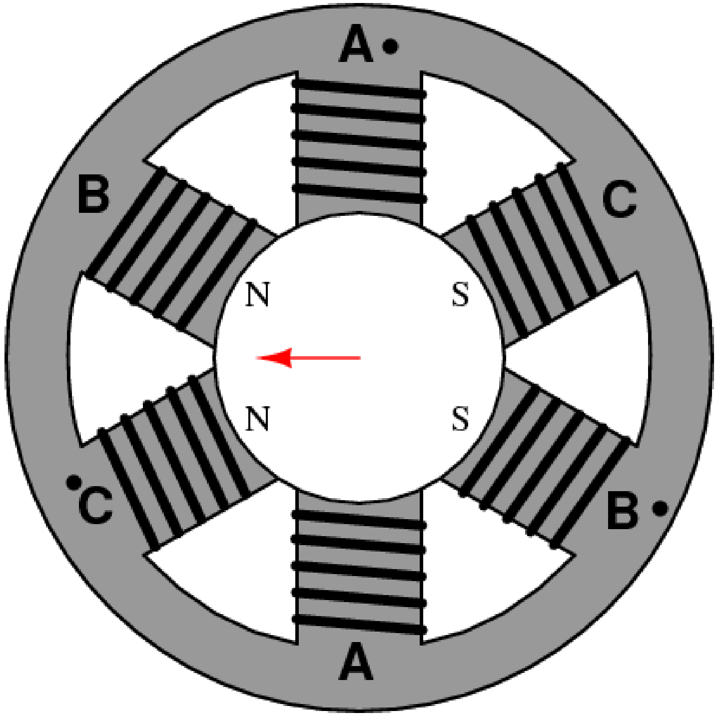
Unit 4
Induction Motor



CONTENT

This unit explains the principle of operation of 3- phase induction motor and its applications

- Induction Motor Construction
- Principles of Operation
- Types
- Torques
- Characteristics
- Speed control methods
- Applications

Introduction to Motor Construction

Earlier we saw, it was obvious that it is possible to obtain a wide range of performance characteristics from DC machines (motors\generators)

Now!

The question is do we insist on using DC, which requires the use of additional hardware to rectify and regulate the DC supplies?

Or

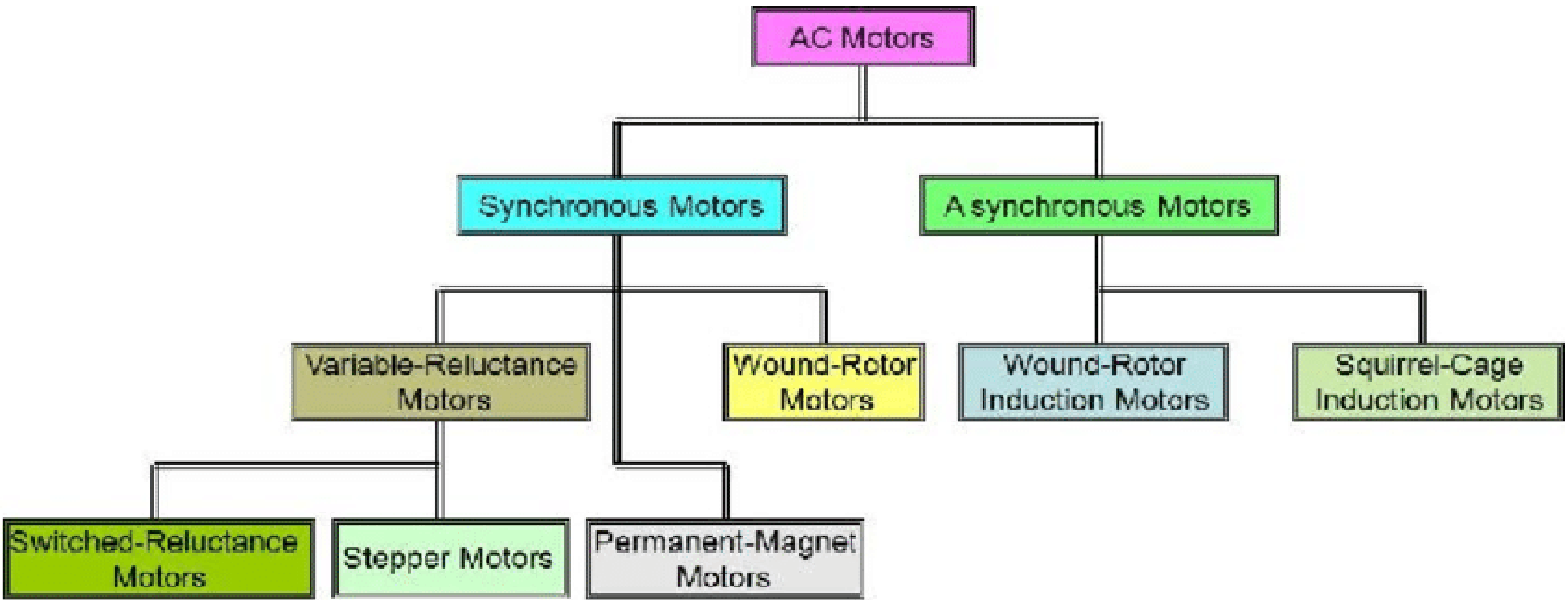
Should we consider using AC, which is more convenient as it is readily available in single or multi-phase form.

The answer to this question is yes we should consider using AC.

Then we should consider AC machines, and study their

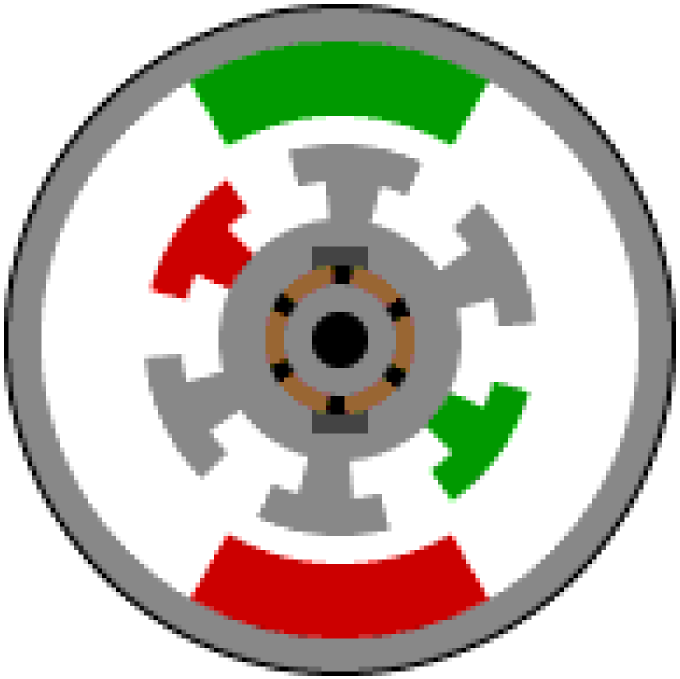
- Basic operation (that is synchronous and induction),
- Advantages and disadvantages, in comparison with direct-current machines.

Classification of AC Machines



DC MOTORS| JUST TO REMIND YOU

Structure



- **The stator** is the outside stationary part of the motor.
- The rotor is the inner rotating part.
- In the animation:
  - **Red** represents a magnet or winding with a **North polarization**,
  - **Green** represents a magnet or winding with a **South polarization**.
  - Opposite, red and green, polarities attract.

Operation

- As the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding.
- In the animation:
  - The commutator contacts are brown,
  - The brushes are dark grey.
  - A yellow spark shows when the brushes switch to the next winding.

INDUCTION MOTOR

Advantages:

- It has very simple and extremely rugged, almost unbreakable construction (especially squirrel cage type).
- Its cost is low and it is very reliable.
- It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
- It requires minimum of maintenance.
- It starts up from rest and needs no extra starting motor and has not to be synchronised. Its starting arrangement is simple especially for squirrel-cage type motor.

Induction Motor

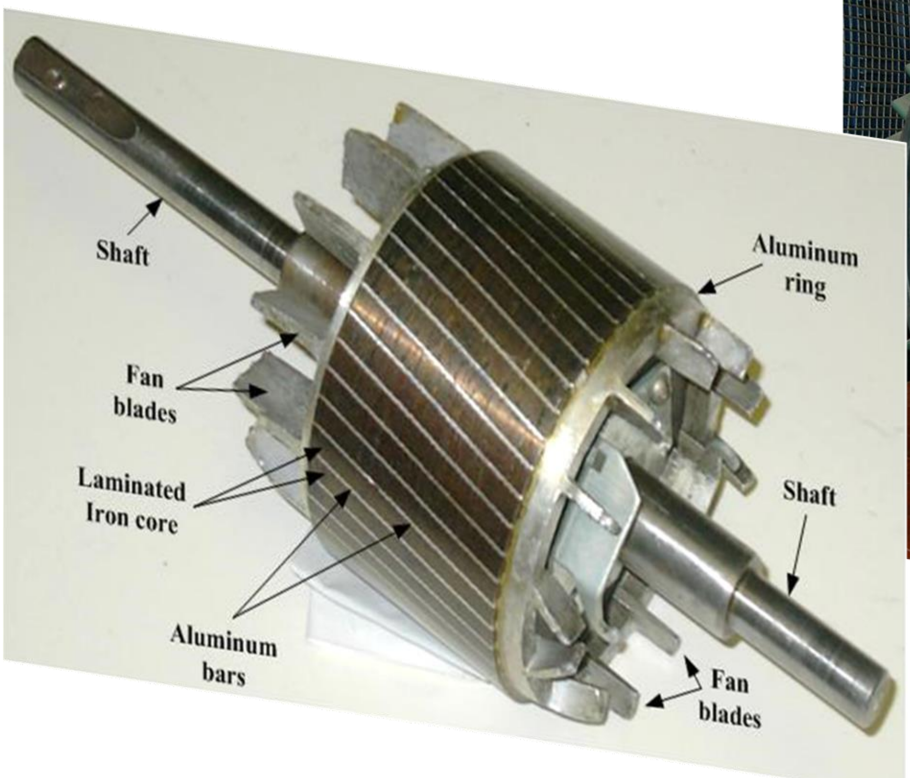
Disadvantages:

