ELECTRICAL MACHINES

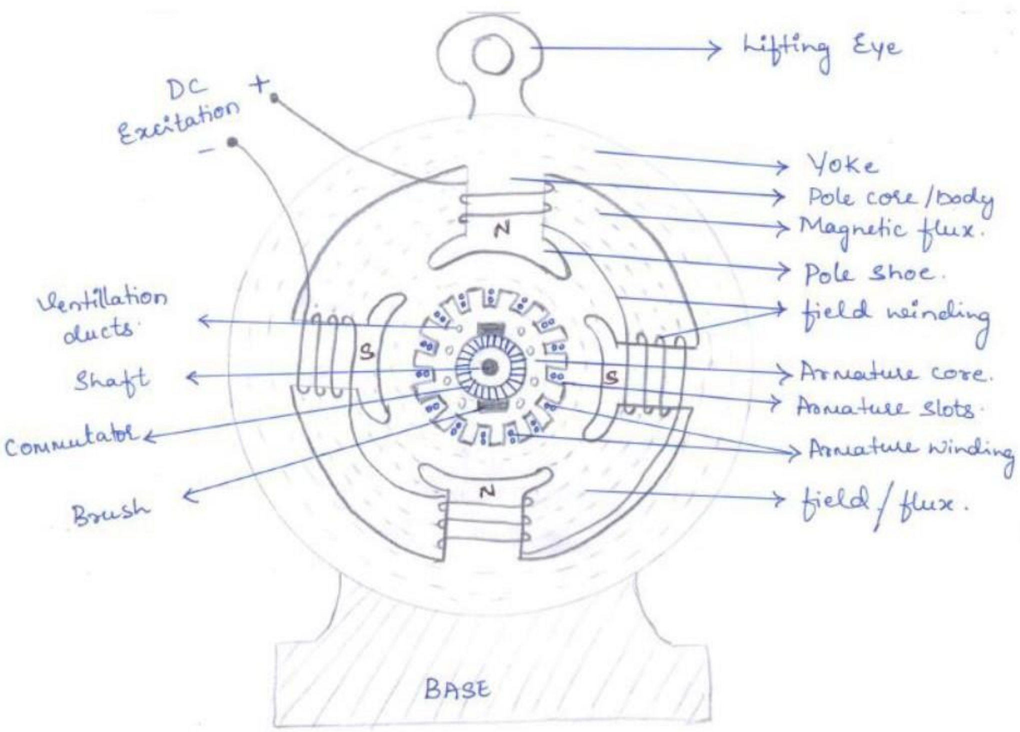
DC MACHINE

A DC Machine is an electromechanical energy conversion device which converts mechanical energy to electrical energy (Generator) or electrical energy to mechanical energy (Motor).

Construction wise, a DC Generator and a DC Motor are exactly same.

The DC Machine discussed here is called a separately excited DC Machine. In such DC Machines, field winding is excited by a separate DC source.

Construction Details:



Field System:

The objective of the field system is to create a uniform magnetic field necessary for electromechanical energy conversion. Electromagnets are preferred over permanent magnets since the magnetic field strength can be varied by varying the field current.

The field system consists of the following parts:

i) Yoke
ii) Pole Core
iii) Pole Shoe
iv) Field Winding

Yoke is the outer frame which protects DC Machine from dust and moisture. Poles are fixed to the Yoke. Yoke also provides a good magnetic path for magnetic flux to pass through it. It is usually made of cast iron or cast steel.

Pole Core is that part of electromagnet on which field winding is wound. Pole Shoe, also called Pole face is fixed to pole core by means of screws. It is made wider for uniform distribution of magnetic flux.

Field winding also called Exciting winding is made of copper and wound on pole core and it excites the electromagnets and creates the magnetic field.

Armature System:

Armature consists of armature core and armature winding.

Armature core is a cylindrical structure made of silicon steel laminations. Laminating the core reduces eddy current losses. Armature core acts as a low reluctance path for the magnetic flux to pass through it. On its surface, slots are made to house conductors.

Armature conductors are connected together to make armature winding. Armature winding may be lap connected or wave connected. In armature winding, EMF is induced in case of a Generator and Torque is developed in case of a Motor.

