ICT 103: Electrical Science

<u>UNIT 3 : AC and DC Motors</u>

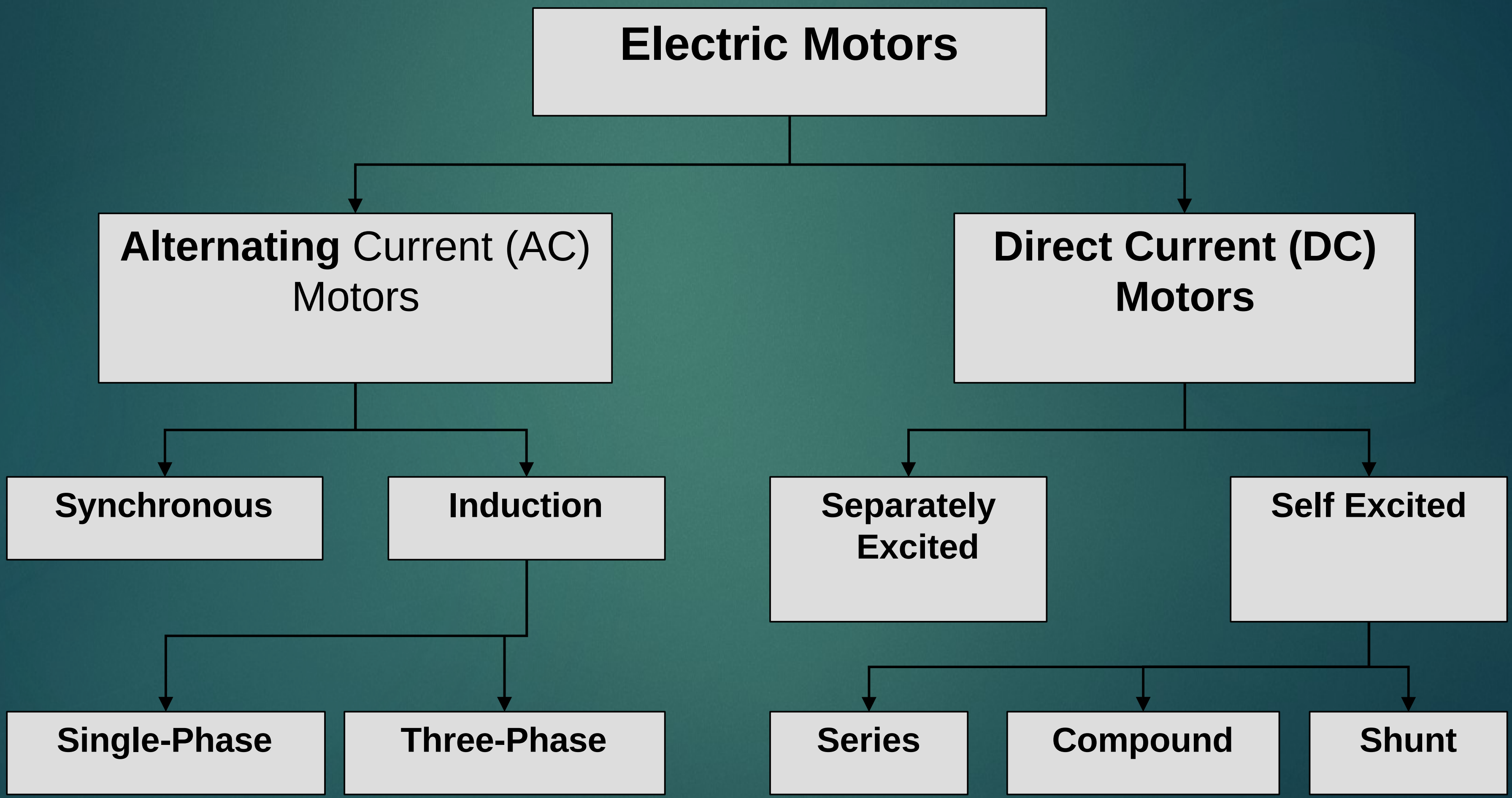
- **Dr KHYATI CHOPRA (PhD IIT Delhi)**

ELECTRIC MOTOR

- An electric motor is an electromechanical device that converts electrical energy to mechanical energy.

- The mechanical energy can be used to perform work such as rotating a pump impeller, fan, blower, driving a compressor, lifting materials etc.

CLASSIFICATION OF MOTORS



- **In AC motors, the armature is stationary while the magnetic field rotates. In DC motors, the armature rotates while the magnetic field remains stationary**. In AC motors, three input terminals (RYB) are present. In DC motors, two input terminals (positive and negative) are present.

- Which is better DC motor or AC motor?

- Overall, both DC and AC motors serve the same function, which is the conversion of electrical energy into mechanical energy. The most fundamental difference, of course, is their power source. Also, specific types of DC motors require more maintenance, have limited speed, and shorter lifecycles.

Synchronous motor and **Asynchronous motor**

Synchronous motor is a machine whose rotor speed and the speed of the stator magnetic field is equal.