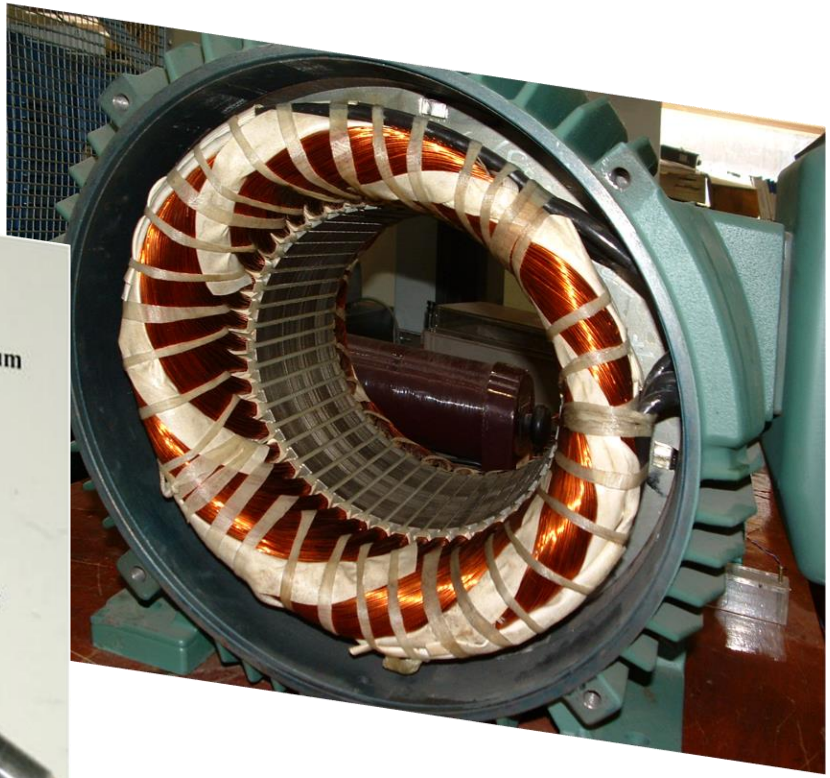
- Its speed cannot be varied without sacrificing some of its efficiency
- Just like a d.c. shunt motor, its speed decreases with increase in load
- Its starting torque is somewhat inferior to that of a d.c. shunt motor

AC Machines Construction

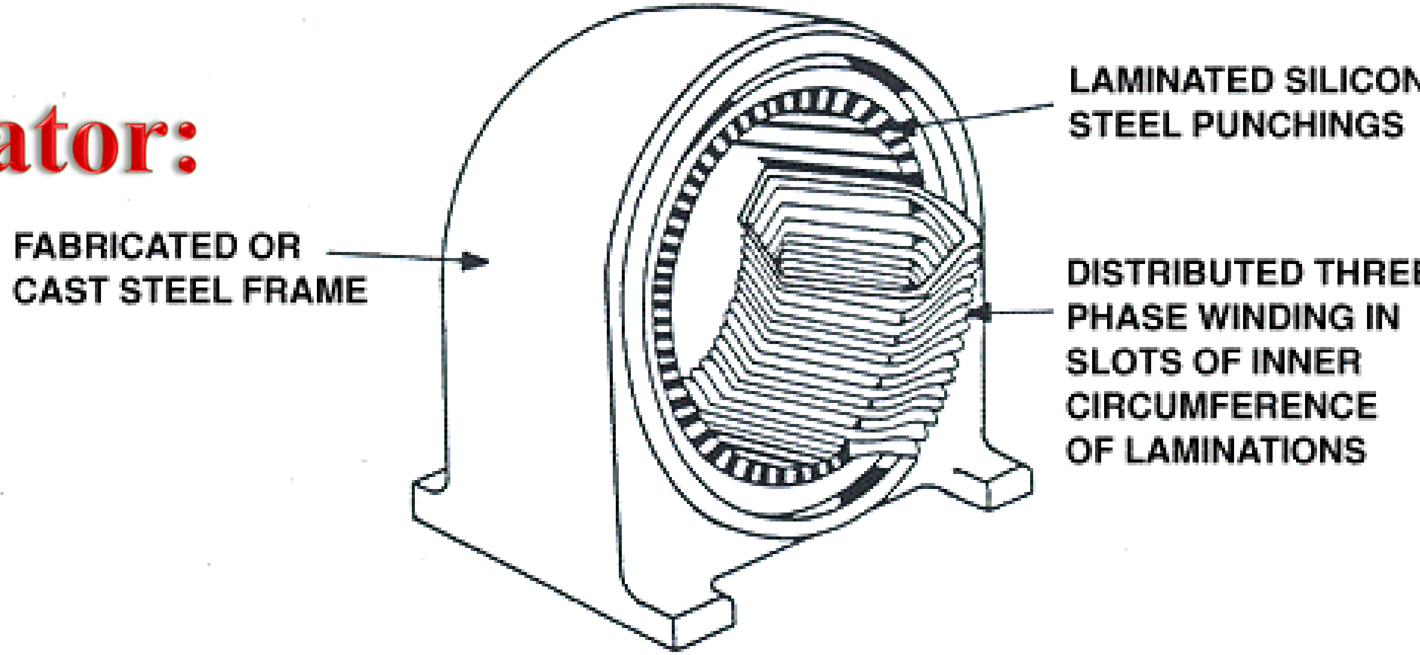
Just Like dc Machines, ac Machines also consist of

- **Stator**, and
- **Rotor**.





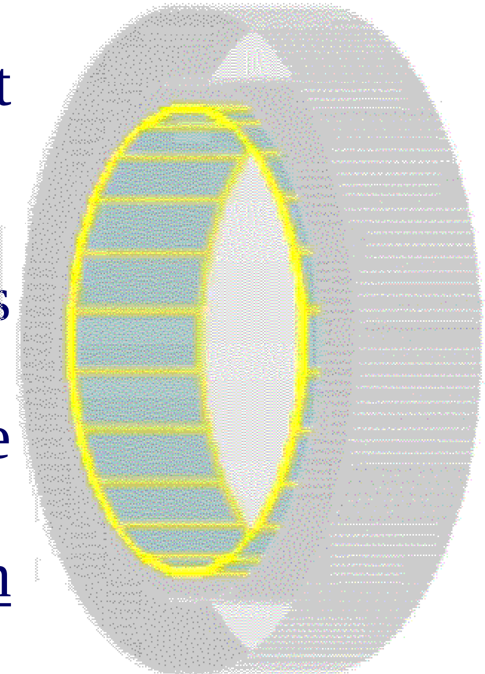
The Stator:

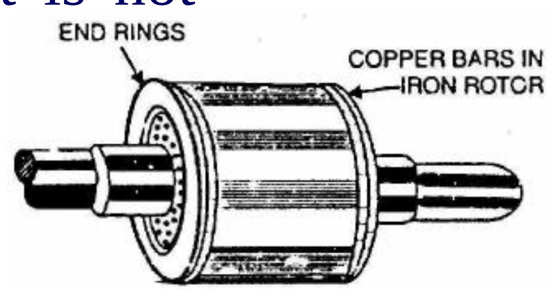


- The outer stationary steel frame enclosing a hollow, cylindrical core.
- A large number of circular silicon steel laminations with slots cut in the inner circumference.
- **Three phase windings mutually displaced by 120° are wound in these slots**.
- The greater the number of poles, the lesser is the speed and vice-versa.
- **Three phase supply induces rotating magnetic field.**
- Air gap between the stator and rotor ranges 0.4mm to 4mm, determines the power of the motor

The Rotor is the inner rotating section

- **Squirrel Cage** is the most common form of rotor:
  - Laminated cylindrical core with parallel slots at the outer periphery
  - Copper or aluminium bars are placed in the slots
  - All the bars are welded at each end by metal rings called “End rings”
  - **End rings** are sometimes castellated to facilitate cooling.
  - <u>It is not connected to the supply and operates on the transformer principle</u>
  - **Advantages**: This is a simple and robust construction
  - **Disadvantage**: Low starting torque as it is not possible to add external resistance.