Ventilating ducts are provided in the armature to dissipate the heat produced due to hysteresis and eddy current losses.

Commutator:

Commutator converts alternating current induced in the armature winding to DC current in the external load circuit. It is built up of wedge-shaped segments made of hard drawn copper. These segments are insulated from one another by thin layers of Mica.

Brushes & Bearings:

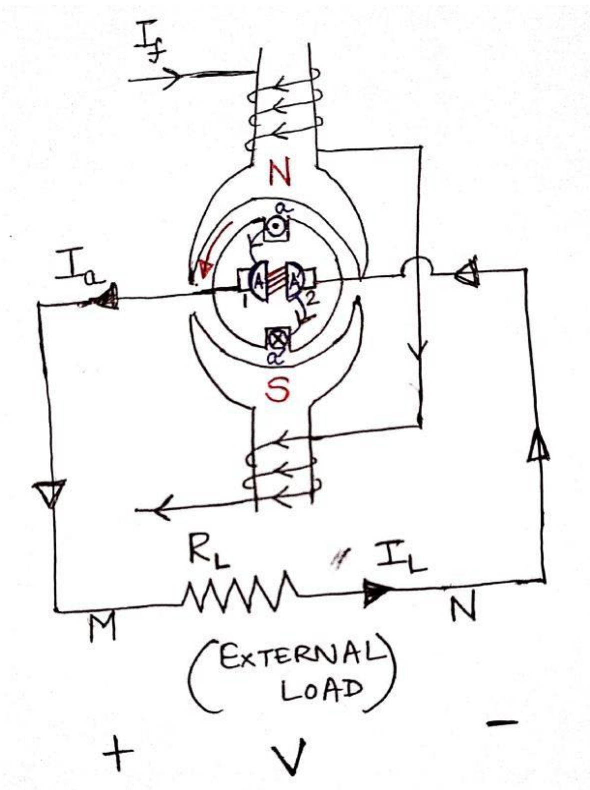
Brushes are used to collect the current from the rotating commutator and are usually made of carbon or graphite. Brushes are accommodated in brush holders and they press the commutator with the help of spring tension.

Bearings help in supporting the rotating parts & allow smooth motion of the rotor with minimum friction.

Shaft is the axial part of the machine to which prime mover is coupled to feed mechanical power in case of Generating mode and a mechanical load is coupled in case of Motoring mode.

Principle of Operation – DC Generator:

It works on the principle of Faraday's laws of Electromagnetic induction i.e., whenever there is rate of change of flux with a conductor or coil, an EMF is induced in it.



As the rotor is rotated with the help of a prime mover, the rotor conductors experience rate of change of flux which induces a dynamically induced EMF in these conductors. The magnitude of this EMF is directly proportional to rate of change of flux linkages and the polarity of this EMF is given by Fleming's Right Hand Rule.

EMF EQUATION OF A DC GENERATOR

Let P = Number of poles in the stator

ϕ = Flux per pole in Weber

Z = Total number of conductors in the Armature winding

A = Number of parallel paths in the armature winding

N = Speed of the rotor in RPM

Number of parallel paths depends on the type of armature winding.

For a lap wound armature winding, A = P

For a wave wound armature winding, A = 2

Consider one revolution of a conductor.

Total change in the flux in one revolution = $d\phi$ = Pϕ Webers

Time taken to complete one revolution = dt = $\frac{60}{N}$ seconds

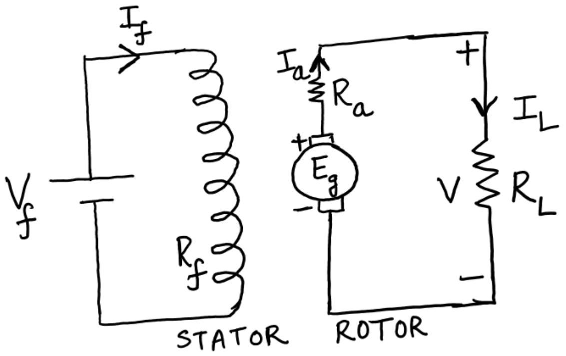
Hence, Average EMF per conductor, $e_C = \frac{d\emptyset}{dt} = \frac{P\emptyset N}{60}$ Volts

