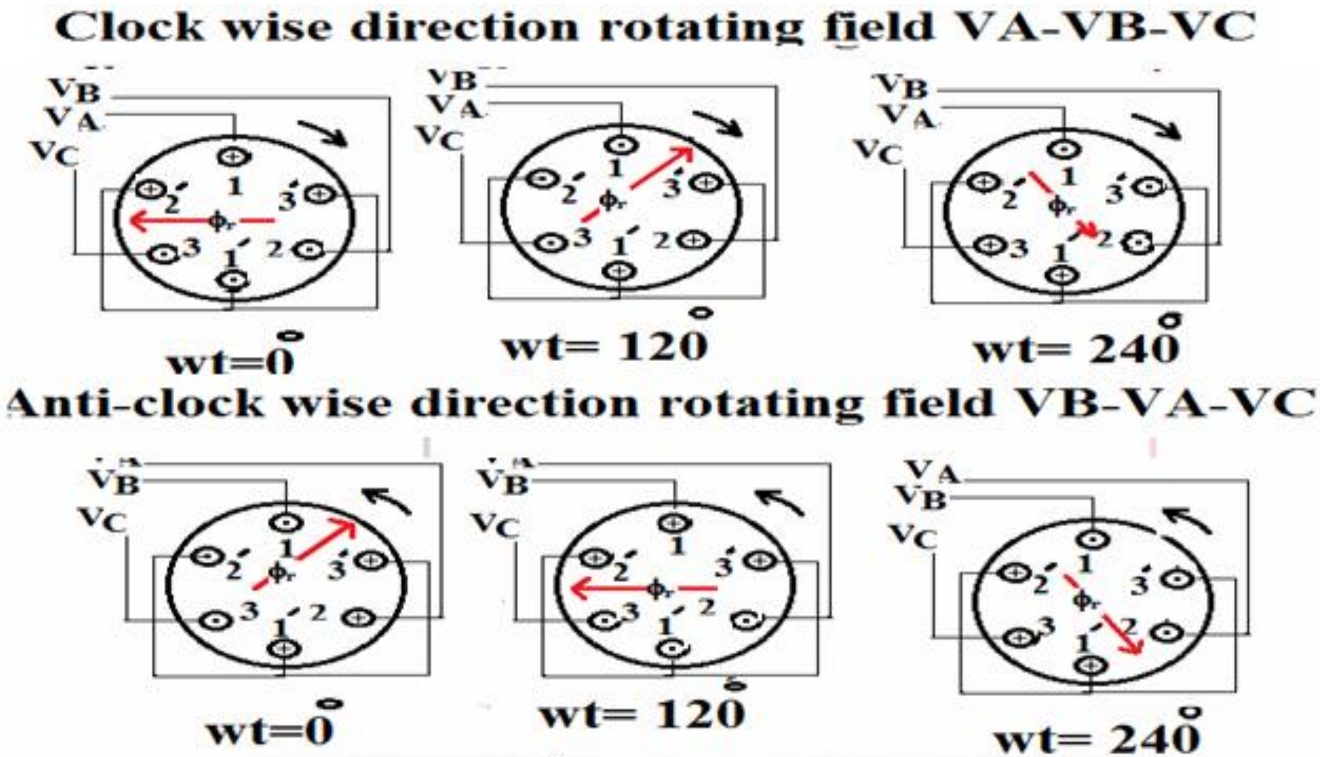
$U\sin g\ the common trigonometriac\ formula:$