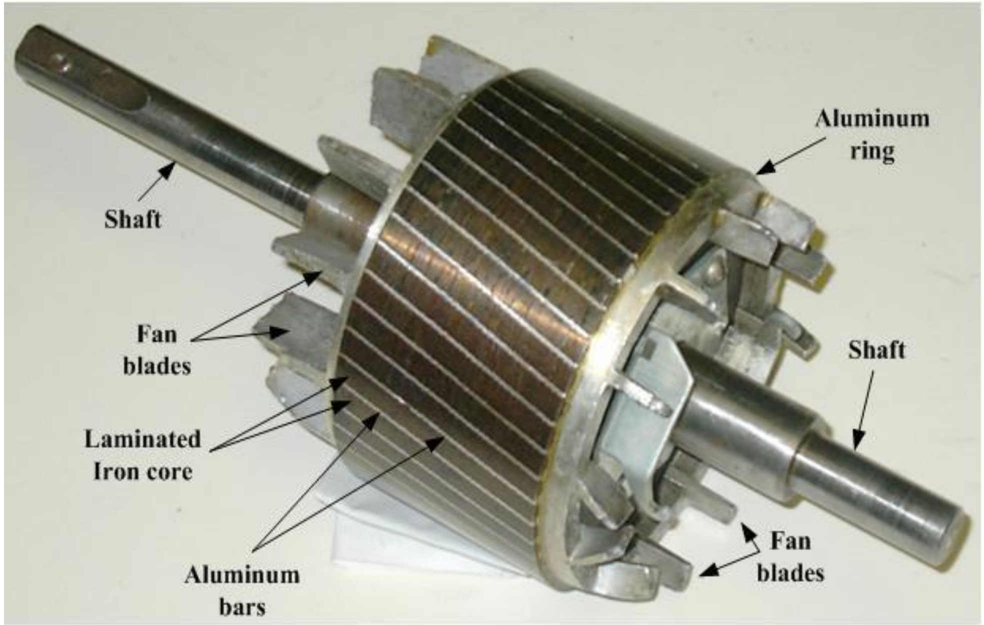




The Rotor is the inner rotating section

❑ Wound / Slip ring

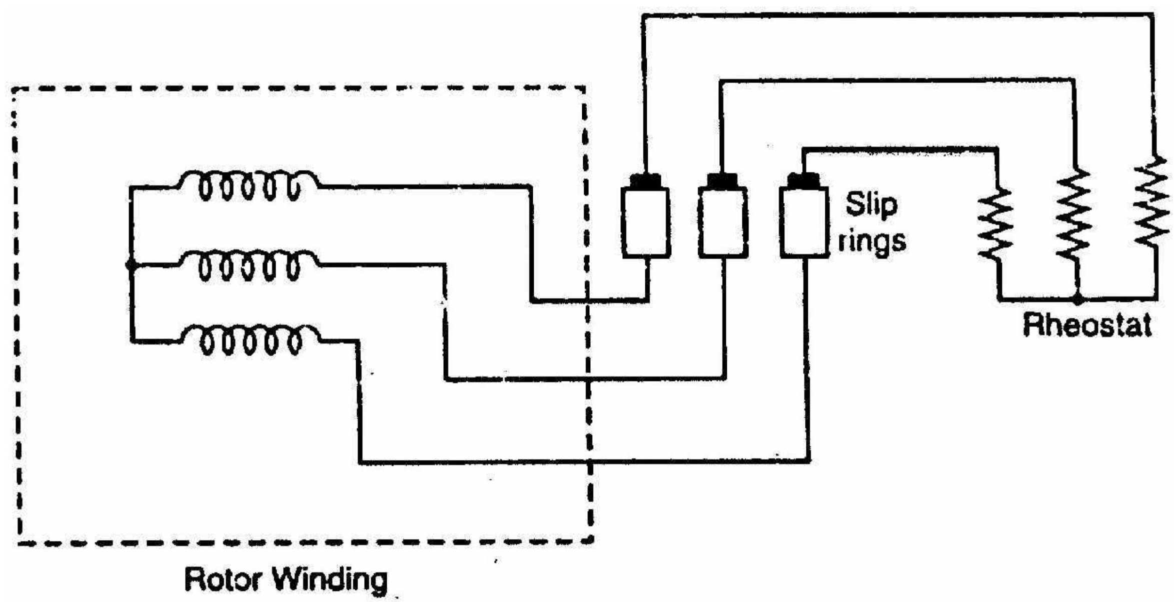
- Laminated cylindrical core
- Has star connected three phase winding
- Open ends are connected to three separate insulated slip rings
- External resistances are connected to increase the starting torque



The Rotor is the inner rotating section

❑ Wound / Slip ring

- The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a 3-phase star-connected rheostat as shown in Figure below

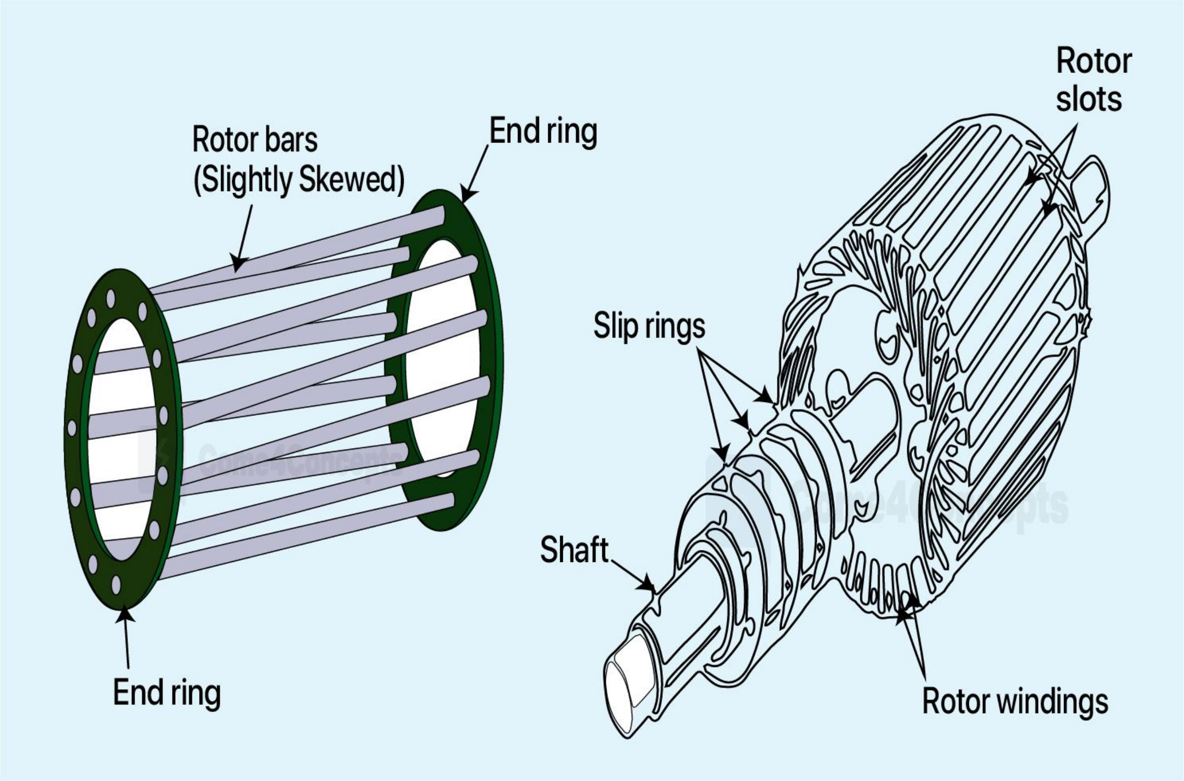


- At starting, the external resistances are included in the rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed.

The Rotor is the inner rotating section

❑ Wound / Slip ring

- Laminated cylindrical core
- Has star connected three phase winding
- Open ends are connected to three separate insulated slip rings
- External resistances are connected to increase the starting torque

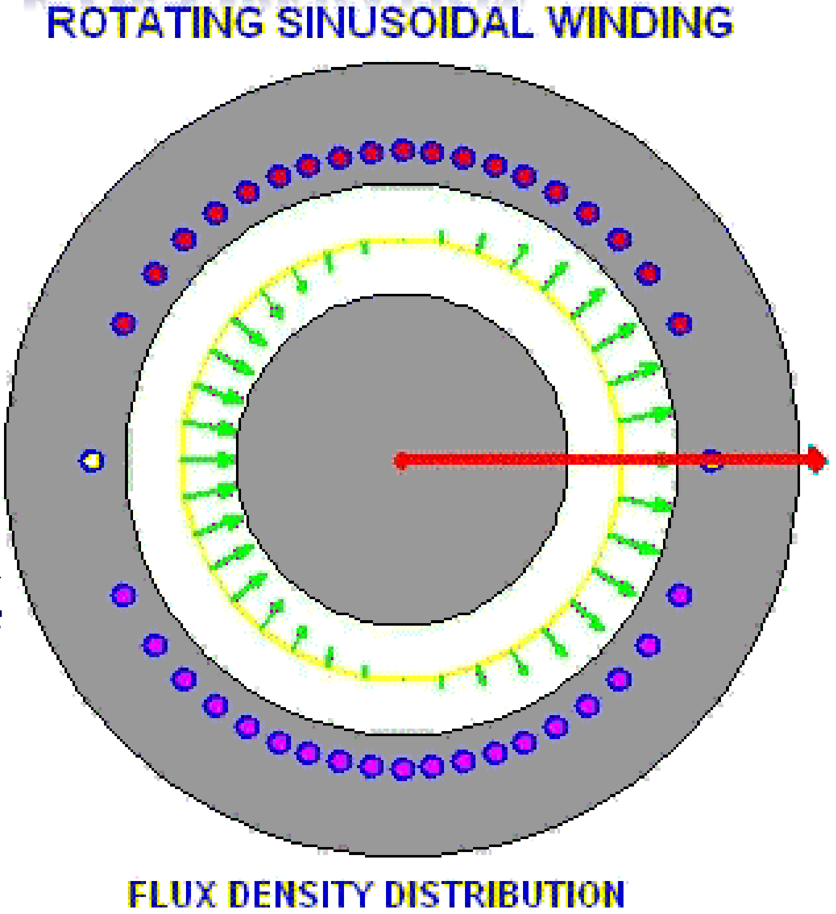


FUNDAMENTAL PRINCIPLE OF OPERATION

The fundamental principle of operation Is:

❑The generation of a rotating magnetic field,

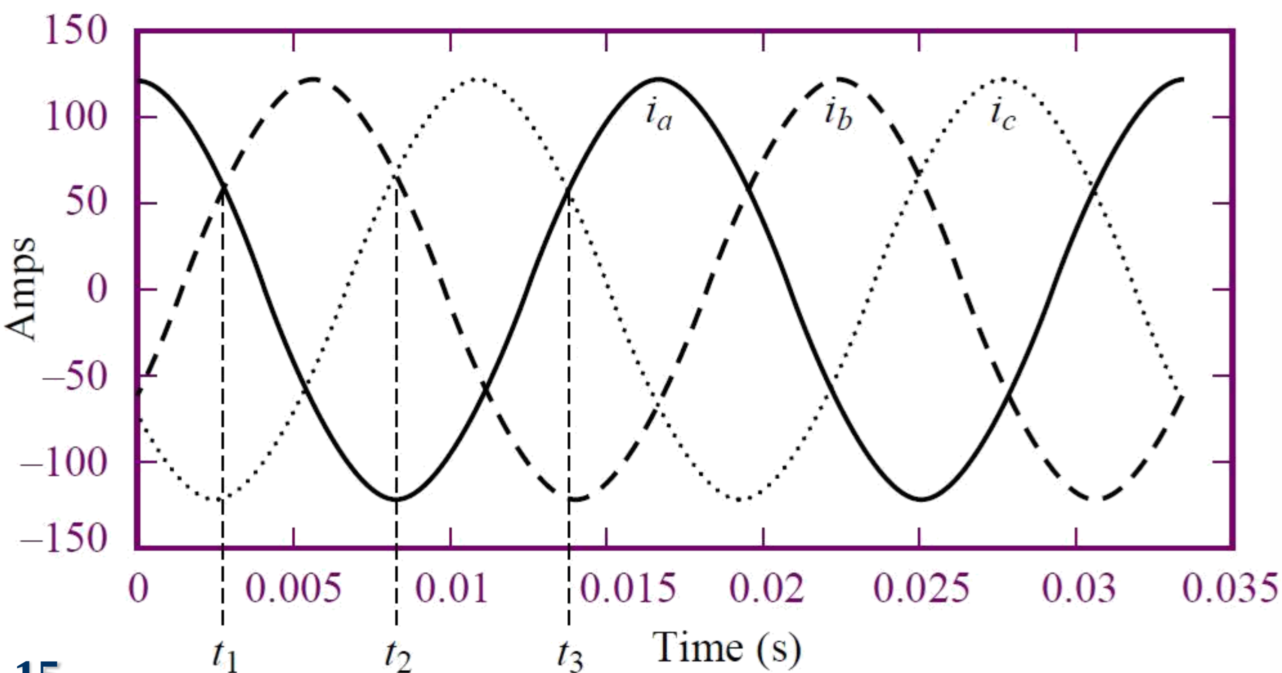
❑This causes the rotor to turn at a speed that depends on the speed of rotation of the magnetic field