EMF of the DC Generator, E_g = EMF of any one parallel path

$$= e_C * \left(\frac{Z}{A}\right)$$

$$= \frac{\emptyset Z N}{60} * \frac{P}{A} \quad \text{Volts}$$

Equivalent Circuit of a Separately excited DC Generator



$$I_f = \frac{V_f}{R_f}$$

$$I_L = \frac{V}{R_L}$$

$$I_a = I_L$$

$$E_g = V + I_a R_a$$

Electrical Power developed = $E_g I_a$

Electrical Power Output = $V I_L$

Armature cu loss = $I_a^2 R_a$

Q. A 6 pole DC Machine working as a Generator has lap connected armature with 480 conductors. The resistance of the armature Circuit is 0.02 Ω. With an output current of 500 A from the armature, the terminal voltage is 230V when the machine is driven at 900 rpm. Calculate the useful flux per pole.

Given data : $P=6$, $Z=480$, $R_a = 0.02\,\Omega$

$I_L = I_a = 500A$; $V = 230V$; $N = 900\,rpm$

$P = A = 6$

$$E_g = V + I_a R_a$$

$$= 230 + (500 \times 0.02)$$

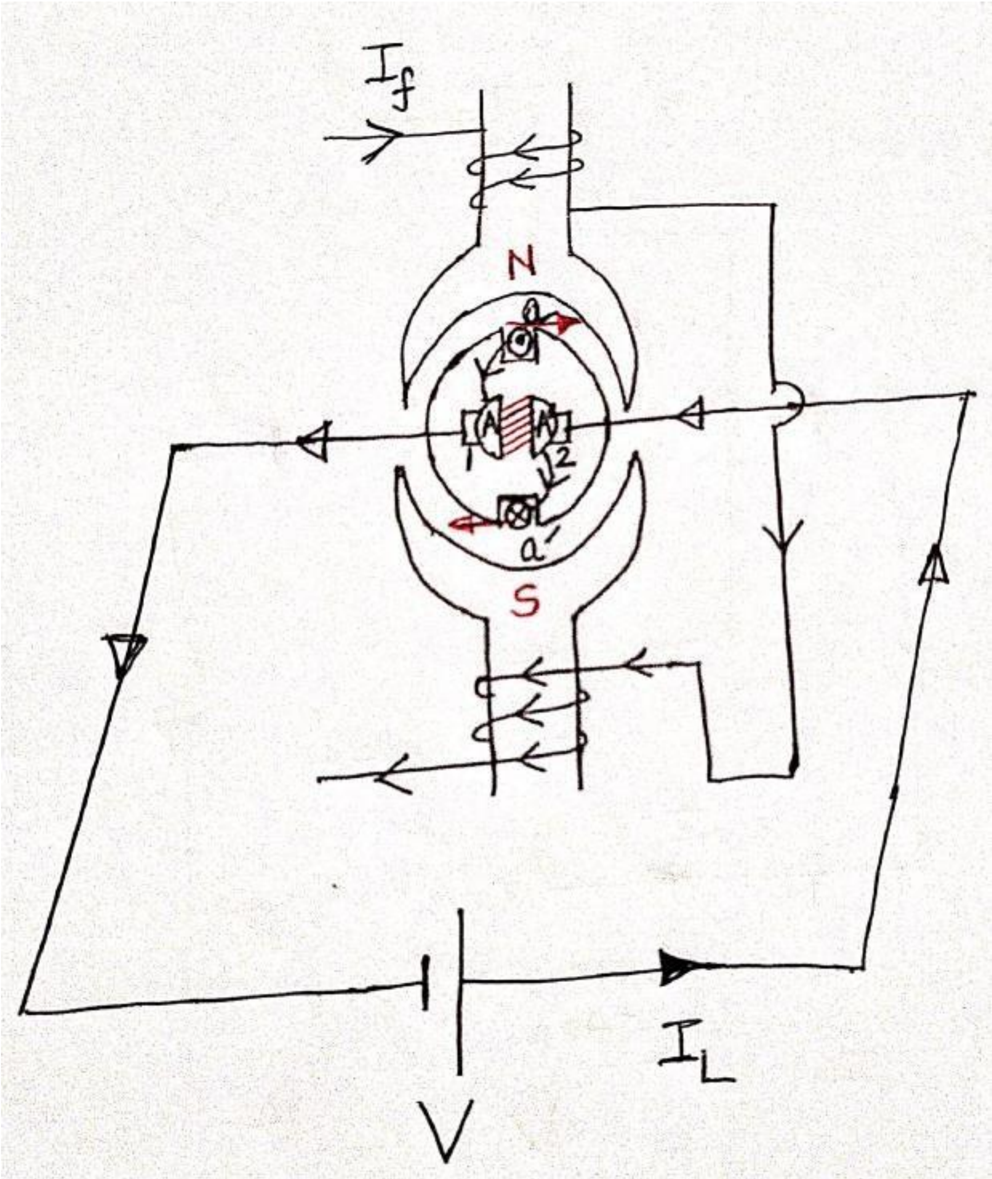
$$\boxed{E_g = 240V}$$

$$E_g = \frac{\phi Z N}{60} \times \frac{\cancel{P}}{\cancel{A}}$$

$$\phi = \frac{E_g \times 60}{Z \times N} = \frac{240 \times 60}{480 \times 900}$$

$$\boxed{\phi = 33.33\,mwb}$$

Principle of Operation – DC Motor:



DC Motor works based on the principle that a current carrying conductor placed in a magnetic field experiences a force.

As current flows in the rotor conductors, these conductors in the presence of stator magnetic field experience a force, which creates a torque & motor runs at uniform speed in one direction.

Torque Equation of a DC Motor – Derivation

Let P = Number of poles in the stator

ϕ = Flux per pole in Weber

Z = Total number of conductors in the Armature winding