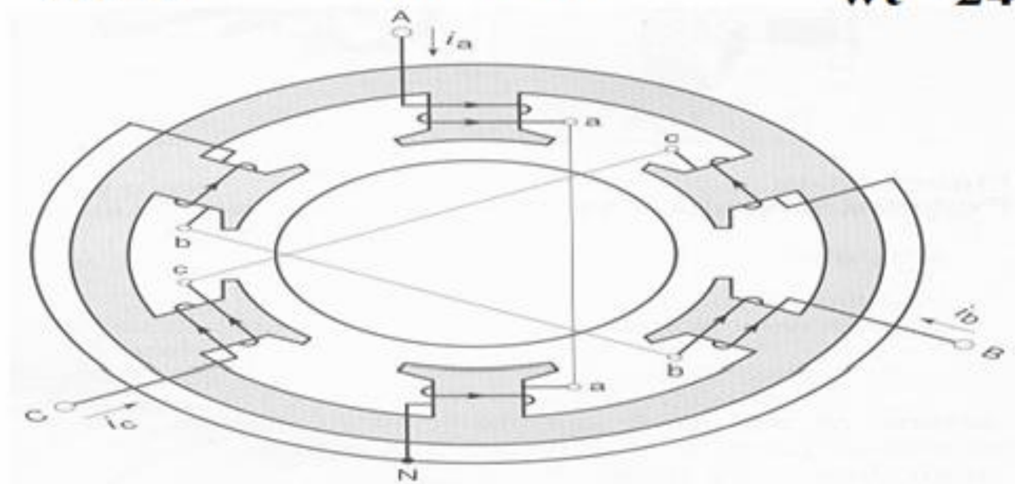
$$\sin\alpha \sin\beta = \frac{1}{2}[\cos(\alpha - \beta) - \cos(\alpha + \beta)]$$

$$\therefore \qquad \phi_r = \frac{3}{2}\phi_{\max}\cos(\omega t - \theta)$$

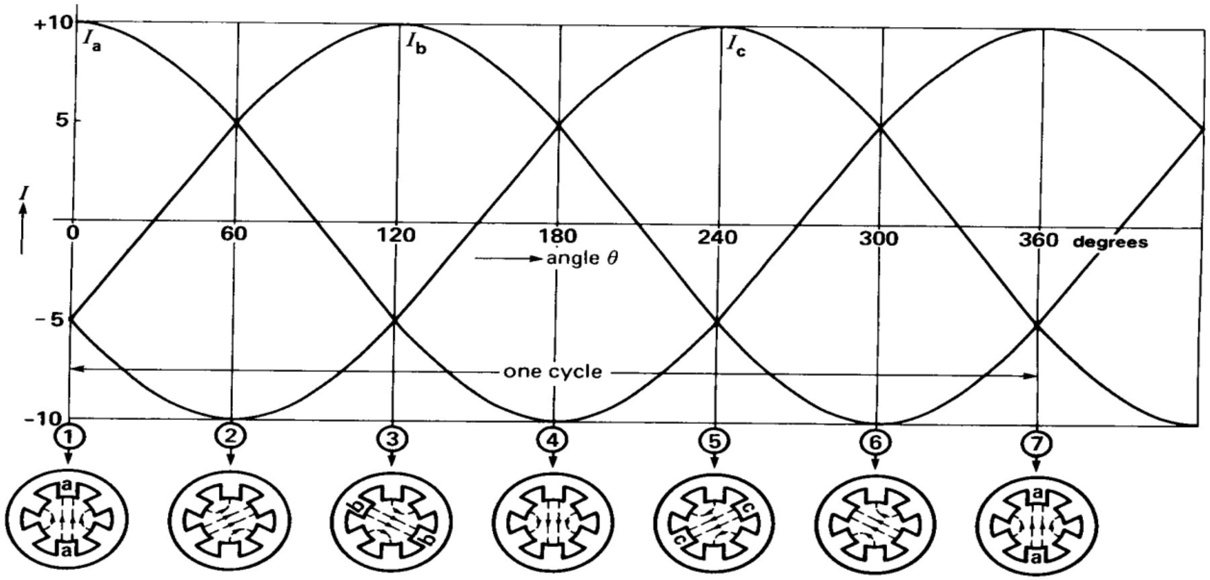
Conclusion: The resultant flux is of constant value which is 1.5 times the maximum value of the flux due to any phase.