Asynchronous motor is a machine whose rotor rotates at the speed less than the synchronous speed

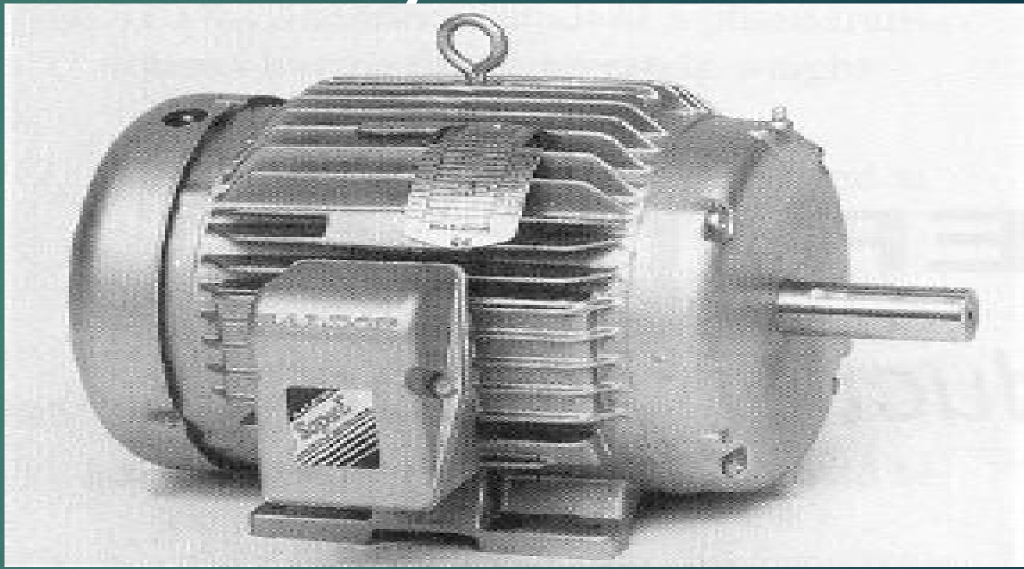
Generation of rotating magnetic fields

- The rotating magnetic field is produced by the **three-phase current of** the stator in the actual three-phase induction motor. It can be replaced by permanent magnets in a permanent magnet synchronous motor. The three-phase windings of the inner stator are spaced 120° electrical degrees apart.

- When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. ... The three-phase currents **flow simultaneously through the windings and are displaced from each other by 120° electrical**. Each alternating phase current produces its own flux which is sinusoidal.