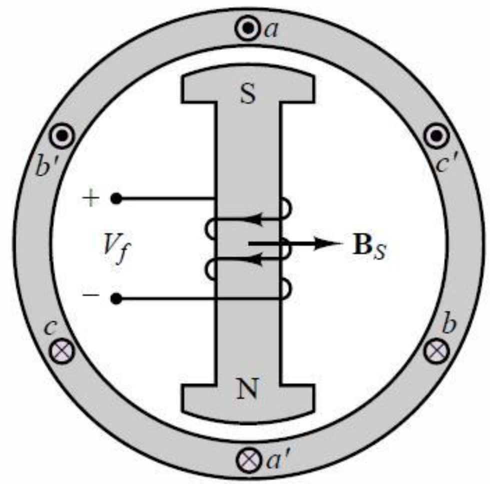


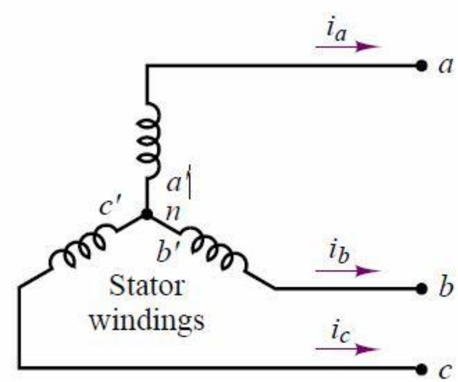
A uniform rotating magnetic field is produced in the air gap between the rotor and stator by applying balanced 3 phase supply.

Principle of Operation

- The stator supports windings ***a-a***, ***b-b*** and ***c-c***, which are geometrically spaced 120◦ apart.
- Therefore, the currents generated by a 3-phase source are also spaced by 120◦.







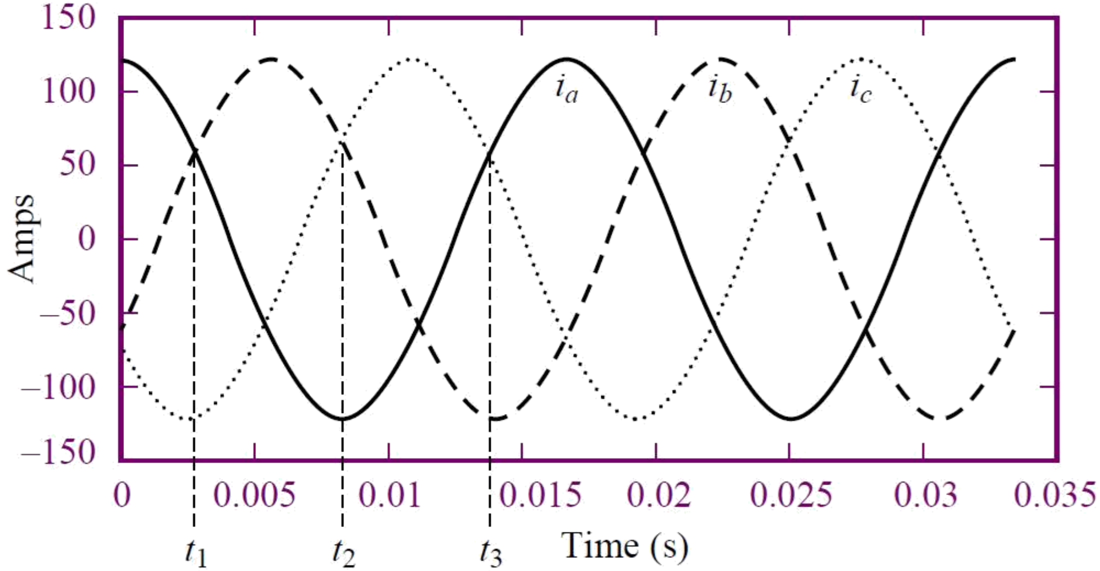
Principle of Operation

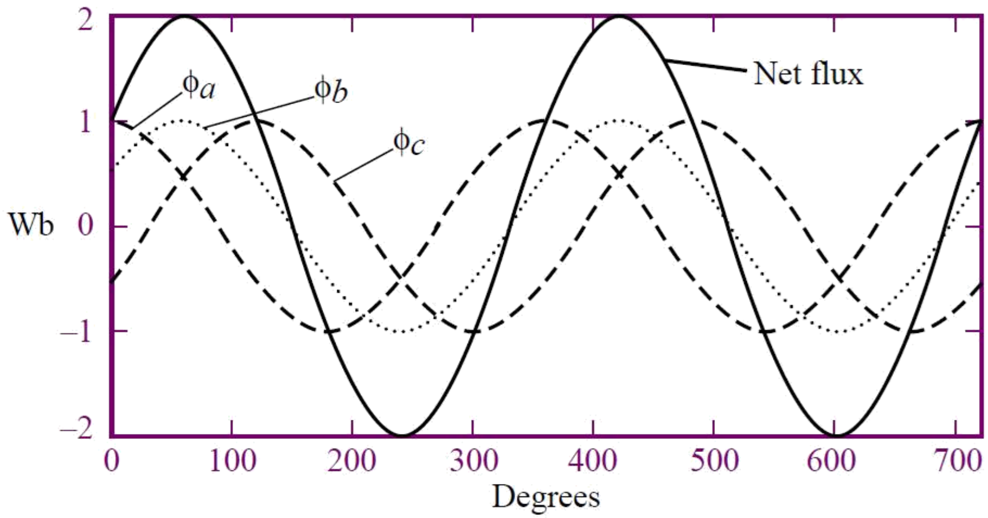
The phase voltages referenced to the neutral terminal, would then be given by the expressions