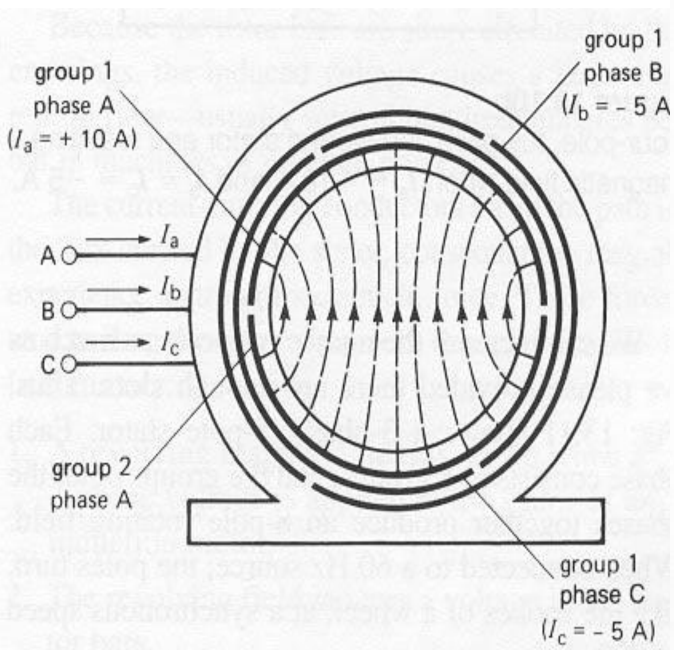
Direction of Rotating Field

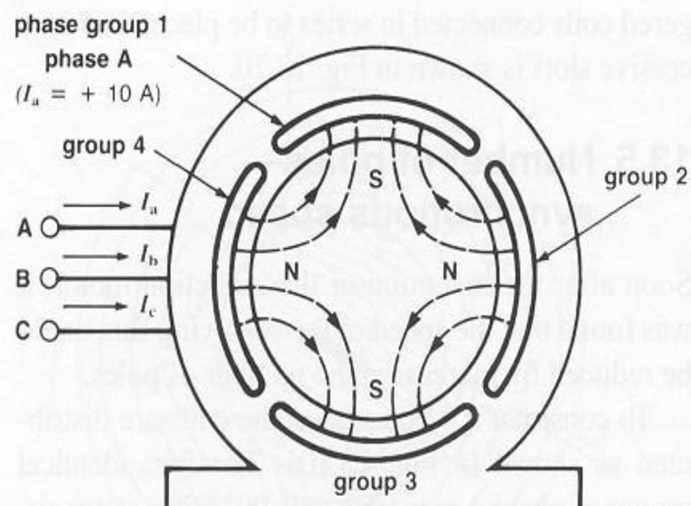




The Speed of Rotating Field







The four phase groups of phase A produce a 4-pole magnetic field.

The speed of rotating field is measured by rpm(revolution per minute) or in SI unit in rad/sec.