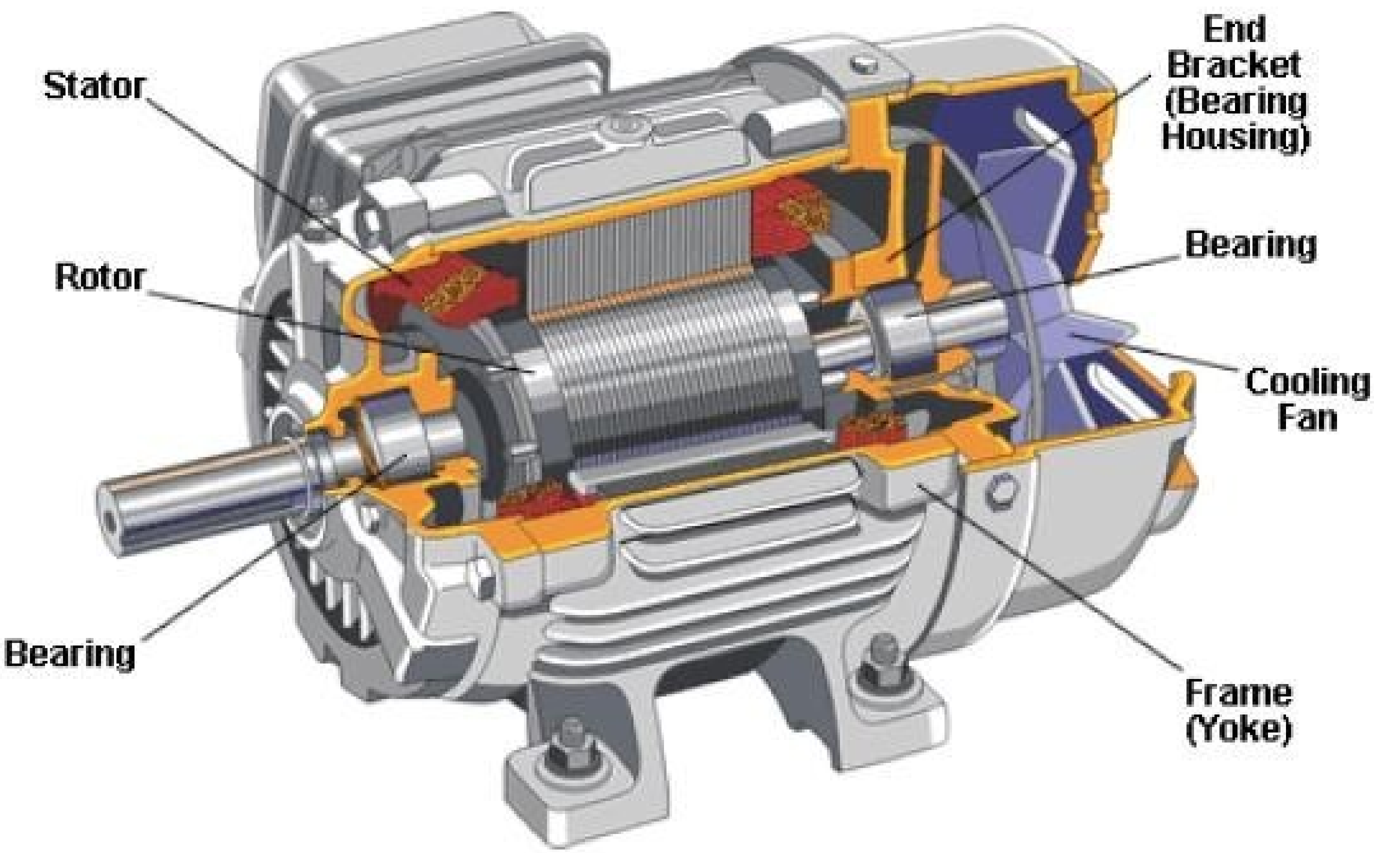
AC MOTOR: INDUCTION MOTOR

- Most common motors in industry



- Advantages:
  - Simple design
  - Inexpensive
  - High power to weight ratio
  - Easy to maintain
  - Direct connection to AC power source

Parts of AC Motor



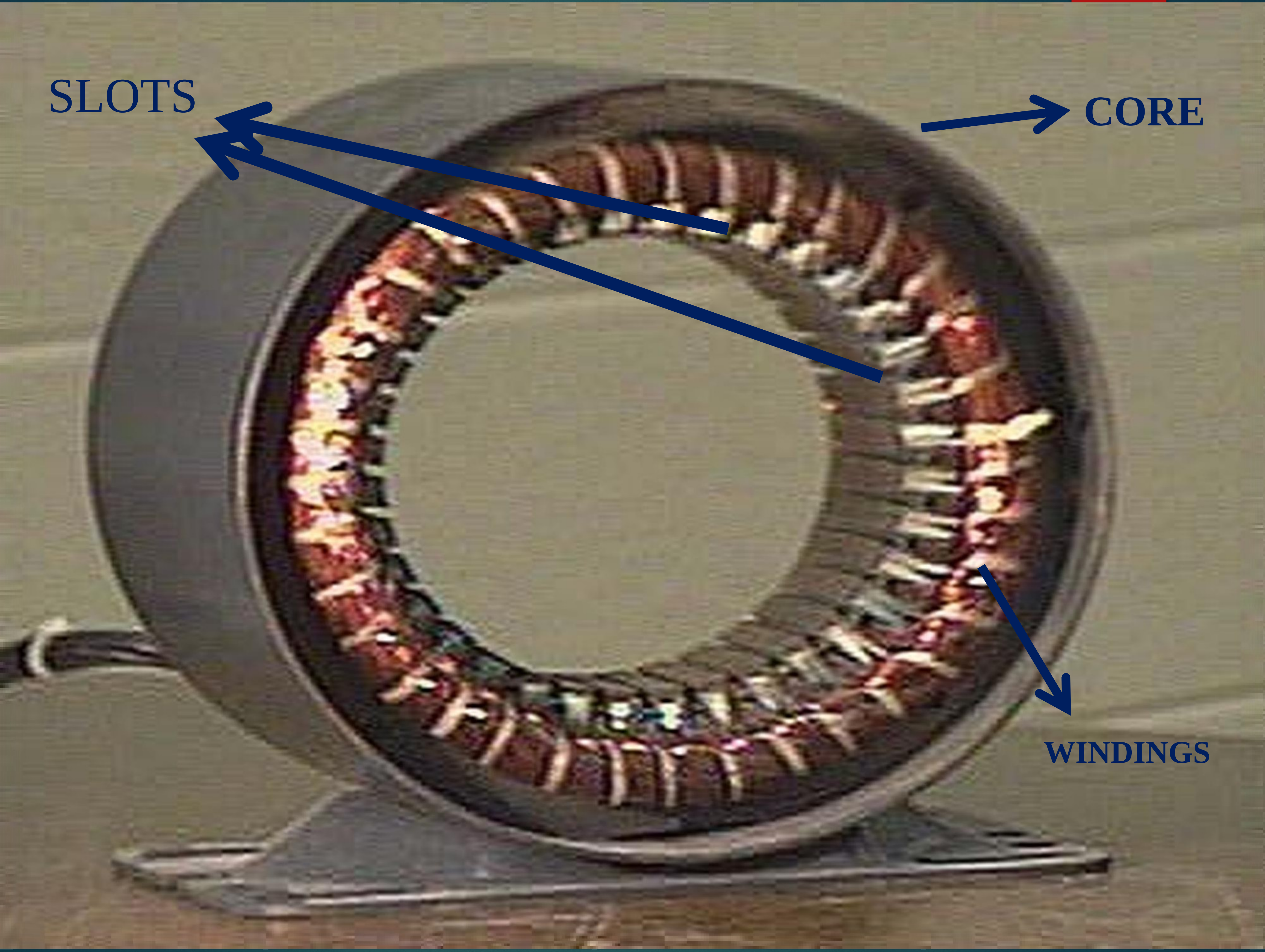
- *An induction motor works on transforming action.*
- *The stator works as the primary while the rotor works as the secondary.*
- *It is also called asynchronous motor.*

- It consists of two parts:

1. ***Stator*** - It is the stationary part of the motor.