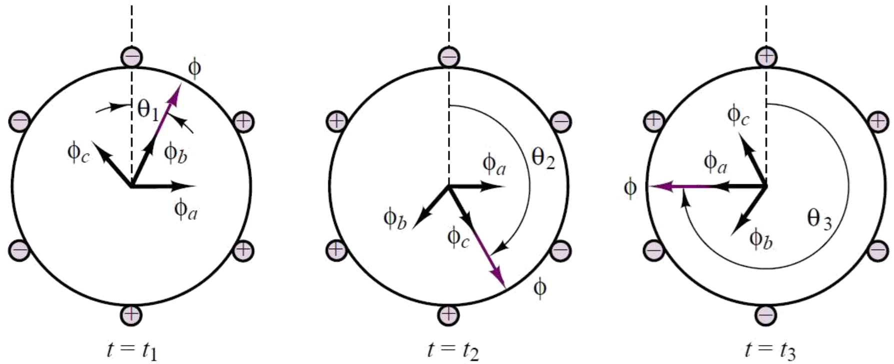
$$v_a = A\cos(\omega_e t)$$

$$v_b = A\cos\left(\omega_e t - \frac{2\pi}{3}\right)$$

$$v_c = A\cos\left(\omega_e t + \frac{2\pi}{3}\right)$$



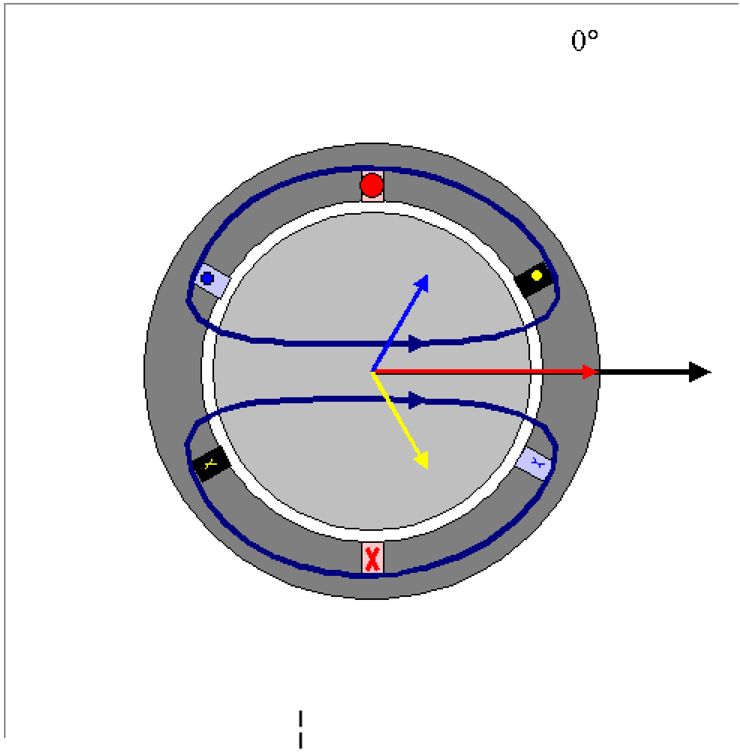


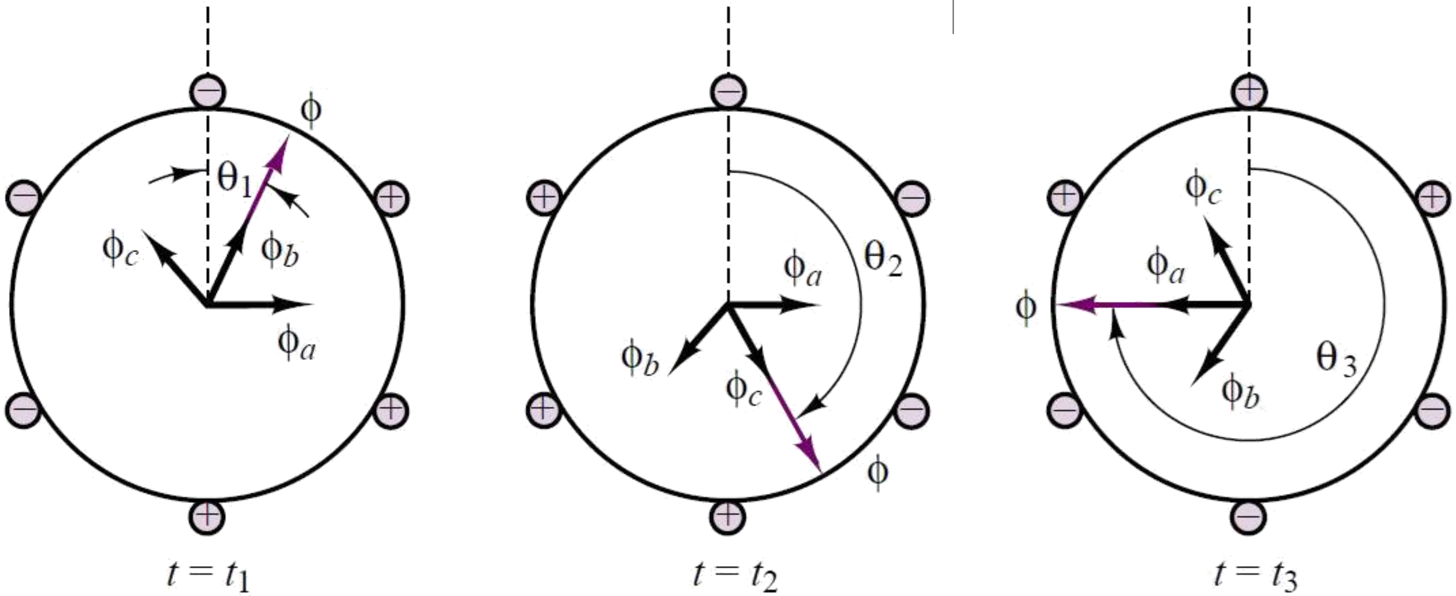


- ❑ The coils are arranged so that the flux distribution generated by any one winding is approximately sinusoidal.
- ❑ Since the coils are spaced 120◦ apart, the flux distribution resulting from the sum of the contributions of the three windings is the sum of the fluxes due to the separate windings.

- Thus, the flux (in a three-phase machine) is a rotating vector in space, with constant amplitude.

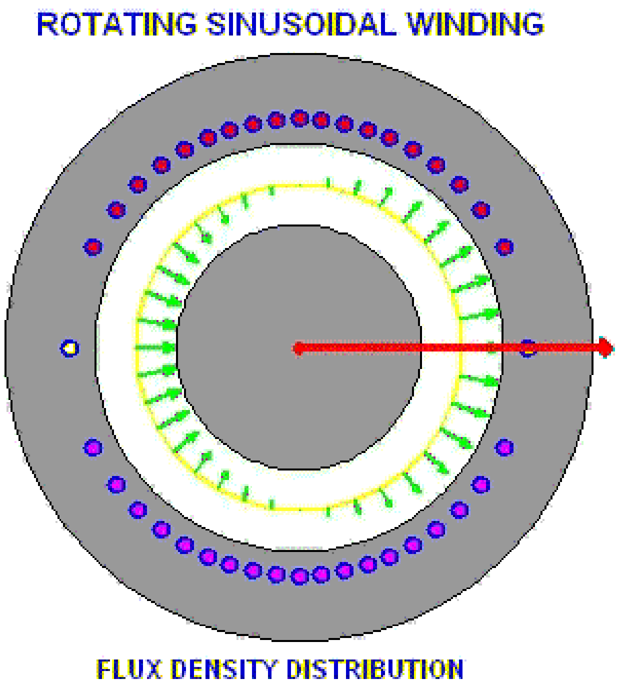
- Hence, A stationary observer on the machine's stator would see a sinusoidally varying flux distribution.





- Since the resultant flux is generated by the currents, the speed of rotation of the flux must be related to the frequency of the sinusoidal phase currents.

- The number of magnetic poles resulting from the stator winding configuration is two. However, it is possible to configure the windings so that they have more poles.



In general,

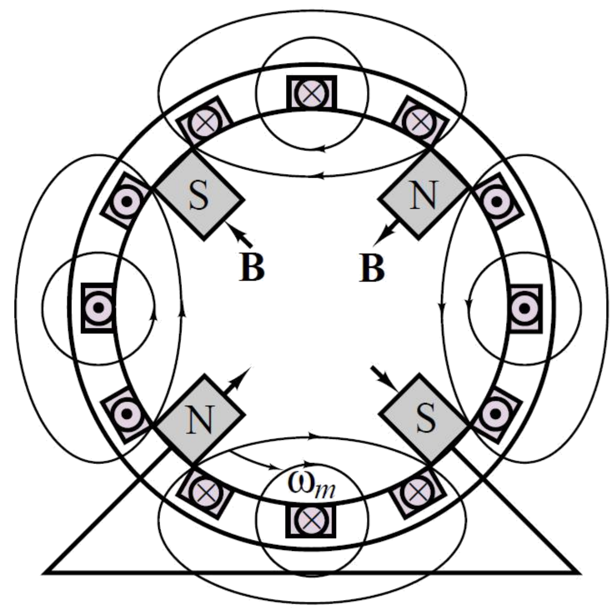
- The speed of the rotating magnetic field is determined by the frequency of the excitation current, **f** , and

- By the number of poles present in the stator, **p**, according to the equation

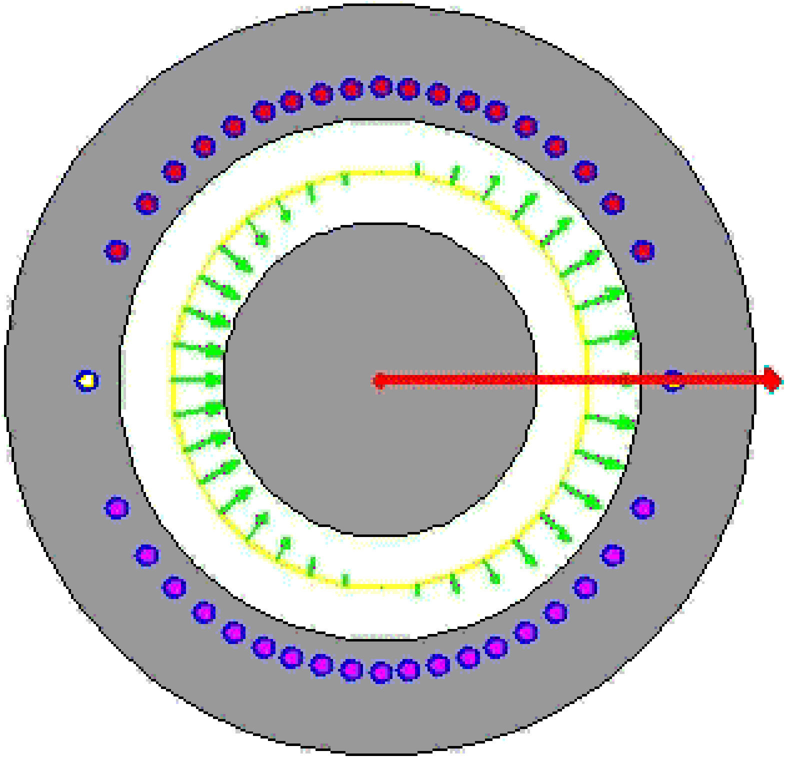
$$n_s = \frac{120}{p} f \ \ \text{rev/min}$$

$$\omega_s = \frac{2\pi n_s}{60} = \frac{2\pi f}{p} \ \ \text{rev/min}$$

where n_s *(or ω_s) is usually called the* ***synchronous speed.***



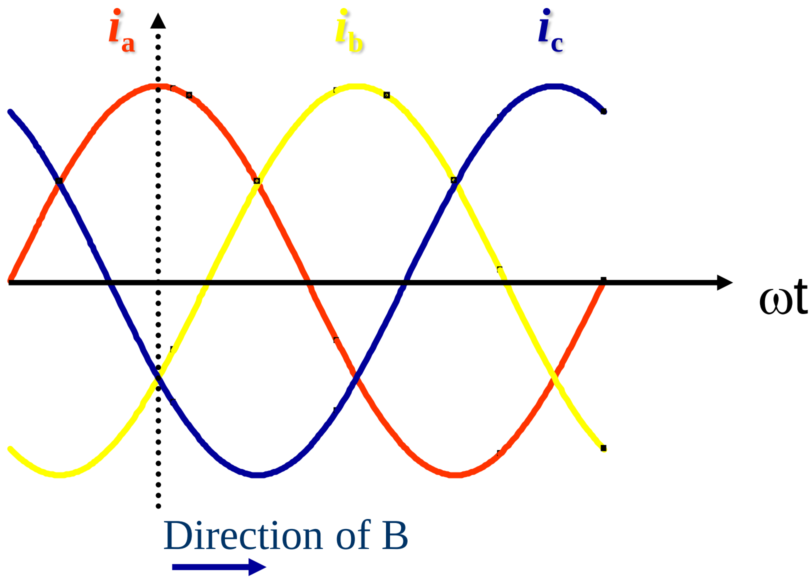
- The stator magnetic field rotates in an AC machine, and
    - therefore the rotor cannot "catch up" with the stator field and is in constant pursuit of it.
    - The speed of rotation of the rotor will therefore depend on the number of magnetic poles present in the stator and in the rotor.
- The magnitude of the torque produced is a function of the angle γ between the stator and rotor magnetic fields
- The number of stator and rotor poles must be identical if any torque is to be generated.