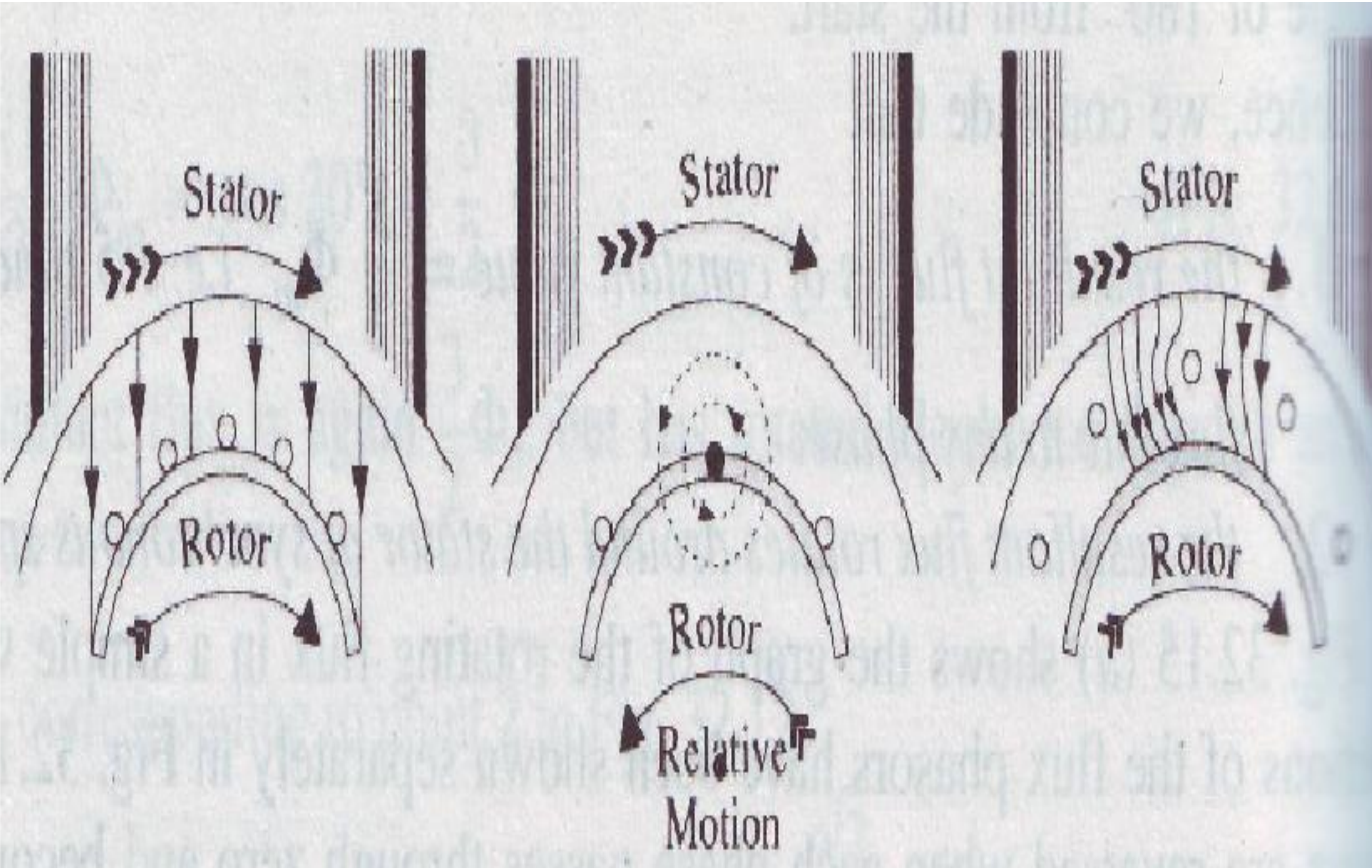
2π=one revolution, each pair of poles produces one revolution.

$$\omega_s = 2\pi n_s \qquad = 2\pi \frac{2f}{p} = \frac{4\pi f}{p}$$

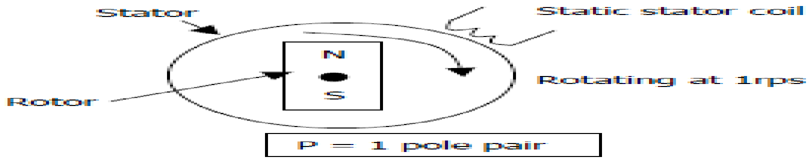
$$n_s = \frac{120f}{p}, \quad \therefore \frac{\omega_s}{n_s} = \frac{\pi}{30}$$

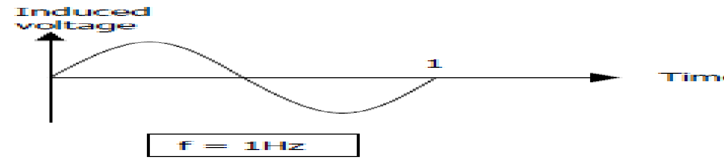
$$\omega_s = \frac{\pi}{30} n_s$$

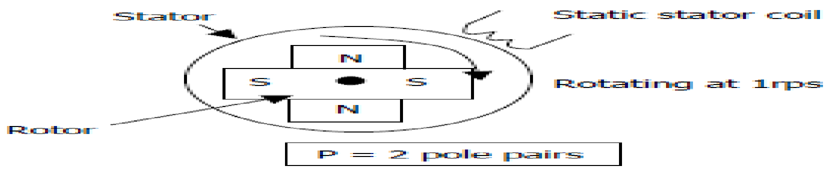
Principle of Operation:

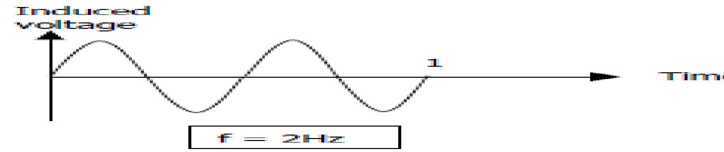


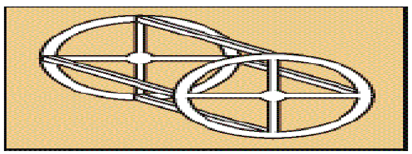
(a) (b) (c)

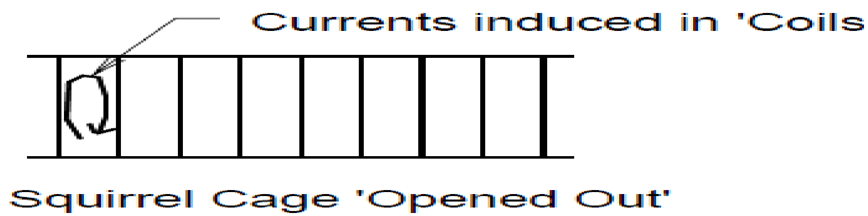

Stator
Static stator coil
N
S
Rotor
Rotating at 1rps
P = 1 pole pair

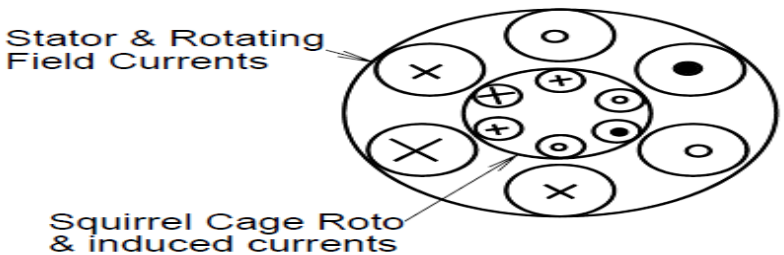

Induced voltage
1
Time
f = 1Hz

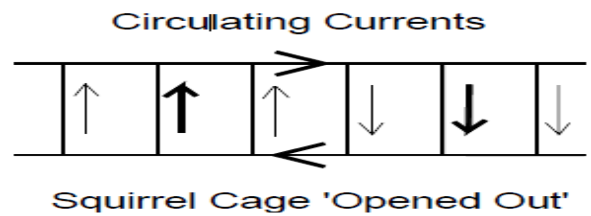

Stator
Static stator coil
N
S
S
N
Rotor
Rotating at 1rps
P = 2 pole pairs

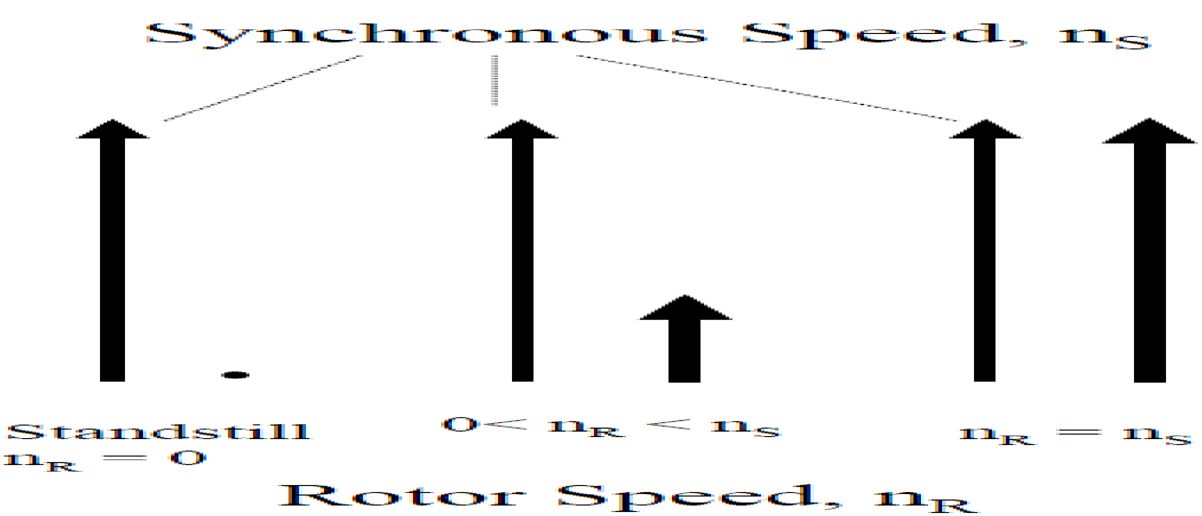

Induced voltage
1
Time
f = 2Hz




Currents induced in 'Coils
Squirrel Cage 'Opened Out'