2. ***Rotor*** - It is the rotating part of the motor.

STATOR


SLOTS
CORE
WINDINGS

- Stator has three main parts:

➢ ***Outer Frame*** – It is the outer body of the of the motor.

It protects the inner part of the machine.

➢ ***Stator Core*** – Built up of high grade silicon steel.

Carries the alternating magnetic field.

➢ ***Stator winding*** – Has a three phase winding.

ROTOR

- There are two types of rotors which are employed in 3 – phase induction motor.

  - ***Squirrel Cage Rotor.***

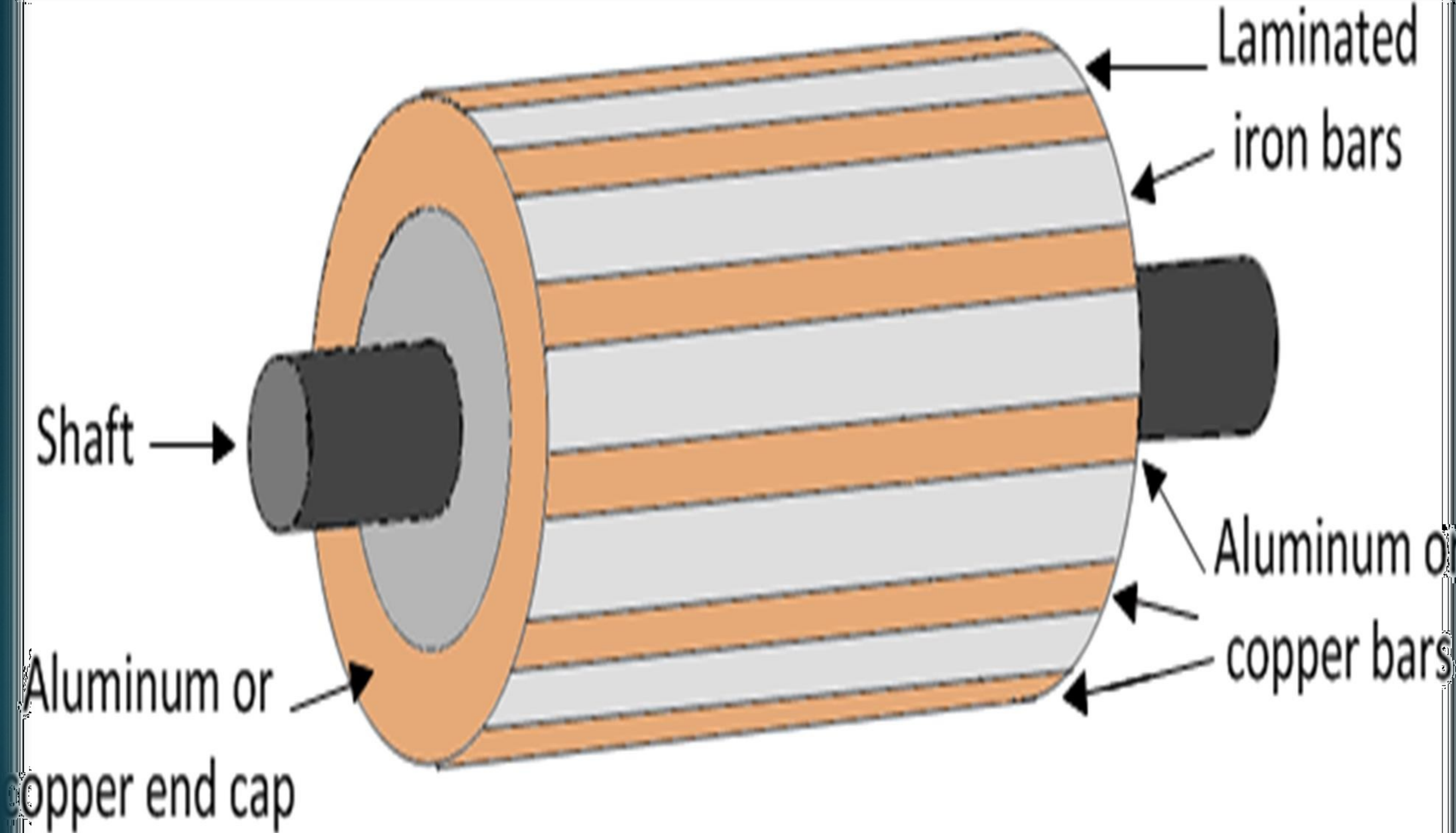
  - ***Phase Wound/ Slip Ring Rotor.***

SQUIRREL CAGE ROTOR

- It consists of a laminated cylindrical core having semi closed circular slots at the outer periphery.
- Copper or aluminum bar conductors are placed in these slots and short circuited at each end by copper or aluminum rings called short circuiting rings.
- The rotor winding is permanently short circuited and it is not possible to add any external resistance.