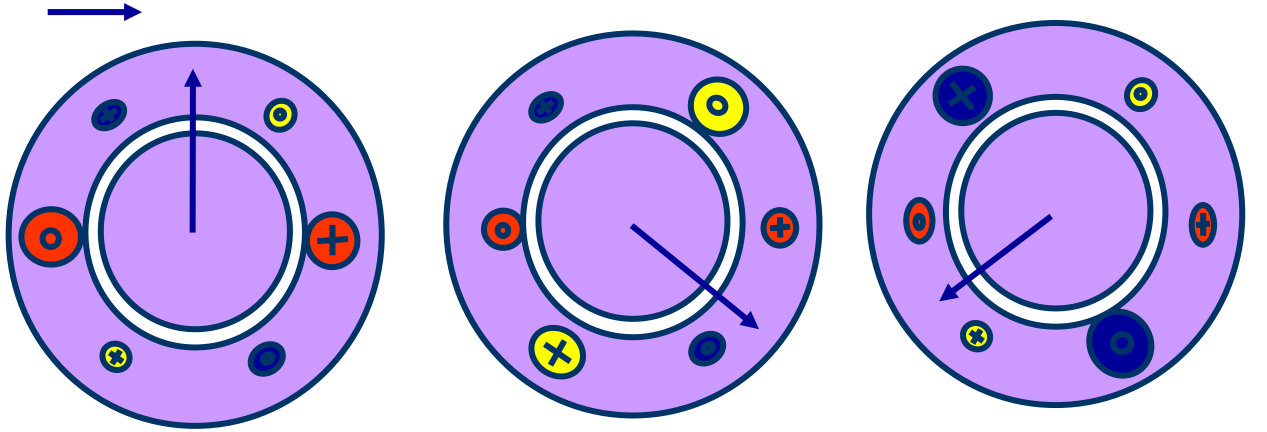
It is important to generate a constant electromagnetic torque to avoid torque pulsations

Pulsations could lead to undesired mechanical vibration in the motor itself and in other mechanical components attached to the motor (e.g., mechanical loads, such as spindles or belt drives).

Three Phase Currents



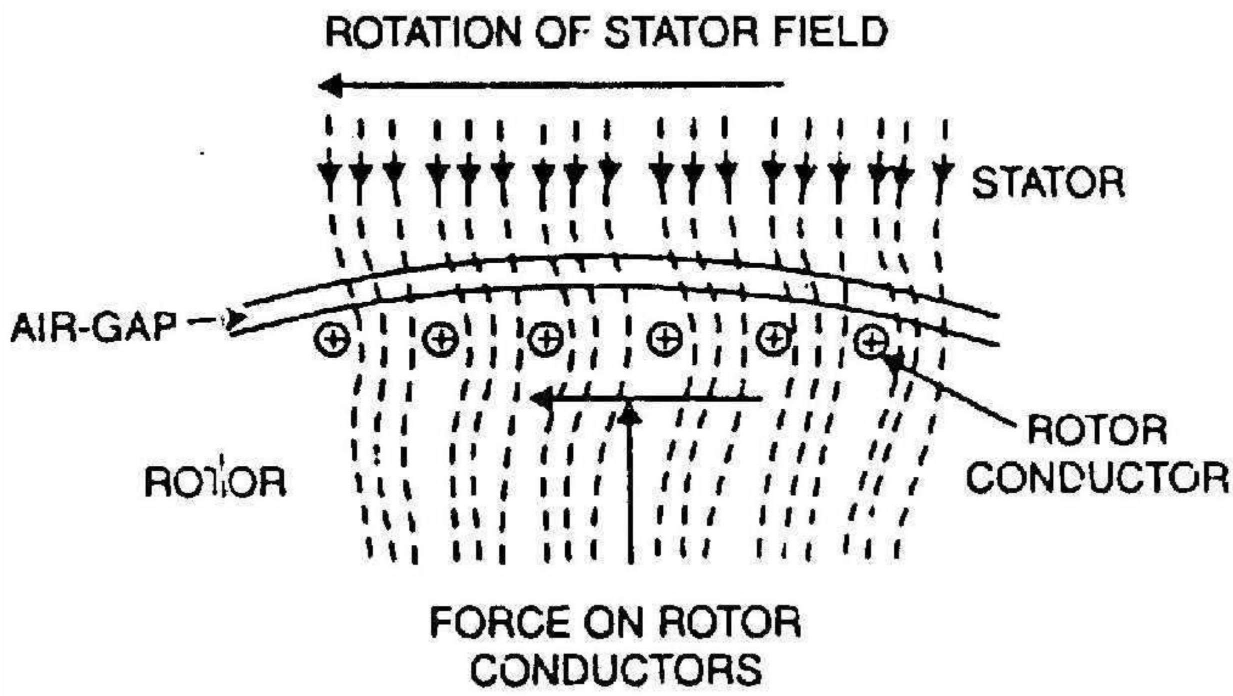
$$i_a = I_m \cos \omega o$$
$$i_b = I_m \cos(\omega o - 120^o)$$
$$i_c = I_m \cos(\omega o + 120^o)$$



A Current Maximum **B Current Maximum** **C Current Maximum**

Time

Principle of operation:



- 3-phase stator winding is energized from a 3-phase supply → a rotating magnetic field is set up which rotates round the stator at synchronous speed Ns (= 120 f/P)

Principle of operation:

- The rotating field passes through the air gap and cuts the rotor conductors, which as yet, are stationary. Due to the relative speed between the rotating flux and the stationary rotor, e.m.f.s are induced in the rotor conductors. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.
- The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, mechanical force acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the same direction as the rotating field.
- *Lenz's law: According to this law, the direction of rotor currents will be such that they tend to oppose the cause producing them. Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.*

What will happen if the rotor reaches the speed of the stator flux?

- No relative speed between stator field and rotor conductor
- No induced current
- No torque

Is it practically possible?

No, Because friction will slow down the rotor

Hence the rotor speed is always less than the stator rotating field speed and the difference is called "*Slip*"

$$\mathbf{Slip} = \frac{(\text{synchronous speed}, n_s) - (\text{actual rotor speed}, n)}{(\text{synchronous speed}, n_s)} = \frac{n_s - n}{n_s} = 1 - \frac{n}{n_s}$$

Note:

(i) The quantity Ns - N is sometimes called slip speed.

(ii) When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.

(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

Rotor current frequency:

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the general formula;

$$\text{Frequency} = \frac{NP}{120}$$

where N = Relative speed between magnetic field and the winding
P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s - N$. Consequently, the rotor current frequency f' is given by;

$$f' = \frac{(N_s - N)P}{120}$$

$$= \frac{s N_s P}{120} \qquad \left(Q \;\; s = \frac{N_s - N}{N_s} \right)$$

$$= sf \qquad \left(Q \;\; f = \frac{N_s P}{120} \right)$$

i.e., Rotor current frequency = Fractional slip x Supply frequency

Effect of slip on the rotor circuit:

- When the rotor is stationary, s = 1
- Under these conditions, the per phase rotor e.m.f. E2 has a frequency equal to that of supply frequency f. At any slip s, the relative speed between stator field and the rotor is decreased
- Consequently, the rotor e.m.f. and frequency are reduced proportionally to sEs and sf respectively
- At the same time, per phase rotor reactance X2, being frequency dependent, is reduced to sX2

- Thus at any slip s,

  Rotor e.m.f./phase = sE2

  Rotor reactance/phase = sX2

  Rotor frequency = sf

where E2,X2 and f are the corresponding values at standstill

EFFECT OF SLIP ON THE ROTOR CIRCUIT:

Rotor current:

At standstill

$$\text{Rotor current/phase, } I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

$$\text{Rotor p.f., } \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

When running at a slip s,

$$\text{Rotor current, } I'_2 = \frac{sE_2}{Z'_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor p.f., } \cos\phi'_2 = \frac{R_2}{Z'_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

TORQUE

The torque T developed by the rotor is directly proportional to:
(i) rotor current
(ii) rotor e.m.f.
(iii) power factor of the rotor circuit

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

$$\text{or} \quad T = K E_2 I_2 \cos\phi_2$$

Where E_2 = rotor emf per phase at standstill
I_2 = rotor current at standstill
X_2 = rotor reactance per phase at standstill
R_2 = rotor resistance per phase
$\cos\phi_2$ = rotor power factor per phase

Starting Torque

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$\therefore$ Starting torque, $T_s = K E_2 I_2 \cos\phi_2$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

STARTING TORQUE

Generally, the stator supply voltage V is constant → flux per pole ϕ set up by the stator is also fixed → e.m.f. E2 induced in the rotor will be constant.

$$\therefore \quad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It can be shown that K_1 = 3/2 p Ns

$$\therefore \quad T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here Ns is in r.p.s

It is clear that the magnitude of starting torque would depend upon the relative values of R2 and X2 i.e., rotor resistance/phase and standstill rotor reactance/phase.

Condition for Maximum Starting Torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase

$$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

Differentiating eq. w.r.t. R2 and equating the result to zero, we get,.

$$\frac{dT_s}{dR_2} = K_1\left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2}\right] = 0$$

or $$R_2^2 + X_2^2 = 2R_2^2$$

or $$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Effect of change in supply voltage on Starting Torque

$$T_s = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Since $E_2 \propto$ Supply voltage V

$$\therefore \quad T_s = \frac{K_2 V^2 R_2}{R_2^2 + X_2^2}$$

where K_2 is another constant.

$$\therefore \quad T_s \propto V^2$$

Therefore, the starting torque is very sensitive to changes in the value of supply voltage. For example, a drop of 10% in supply voltage will decrease the starting torque by about 20%. This could mean the motor failing to start if it cannot produce a torque greater than the load torque plus friction torque.

Torque under running conditions

Let the rotor at standstill have per phase induced e.m.f. E_2, reactance X_2 and resistance R_2. Then under running conditions at slip s,

$$\text{Rotor e.m.f./phase, } E'_2 = sE_2$$

$$\text{Rotor reactance/phase, } X'_2 = sX_2$$

$$\text{Rotor impedance/phase, } Z'_2 = \sqrt{R_2^2 + (sX_2)^2}$$

$$\text{Rotor current/phase, } I'_2 = \frac{E'_2}{Z'_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor p.f., } \cos\phi'_m = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Torque under running conditions

$$\text{Running Torque, } T_r \propto E'_2 I'_2 \cos\phi'_2$$

$$\propto \phi I'_2 \cos\phi'_2$$

$$\propto \phi \times \frac{s E_2}{\sqrt{R_2^2 + (s X_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}$$

$$\propto \frac{\phi s E_2 R_2}{R_2^2 + (s X_2)^2}$$

$$= \frac{K \phi s E_2 R_2}{R_2^2 + (s X_2)^2}$$

$$= \frac{K_1 s E_2^2 R_2}{R_2^2 + (s X_2)^2} \qquad (\because E_2 \propto \phi)$$

Torque under running conditions

If the stator supply voltage V is constant, then stator flux and hence E_2 will be constant.

$$\therefore \qquad T_r = \frac{K_2 \, s \, R_2}{R_2^2 + (s\,X_2)^2}$$

where K_2 is another constant.