Stator & Rotating
Field Currents
Squirrel Cage Roto
& induced currents


Circullating Currents
Squirrel Cage 'Opened Out'


Synchronous Speed, n_S
Standstill
$n_R = 0$
$0 < n_R < n_S$
$n_R = n_S$
Rotor Speed, n_R

The slip

$$\Delta_n = n_s - n$$

$$s = \frac{\Delta n}{n} = \frac{n_s - n}{n_s}$$

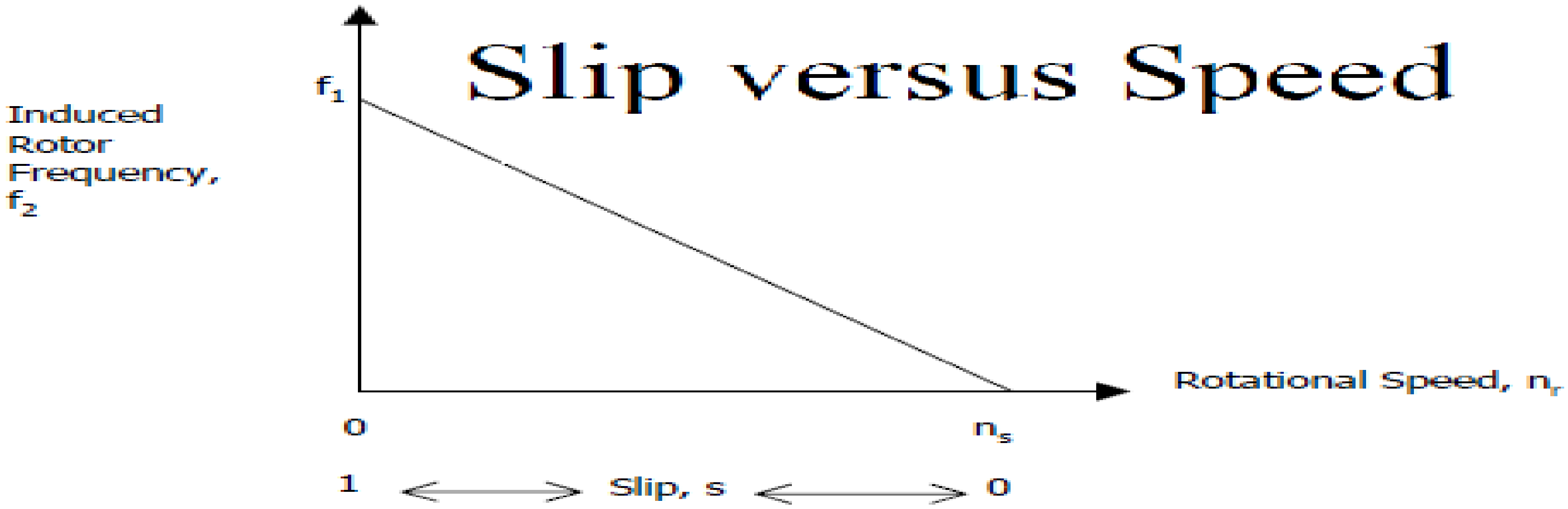
$$n_s - n = \frac{120 f_r}{p} \quad \& \, n_s = \frac{120 f}{p}$$