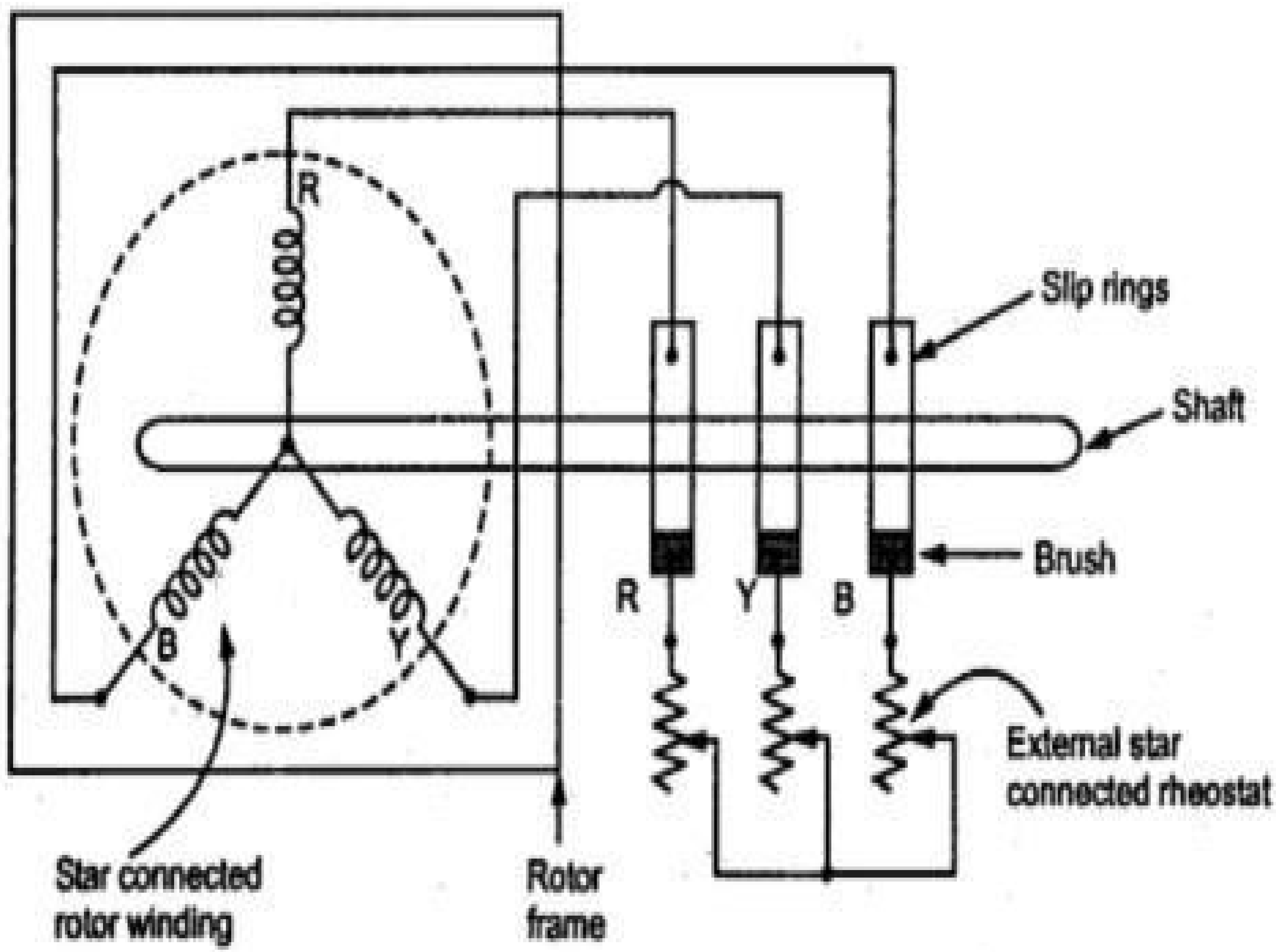
- The rotor slots are not parallel to the shaft but skewed to –

  - ✓ Reduce humming .
  - ✓ Provide smoother torque for different positions of rotor.
  - ✓ Reduce magnetic locking of stator and rotor.



Induction Motor Squirrel Cage Rotor

PHASE WOUND ROTOR



R
Slip rings
Shaft
Brush
R
Y
B
B
Y
External star
connected rheostat
Star connected
rotor winding
Rotor
frame

- It is also called ***SLIP RING ROTOR***

- Consists of a laminated core having semi closed slots at the outer periphery and carries a 3-phase insulated winding.

- The rotor is wound for the same number of poles as that of stator.

- The three finish terminals are connected together forming a star point and the three star terminals are connected to three slip rings fixed on the shaft.