It may be seen that running torque is:

(i) directly proportional to slip i.e., if slip increases (i.e., motor speed decreases), the torque will increase and vice-versa.

(ii) directly proportional to square of supply voltage $(\because E_2 \propto V)$.

It can be shown that value of $K_1 = 3/2\,\pi\,N_s$ where N_s is in r.p.s.

$$\therefore \qquad T_r = \frac{3}{2\pi N_s} \cdot \frac{s\,E_2^2\,R_2}{R_2^2 + (s\,X_2)^2} = \frac{3}{2\pi N_s} \cdot \frac{s\,E_2^2\,R_2}{(Z'_2)^2}$$

At starting, s = 1 so that starting torque is

$$T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2\,R_2}{R_2^2 + X_2^2}$$

Maximum torque under running conditions

$$T_r = \frac{K_2 \, s \, R_2}{R_2^2 + s^2 \, X_2^2}$$

In order to find the value of rotor resistance that gives maximum torque under running conditions, differentiate above expression w.r.t. s and equate the result to zero.

We get,

$$R_2 = s \, X_2$$

Thus for maximum torque (Tm) under running conditions :
Rotor resistance/phase = Fractional slip X Standstill rotor reactance/phase

Now,

$$T_r \propto \frac{s \, R_2}{R_2^2 + s^2 \, X_2^2}$$

Maximum torque under running conditions

For maximum torque, R2 = s X2. Putting R2 = s X2 in the above expression, the maximum torque Tm is given by;

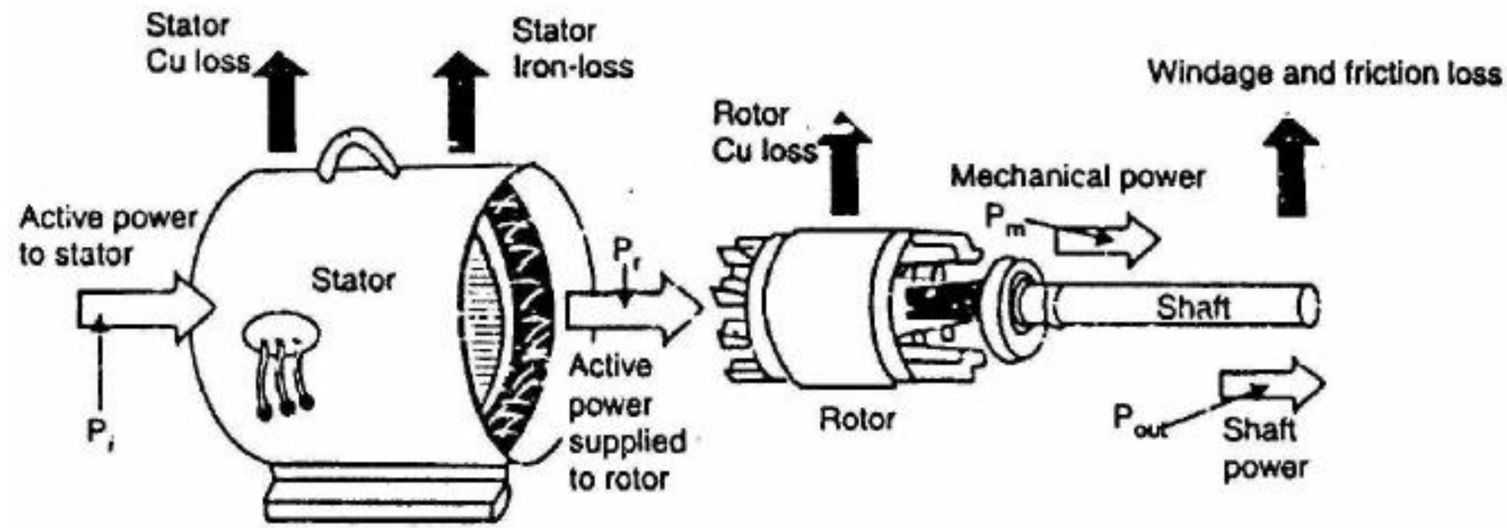
$$T_m \propto \frac{1}{2\,X_2}$$

Slip corresponding to maximum torque, $s = R_2/X_2$.

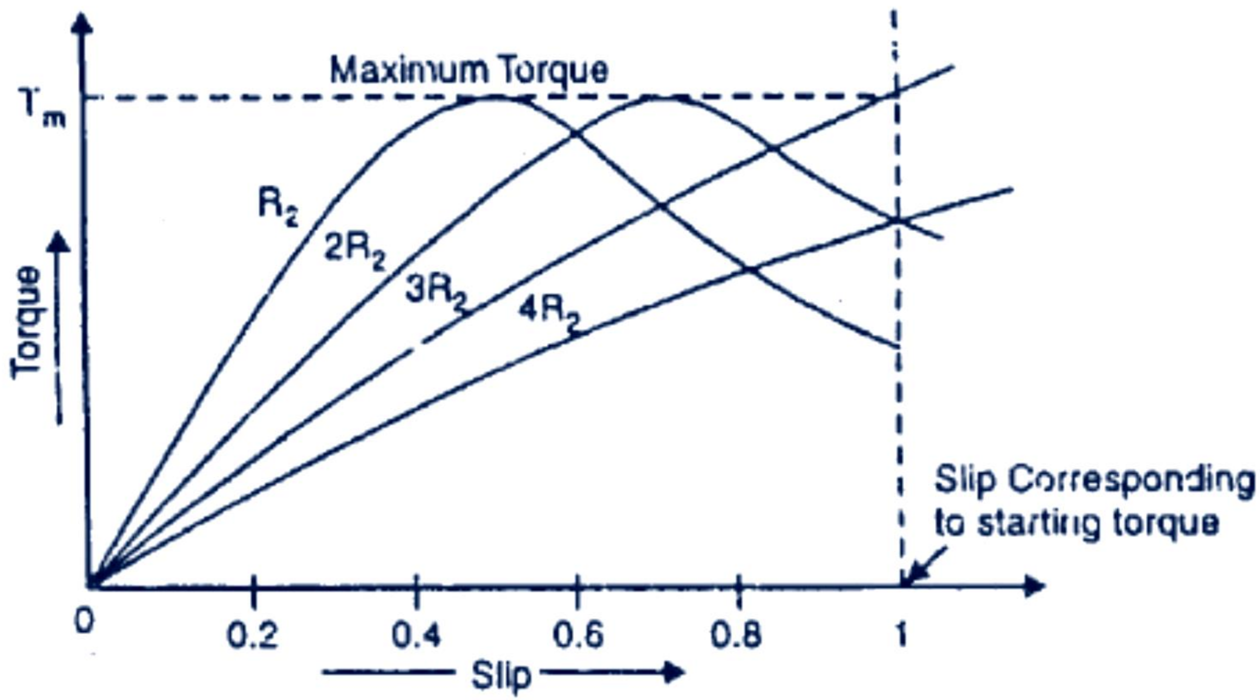
It can be shown that:

$$T_m = \frac{3}{2\pi N_s} \cdot \frac{E_2^2}{2\,X_2} \text{ N - m}$$

Power Stages in an Induction motor



Torque – Slip charateristics



$$T_r = \frac{K_2\ s\ R_2}{R_2^2 + s^2\ X_2^2}$$

TORQUE

$$\mathbf{Torque, T} = \frac{\mathbf{3}}{\boldsymbol{\omega}} \times \frac{\mathbf{E_2{}^2 as}}{\mathbf{X_2\left(a^2 + s^2\right)}} \mathbf{Nm}$$

Where	E_2 =	emf induced in rotor winding at standstill
	s =	per unit slip
	ω =	$2\pi f$ (f = supply frequency in Hz)
	X_2 =	*standstill* rotor reactance per phase
	$a = \frac{R_2}{X_2}$	(R_2 = rotor resistance per phase)

Mechanical output power = Torque $\times$ Angular velocity of rotor

$P_m = T \times (2\pi n)$

$P_m = 2\pi T n_s(1\text{-}s)$

But $n_s = f$ and $\omega = 2\pi f$

$$P_m = T\omega(1\text{-}s) = \frac{3\,E_2{}^2\,as(1-s)}{X_2(a^2+s^2)} watts$$

EXERCISE

A 3-phase 415V 2 pole 50Hz induction motor has an effective stator : rotor turns ratio of 2:1, rotor resistance 0.15Ω/phase and rotor standstill reactance 0.75Ω/phase. The motor runs at 2900 rev min^{-1}. Calculate

- a) per unit slip
- b) torque
- c) mechanical output power

Solution

Per Unit Slip

$$n_s = f$$

$$s = 1 - \frac{n}{n_s}$$

$$s = 1 - \frac{\left(2900/_{60}\right)}{50} = 0.0333$$

Torque

$$T = \frac{3}{\omega} \times \frac{E_2{}^2 as}{X_2\left(a^2 + s^2\right)}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}; \qquad E_1 = \frac{415}{\sqrt{3}}$$

$$E_2 = \left(415/\sqrt{3}\right) \times \frac{1}{2} = 119.8V$$

$$a = \frac{R_2}{X_2} = \frac{0.15}{0.75} = 0.2$$

$$T = \frac{3}{2\pi 50} \times \frac{119.8^2 \times 0.2 \times 0.0333}{0.75 \times \left(0.2^2 + 0.0333^2\right)}$$