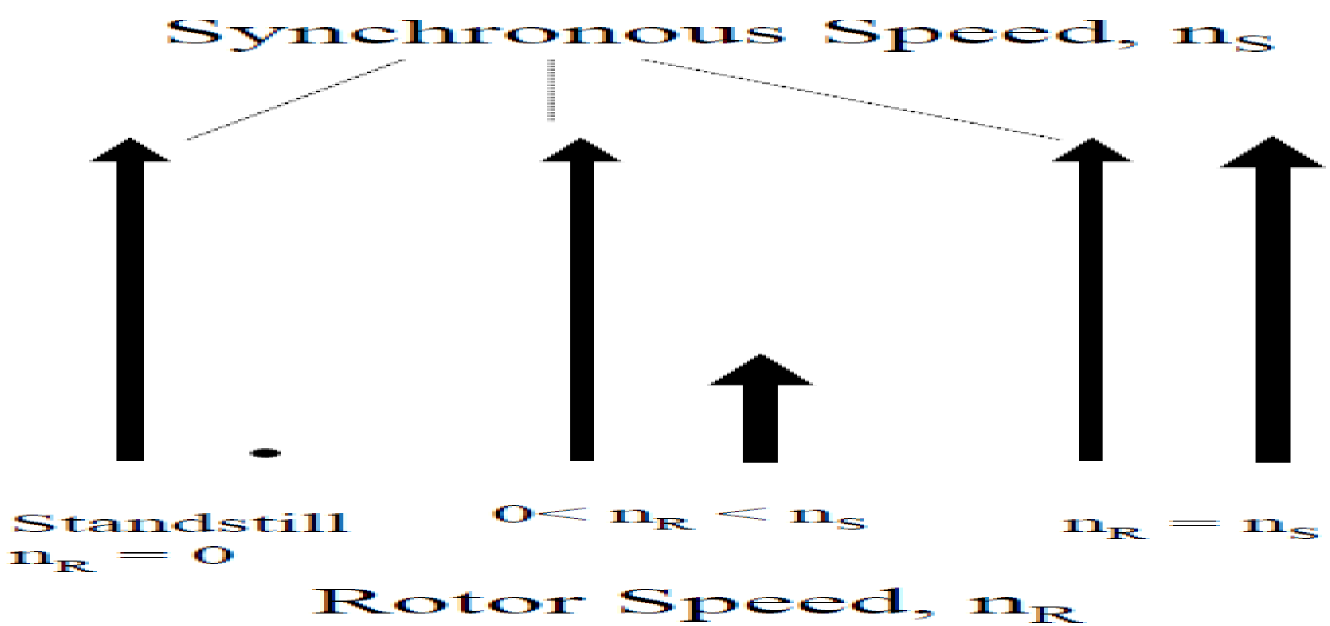
$$\frac{n_s - n}{n_s} = \frac{\dfrac{120 f_r}{p}}{\dfrac{120 f}{p}}, \quad S = \frac{f_r}{f}$$

$$f_r = sf$$

Therefore speed of rotor field in space = speed of field relative to rotor + speed of rotor relative to space = $sn_s + n_s(1-s) = n_s$

The slip


Slip versus Speed
f_1
Induced Rotor Frequency, f_2
Rotational Speed, n_r
0
n_s
1
Slip, s
0


Synchronous Speed, n_S
Standstill
$n_R = 0$
$0 < n_R < n_S$
$n_R = n_S$
Rotor Speed, n_R

Example:

A 208V, 10hp, 4-pole, 50HZ, y-connected IM has the full load slip of 5%.

Find:1- The synchronous speed(n_s), 2- The rotor speed(n) at full load,
3-The rotor frequency f_r, and 4- The shaft torque at rated load.

Solution:

1-

$$n_s = \frac{120f}{p} = \frac{120 \bullet 50}{4} = 1500 rpm = 25 rps = 157 rad/\sec$$

2- The roor speed of the motor is given by:

n=n$_s$(1-S)= 1500(1-0.05)= 1425rpm=23.75rps=149.22rad/sec

3-f$_r$=Sf=0.05*50= 2.5Hz

4-The relation between rotor speed and developed output torque is given by;

$$T_{output} = \frac{P_{out}}{\omega_r}$$

$$P_{out} = 2\pi n T_{output}, \implies 10 \times 746 = 2\pi \times 23.75 \times T_{output}$$

$$T_{output} = 50 N.m$$

Example:

Determine the number of poles, the slip, and the frequency of the rotor currents at rated load for three-phase, induction motors rated at:. 2200 V, 60 Hz, 588 r/min.