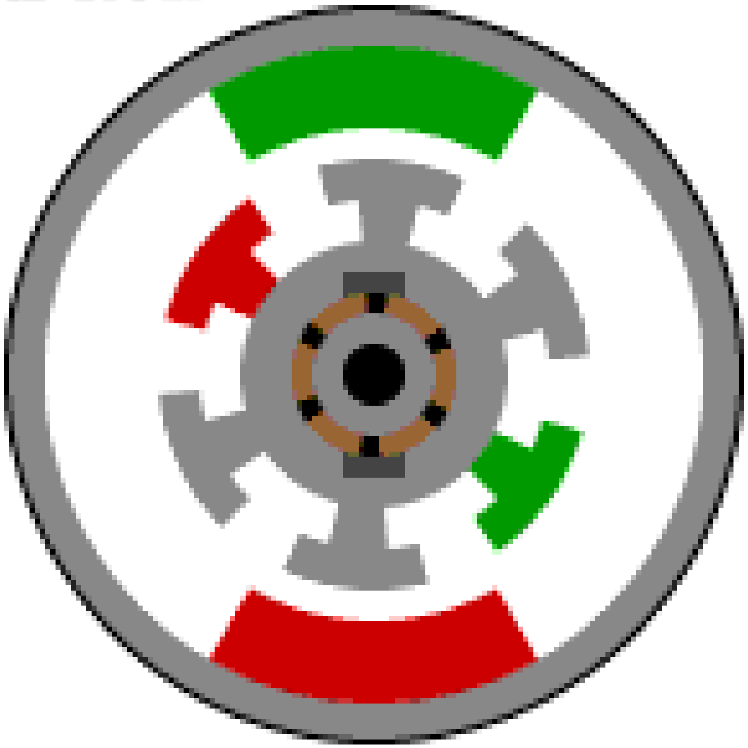
- ***Principle of Operation***
  - ➢ A rotating field is set up in the stator when 3-Phase supply is given.
  - ➢ The stationary rotor cut the revolving field and due to electromagnetic induction an *e.m.f.* is induced in the rotor conductor.
  - ➢ As the rotor conductor is short circuited current flows through them.
  - ➢ It becomes a current carrying conductor in magnetic field and start rotating.

INTRODUCTION TO MOTOR CONSTRUCTION

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.