$$= 29.6 \text{ Nm}$$

Mechanical output power

$$P_m = T\omega\,(1 - s)$$

$$= 29.6\,(2\pi 50)\,(1 - 0.333)$$

$$= 8989 \text{ W}$$

Starting and Maximum Torque

- **Starting Torque**
  - On starting, rotor speed n = 0 and slip, s = 1

$$T_{start} = \frac{3}{\omega} \times \frac{E_2^{\,2} a}{X_2(a^2+1)} \; Nm$$

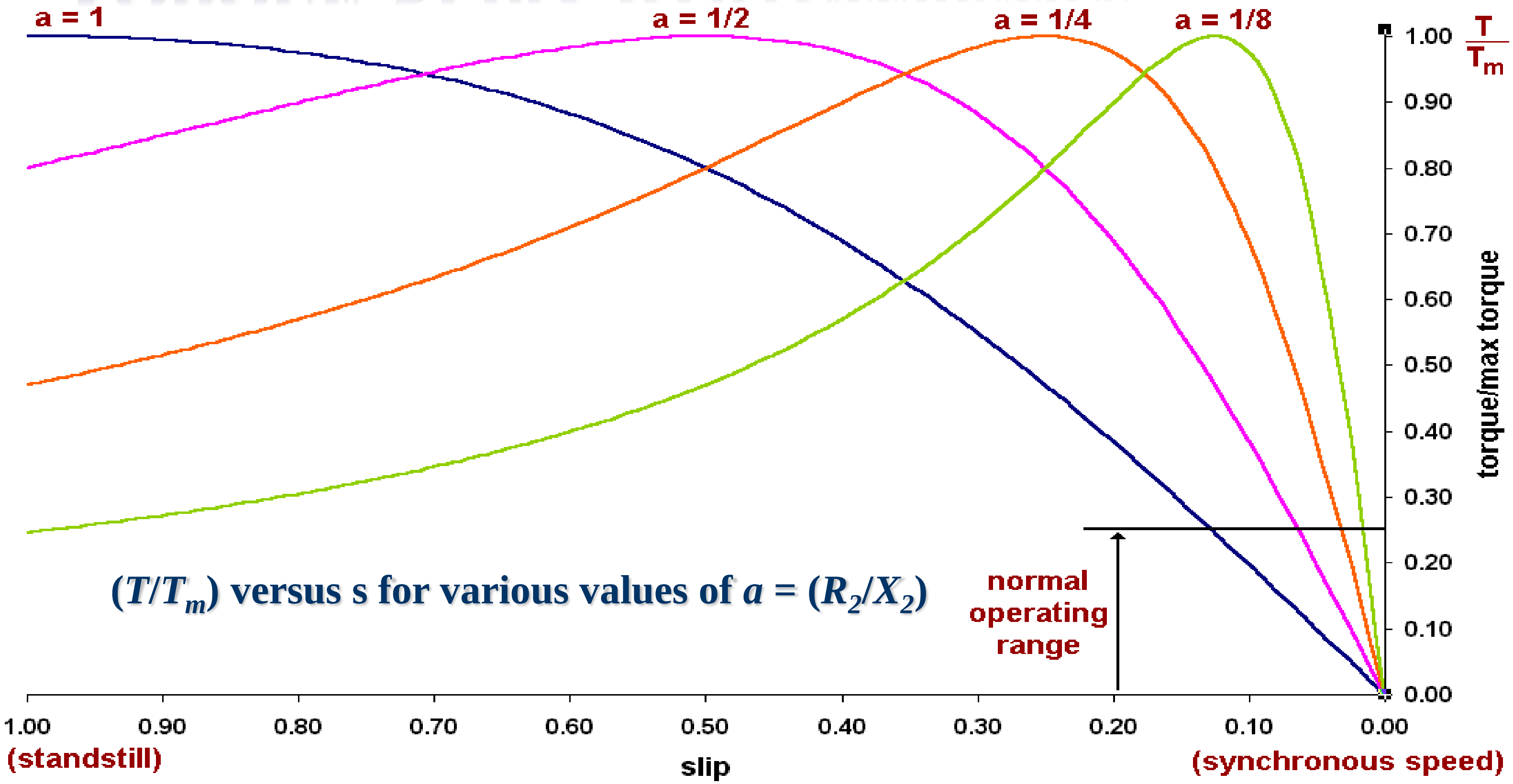
- **Maximum Torque**

$$\frac{dT}{ds} = \frac{3}{\omega} \times \frac{E_2^{\,2}}{X_2} \times \frac{a(a^2 - s^2)}{(a^2+s^2)^2} = 0$$

i.e. when $a = s$

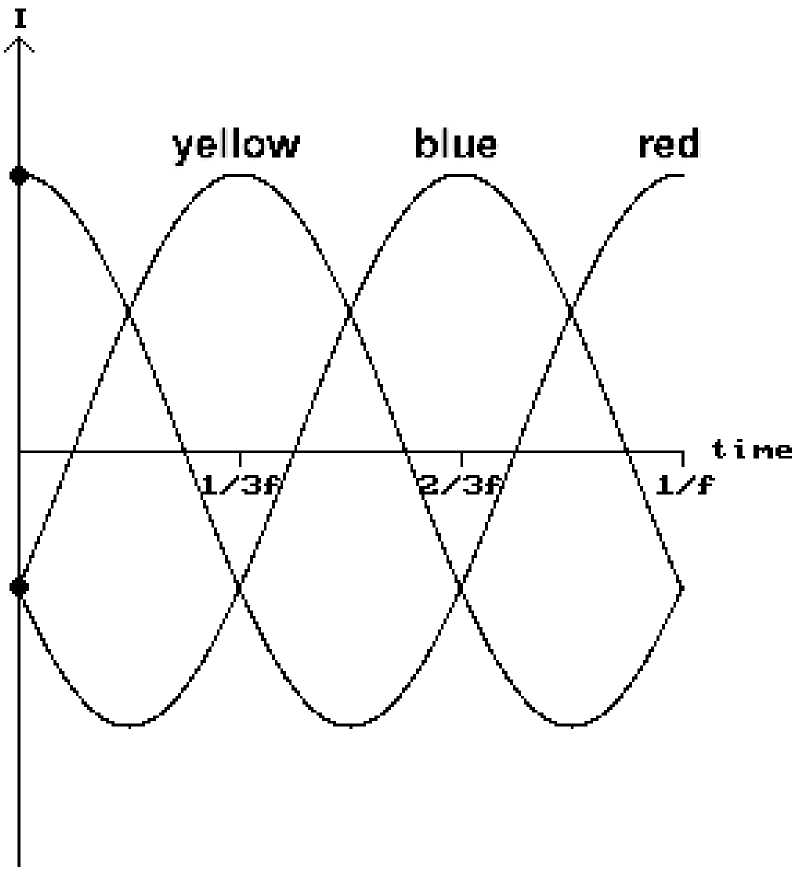
$$T_m = \frac{1}{2} \cdot \frac{3}{\omega} \cdot \frac{E_2^{\,2}}{X_2} \; Nm$$

Torque-Slip Characteristics

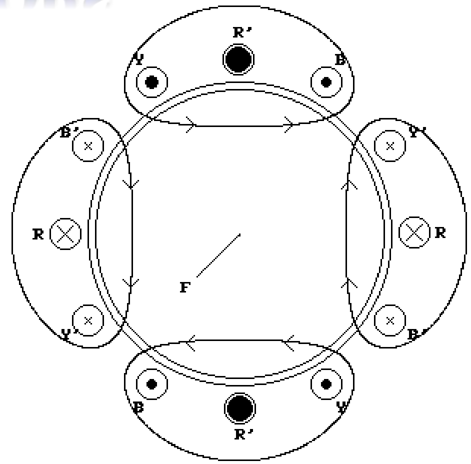


The graphs show that in steady state conditions induction motors with the smallest value of "a" run at practically constant speed over the normal operating range of the machine. Unfortunately, these machines generally have poor starting torques and for a motor to start it is necessary that ***Starting torque > load torque***

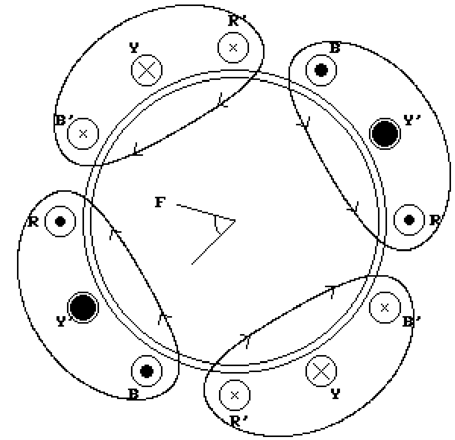
Multi-Pole Motors



t = 0, red at positive maximum

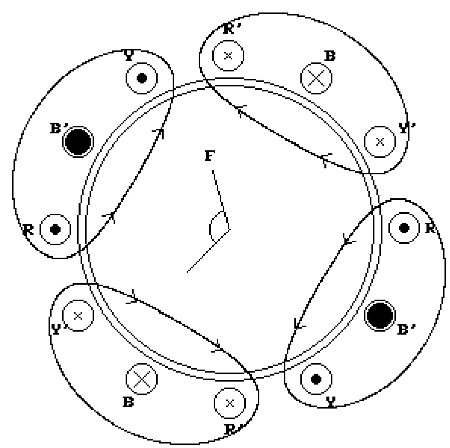


t = 1/3f, (1/3rd of a cycle later) yellow at positive maximum



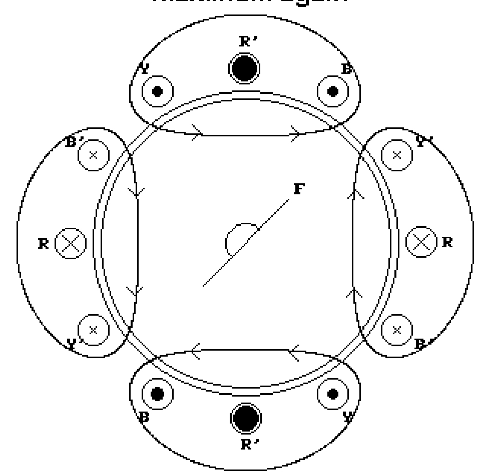
field has moved clockwise through 60 mechanical degrees

t = 2/3f, blue at positive maximum



field has moved through a further 60 degrees

t = 1/f, (one cycle after start) red at positive maximum again



in one cycle (360 degrees electrical) field has moved through 180 mechanical degrees

No of poles	Pole Pairs	Synchronous speed @ frequency = 50Hz	
		rev s^{-1} (= n_s)	rev min^{-1}
2	**1**	50	3000
4	**2**	25	1500
6	**3**	16.67	1000
8	**4**	12.5	750
2*p*	***p***	$(50/p) = (f/p)$	$(3000/p)$

Conclusion

- In this unit we explained the principle of operation of 3- phase induction motor and its applications, with particular focus on Induction Motors:
    - Its Construction
    - Principles of Operation
    - Torque
    - Torque vs. Slip Characteristics
    - Multi-pole Motors