A = Number of parallel paths in the armature winding

I_a = Armature winding current in Amperes

l = length of each conductor in meters

r = radius of the rotor (or) armature in meters

Number of parallel paths depends on the type of armature winding.

For a lap wound armature winding, A = P

For a wave wound armature winding, A = 2

Force experienced by one conductor, $F_C = B*I_C*l*\sin\theta$ (1)

B = Flux Density $= \dfrac{Total\ flux\ of\ all\ the\ Poles}{Total\ Surface\ area\ of\ all\ the\ Poles}$

$= \dfrac{P\emptyset}{2\pi rl}$

Conductor current, $I_C = \dfrac{Ia}{A}$

& since conductor & magnetic field are perpendicular, θ = 90 degrees

Substituting for B, I_C & θ in equation (1),

$$F_C = \frac{P\emptyset Ia}{2\pi r A} \quad \text{Newton}$$

Torque experienced by each conductor, $T_C = F_C * r$

Hence, $$T_C = \frac{P\emptyset Ia}{2\pi A} \quad \text{Newton-Meter}$$

Torque developed in the Motor, $T_e = T_C * Z$

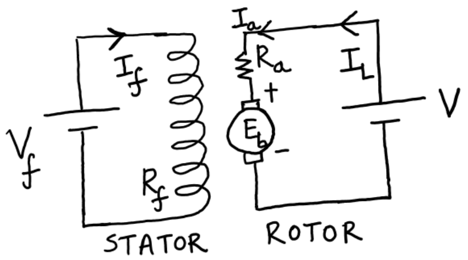
Hence, $$T_e = \frac{\emptyset Z Ia}{2\pi} * \frac{P}{A} \quad \text{Newton-Meter}$$

CONCEPT OF BACKEMF IN A DC MOTOR

As the motor starts running, the armature conductors are moving in the magnetic field and hence experience rate of change of flux. This leads to a dynamically induced EMF in these conductors. The polarity of this EMF can be obtained by applying Fleming's Right-Hand Rule. It can be observed that the polarity of this EMF is opposite to the Supply Voltage. Hence it is called Back EMF or counter EMF represented by Eb.

The electrical power which is spent in overcoming the opposition of the back EMF i.e., Eb*Ia is converted from electrical form to mechanical form.