Solution:

We use $P = 120f/n_s$, to obtain P, using n_r, the rotor speed given to obtain the slip. 12.245=120*60/588

But P should be an even number. Therefore, take P = 12.

Hence n_s=600 rpm

The slip is thus given by, $S= (n_s-n)/n=(600-588)/588=0.02$

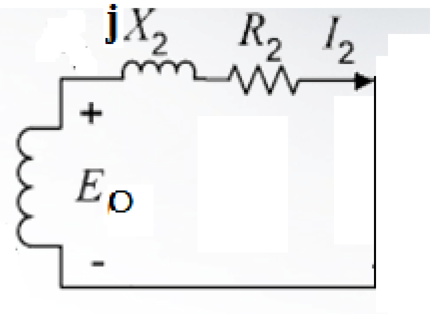
The rotor frequency is $f_r = sf_s = 0.02\times 60 = 1.2$ Hz

The Rotor emf, Current, Frequency and Torque:

If E_2= emf induced in rotor conductor /phase at any slip

E_2=sE_o

$$|Z_{2o}| = \sqrt{R_2{}^2 + X_{2o}{}^2}$$



$$\theta_2 = \tan^{-1}\frac{X_{2o}}{R_2}$$

$$\cos\varphi = \frac{R_2}{\sqrt{R_2^2 + X_{2o}^2}} = \frac{R_2}{|Z_{2o}|}$$

$$I_2 = \frac{E_{2o}}{Z_{2o}} = \frac{E_{2o}}{\sqrt{R_2^2 + X_{2o}^2}}$$

At running condition(any speed) (S<1)

$$X_2 = 2\pi f S L_2 = S X_{2o},$$

$$E_2 = S E_o, \quad f_r = S\,f$$

$$\therefore I_2 = \frac{S E_o}{\sqrt{R_2^2 + (S X_{2o})^2}}$$

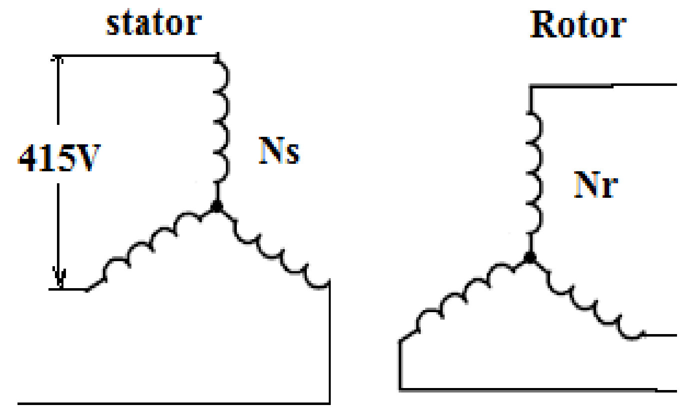
$$\cos\varphi_2 = \frac{R_2}{\sqrt{R_2^2 + (S X_{2o})^2}}$$

$$T_e = K_t \times \phi \times \frac{S E_o}{\sqrt{R_2^2 + (S X_{2o})^2}} \times \frac{R_2}{\sqrt{R_2^2 + (S X_{2o})^2}}$$

Example:

A three phase IM, 415V, Y-connected , slip ring induction motor has stator to rotor turn ratio as 6. The rotor resistance and standstill reactance per phase are 0.06Ω and 0.3Ω respectively. Find the rotor power factor and current at standstill.

Solution: $S=1$, $R_2=0{,}06\Omega$, $X_2=0.3\Omega$, $V_{l\text{-}l}=415V$,



$V/phase = 415/\sqrt{3} = 239.6V$, $N_s/N_r=6$,

$E_2/\text{ phase} = 239.6*1/6 = 39.93V$

$Z_2=0.06+j0.3=0.306\angle 78.7^0\Omega$

$I_2=(39.93\angle 0^0)/0.306\angle 78.69^0=130.5\angle -78.7^0 A$

$\cos\phi_2 = \cos 78.7 = 0.196$ lagging.