EQUIVALENT CIRCUIT OF A DC MOTOR



$$I_f = \frac{V_f}{R_f}$$

$$I_a = I_L$$

$$E_b = V - I_a R_a$$

Electrical Power Input $= V I_L$

Mechanical Power developed $= E_b I_a$

Armature cu loss $= I_a^2 R_a$

Question:

A 6 pole DC motor has a wave connected armature with 87 slots, each containing 6 conductors. The flux per pole is 20 mWb and the armature has a resistance of 0.13Ω. Calculate the speed of the motor if it is drawing 80A from 240V DC supply. Also calculate torque developed by this motor

Solution:

Given data : $P = 6$; $\phi = 20\,mWb$; No. of slots $= 87$

$Z = 6$; $R_a = 0.13\,\Omega$; $I_L = 80A$; $V = 240V$

$I_a = I_L = 80A$ Wave wound $\Rightarrow \therefore A = 2$

$Z = 87 \times 6 =$

$$E_b = V - I_a R_a$$
$$= 240 - (80 \times 0.13)$$
$$\boxed{E_b = 229.6V}$$

$$E_b = \frac{\phi Z N}{60} \times \frac{P}{A}$$

$$N = \frac{E_b \times 60 \times A}{\phi Z P} = \frac{229.6 \times 60 \times 2}{20m \times 522 \times 6}$$

$$N = 440\ rpm$$

$$T_e = \frac{\phi Z I_a}{2\pi} \times \frac{P}{A}$$

$$\boxed{T_e = 398.77 \text{ Nm}}$$

(or)

$$E_b I_a = T_e \cdot \omega_m = T_e * \frac{2\pi N}{60}$$

$$T_e = \frac{E_b I_a\, 60}{2\pi N}$$

$$\boxed{T_e = 398.77 \text{ N·m}}$$

Question:

Calculate the speed at which DC Motor runs when developing a torque of 355 N-m while drawing a current of 60A from a 480V DC supply. The armature winding resistance is 0.25Ω.

Solution:

$V = 480\ V$

$I_L = 60\ A = I_a$

$R_a = 0.25\ \Omega \qquad T_e = 355\ N\text{-}m$

$N = ?$

$$E_b I_a = T_e \cdot \frac{2\pi N}{60}$$

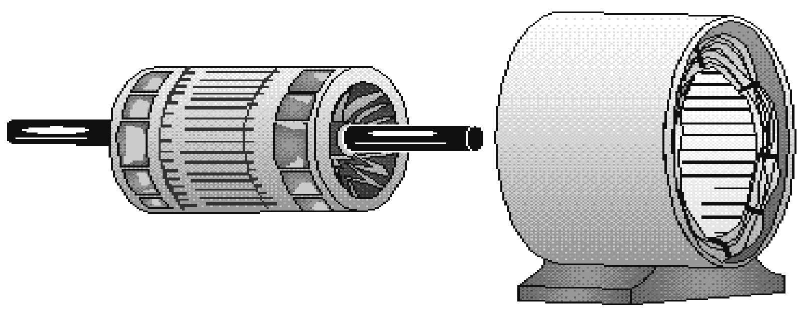
$$E_b = V - I_a R_a$$

$$= 465\ V$$

$$N = \frac{60 \times 465 \times 60}{355 \times 2 \times \pi} \approx \underline{751}\ RPM$$

3ϕ Induction Motor

The induction motor derives its name from the fact that ac voltages are induced in the rotor circuit by the rotating magnetic field of the stator. In many ways, induction in this motor is similar to the induction between the primary and secondary windings of a transformer.



Difference between induction motor and DC motor

INDUCTION MOTOR	
Rotor will not get the electric power by conduction, instead by induction. Hence they are called as **Induction Motor.**	Power is conducted directly to the armature through brushes and commutator. Hence they are **Conduction Motor.**

Advantages of Induction motor

a) Its construction is simple, rugged & almost unbreakable.
b) Its cost is low & is highly reliable.
c) Its efficiency is high.
d) It works with reasonably good power factor at rated speed.
e) Its maintenance is less.
f) IM are self-starting motors & hence do not require a starter.

Construction

A three phase IM mainly consists of two parts.

a) Stator
b) Rotor

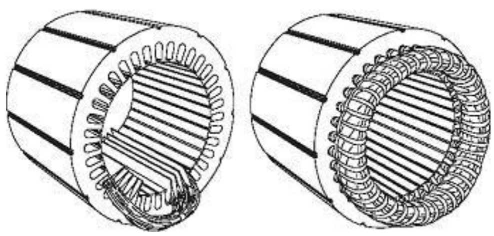
Stator: Stationary part of a machine. It is built up with laminations to avoid eddy current losses. Insulated stator conductors are placed inside the slots which are on the inner periphery. The conductors are either in star or delta to form three phase winding.

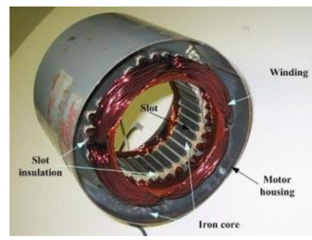
The stator windings are connected directly to the power source. Internally they are connected in such a way, that on applying AC supply, a rotating magnetic field is created.

Rotor

This is the moving part of the motor. Two different technologies can be used for this part, which separate induction motors into two distinct families: those with a "squirrel cage" rotor and those with a wound rotor which are referred to as "slip-ring".

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the periphery. In the most popular type of rotor (squirrel cage rotor), these bars are connected at ends mechanically and electrically by the use of rings.





The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings.

The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons.

- To make the motor run quietly by reducing magnetic hum and to decrease slot harmonics.
- To help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth is equal to the number of rotor teeth.
-

The rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non- driving end for mounting speed or position sensing devices.

Between the stator and the rotor, there exists an air gap, through which due to induction, the energy is transferred from the stator to the rotor. The generated torque forces the rotor and then the load to rotate.

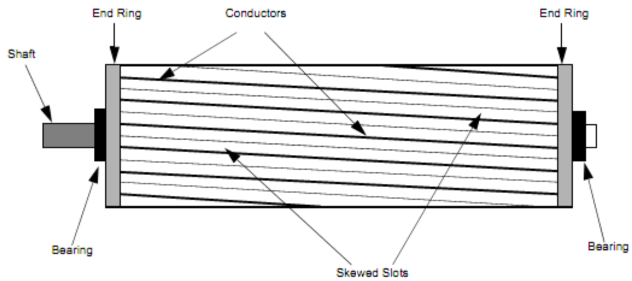
Squirrel-cage Rotor:

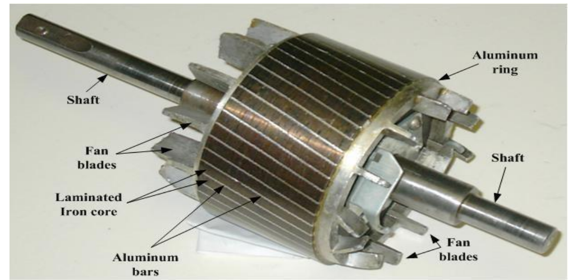
It consists of a cylindrically laminated core with parallel slots for carrying rotor conductor. These slots are not exactly parallel but little tilted or skewed. This helps to reduce magnetic locking and humming during rotation of rotor.

At the each end of rotor, rotor bars (conductors) are shorted by heavy end rings of the same material. Hence it is not possible to add any extra resistance in series with rotor.

These motors have a relatively low starting torque and the current drawn on power-up is much higher than the nominal current On the other hand they have low slip at nominal current.

- These motors are mainly used at high power to improve the efficiency of installations on pumps and fans.
- They are also used with frequency inverters at variable speed.





The torque and current problems on starting are thus fully resolved.

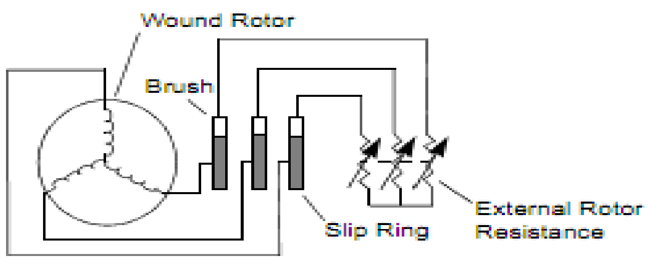
Almost 90% of the three-phase AC Induction motors are of this type. The power ratings range from one-third to several hundred horsepower in the three-phase motors.

When a 3-phase supply is given to the stator winding, a magnetic field of constant magnitude & rotating at synchronous speed , is given by the equation,

$N_S = (120*f)/P$ rpm

<u>Slip-ring Rotor</u>:(phase wound rotor)

In this configuration the rotor windings are similar to stator windings. They are connected in star and open end of this star connected conductors are bought out of the rotor and connected to the three insulated slip rings. These are mounted on shafts with brushes resting on them. Further, these three brushes are externally connected to a three phase star connected external rotor.



The effective rotor resistance is increased by adding external resistance through the slip rings.

Disadvantages of Slip-ring motors

- The slip rings and brush assemblies need regular maintenance, which is a cost not applicable to the standard cage motor.

Concept of Rotating Magnetic Field (RMF):

The stator of a three phase induction motor carries a three phase star or delta connected winding to which three phase AC supply is given. A magnetic flulx is produced which rotates in space with constant magnitude but whose axis is continuously rotating with certain speed. This speed is called synchronous speed (Ns)

Production of RMF:

The three phase currents flow simultaneously through the windings and are displaced by 120º from each other. If the phase sequence is RYB, they produce the fluxes ϕR, ϕy, ϕ**B,** which are displaced by 120º from each other.

Let the magnitude be ϕm.

ϕR= ϕm sinθ = ϕm sinωt ϕY= ϕm sin(ωt-120º),

ϕB= ϕm sin(ωt-240º), the total flux, ϕT= ϕR+ ϕY+

ϕB case 1:- θ=0º

ϕR=0, ϕY= -0.866 ϕm, ϕB=0.866 ϕm

BD perpendicular to OA,

OD=OA= $\frac{\varphi_T}{2}$ In triangle OBD,

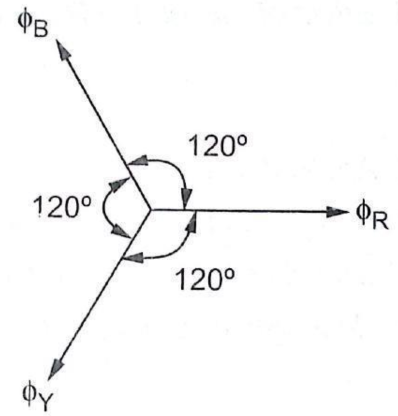
cos 30 º=$\frac{OD}{OB}$ = $\frac{\varphi_T}{2\varphi_B}$ $\varphi_T = 1.5$

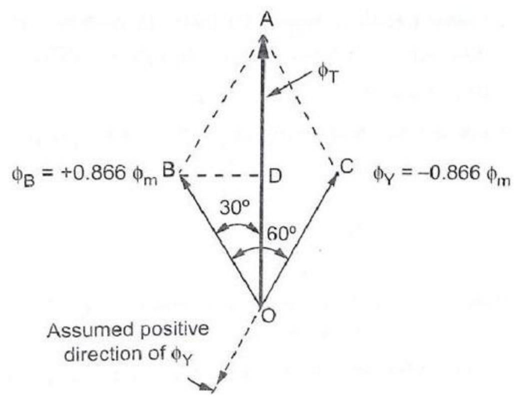
ϕm Its position is vertically

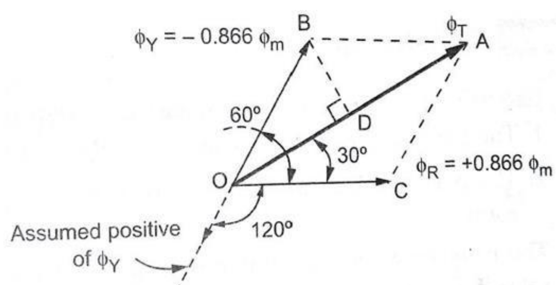
upwards at θ=0 º. case 1:-

θ=60º ϕR=0.866 ϕm, ϕY=

-0.866 ϕm, ϕB=0







In triangle OBD, cos 30 º= $\frac{OD}{OB}$

$\varphi_T = 1.5$ ϕm

Magnitude of resultant flux is 1.5 ϕm, but it has rotated through 60 º in space in clockwise direction.

Similarly if phasor diagram is drawn for various values of θ, it can be shown that, magnitude of φ_T is always 1.5 ϕ_m. But it rotates in space such a magnetic field is called rotating magnetic field. Thus though supply is stationary, windings are stationary, the resultant flux is produced is rotating in space, with constant magnitude and speed. i.e., when three phase stationary windings are excited by balanced three phase supply, the resultant field produced is rotating magnetic field. Though nothing is physically rotating, the field produced is rotating in space having constant amplitude at synchronous speed (NS).

The direction of rotating magnetic field depends on phase sequence of the three phase supply.

By changing phase sequence of the supply, the direction of rotation of rotating magnetic field and the direction of the three phase induction motor can be reversed.

Principle of operation of 3-phase Induction Motor

3-phase Induction motor works on the principle of electromagnetic induction.

When a three phase supply is given to the stator, RMF of constant magnitude is produced. The speed of RMF is called synchronous speed.

Rotor conductors cut the flux (RMF) at this instant rotor conductors are stationary. As there is a relative motion between rotor conductors and stator windings, flux (RMF) emf gets induced in rotor which is called rotor induced emf. As the rotor circuit is closed, induced emf circulates a current in rotor called a rotor current. This current produces flux and interacts with RMF and experiences a torque and starts rotating. The rotor starts rotating in the same direction as that of RMF. But it never succeeds catching up RMF. If it attains the speed of RMF, there will be no relative motion and no emf is induced so the motor stops. Hence always the rotor runs at a speed less than N_s. The difference between synchronous speed N_s and actual speed N_r of the rotor is known as slip.

Slip and its significance:

Slip is defined as the difference between the synchronous speed (Ns) and actual speed of rotor, i.e motor expressed as fraction of synchronous speed (Ns).it is also called absolute slip or fractional slip. Slip is directly proportional to the load on the motor.

$N=N_s(1-S)$

At start, motor is at rest. Hence N=0. S=1 at start.

Slip of an induction motor cannot be zero at any circumstances as N=Ns when S=0. Practically motor operates in the slip range of 0.01 to 0.05 i.e 1% to 5%.

Frequency of rotor currents:

When the rotor is stationary, frequency of rotor current is same as supply frequency.

During operation, the rotor current frequency is obtained by multiplying the supply frequency by the slip. The rotor current frequency is therefore at its maximum on starting.

Frequency of rotor currents is $f_r = Sf$.

Question 1:

A 4 pole three phase induction motor is supplied from a three phase 400V, 50Hz supply. Determine

i) Synchronous speed

ii) Speed of the rotor if slip is 0.05

Solution:

i) Synchronous speed, N_S = (120*f)/P = 1500rpm

ii) Slip = 0.05 = (N_S-N)/N_S

Hence, speed of the rotor = N = 1425rpm

Question 2

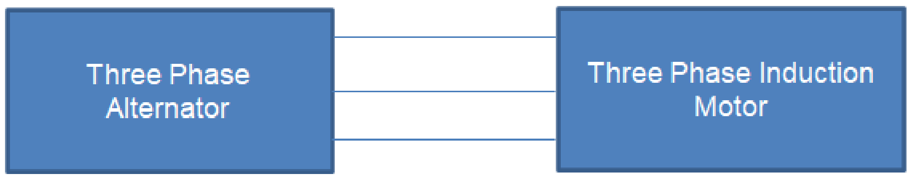
A 12 pole three phase alternator is coupled to an engine running at 500rpm. If it supplies power to a three phase induction motor having full speed of 1440rpm, find

i) Percentage slip

ii) Frequency of rotor currents

iii) No. of poles in the rotor

Solution:



For alternator,

N = 500 rpm & P=

12

f = (P*N)/120 = 50Hz

For Three phase IM, supply frequency = f = 50Hz

Full speed of the motor = 1440 rpm = Rated speed

Synchronous speed, N_S = (120*f)/P = (120*50)/P = 6000/P rpm

Number of poles can't be 2 because it means synchronous speed is 3000 rpm which is not possible because in practical machines, difference between actual speed & synchronous speed is not more than 5%

Number of poles can't be 6 because it means synchronous speed is 1000 rpm which is not possible because synchronous speed can't be less than actual speed

Hence,

Number of poles = 4 & synchronous speed = 1500rpm

- Percentage slip $= \frac{(Ns-N)}{Ns} * 100 = 4\%$
- Frequency of rotor currents = $f_r = s*f = 0.04*50 = 2Hz$