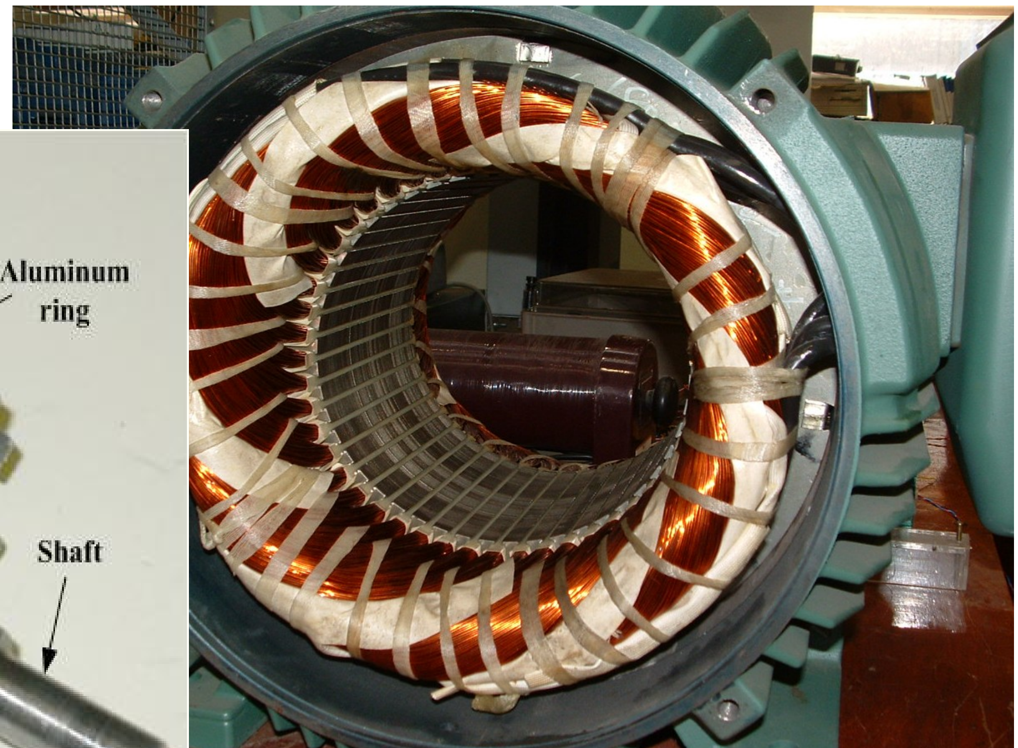
Operation

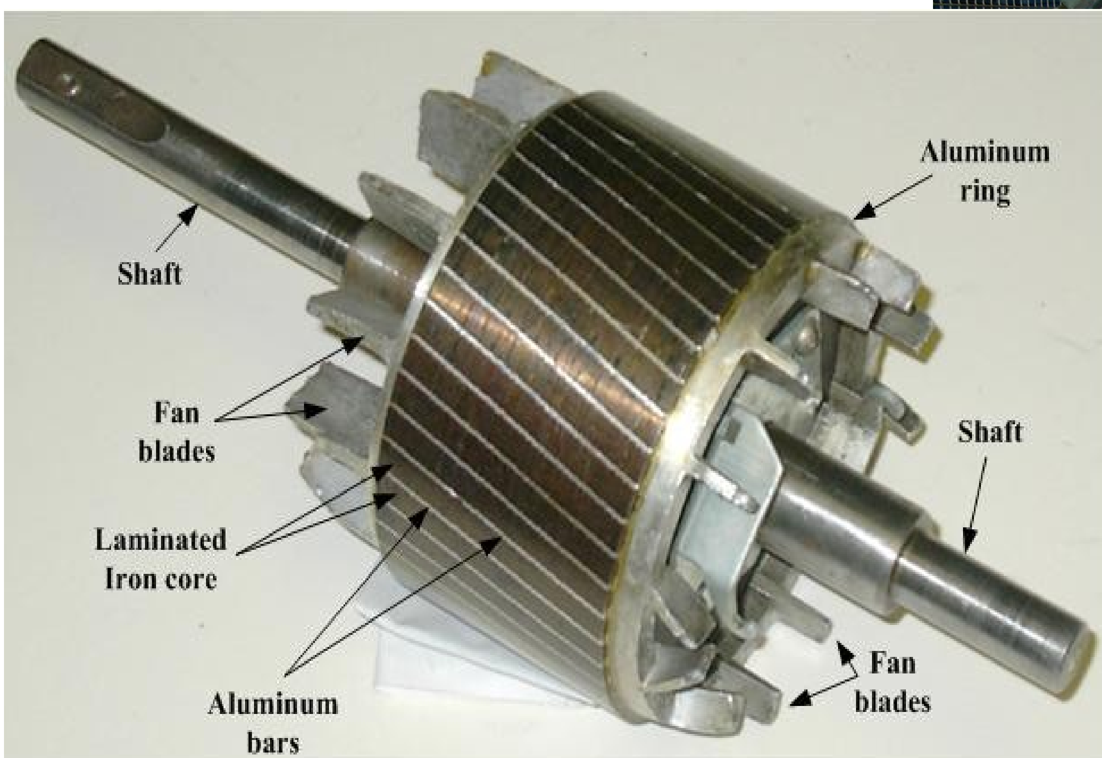
- As the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding.
- In the animation:
  - The commutator contacts are brown,
  - The brushes are dark grey.
  - A yellow spark shows when the brushes switch to the next winding.

AC MACHINES CONSTRUCTION

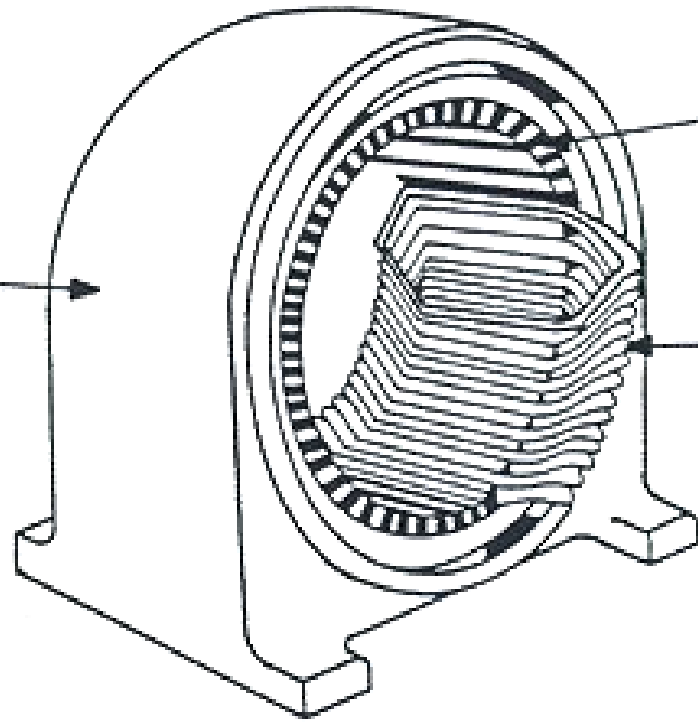
Just Like dc Machines, ac Machines also consist of

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





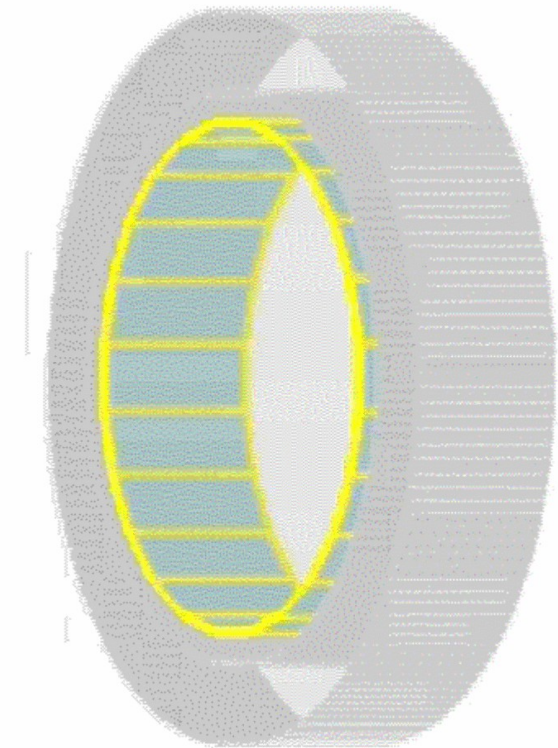
The Stator:



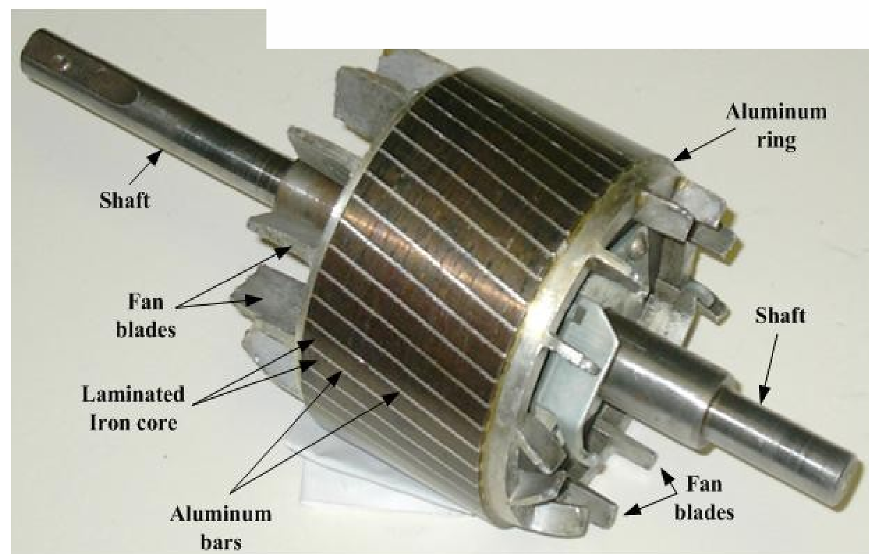
- The outer stationary steel frame enclosing a hollow, cylindrical core.
- A large number of circular silicon steel laminations with slots cut in the inner circumference.
- **Three phase windings mutually displaced by 120° are wound in these slots**.
- The greater the number of poles, the lesser is the 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

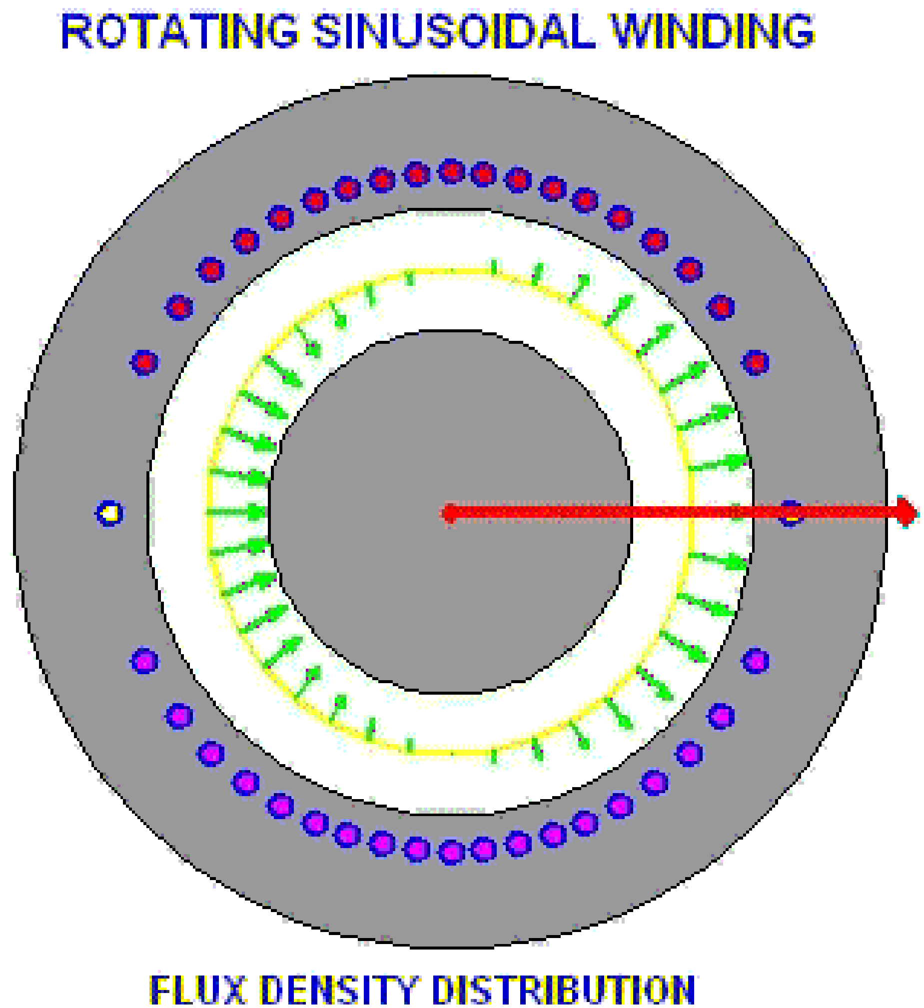
- **Squirrel Cage** is the most common form of rotor:
  - Laminated cylindrical core with parallel slots at the ou periphery
  - Copper or aluminium bars are placed in the slots
  - All the bars are welded at each end by metal rings call "End rings"
  - **End rings** are sometimes castellated to facilitate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



- **Wound**
  - 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



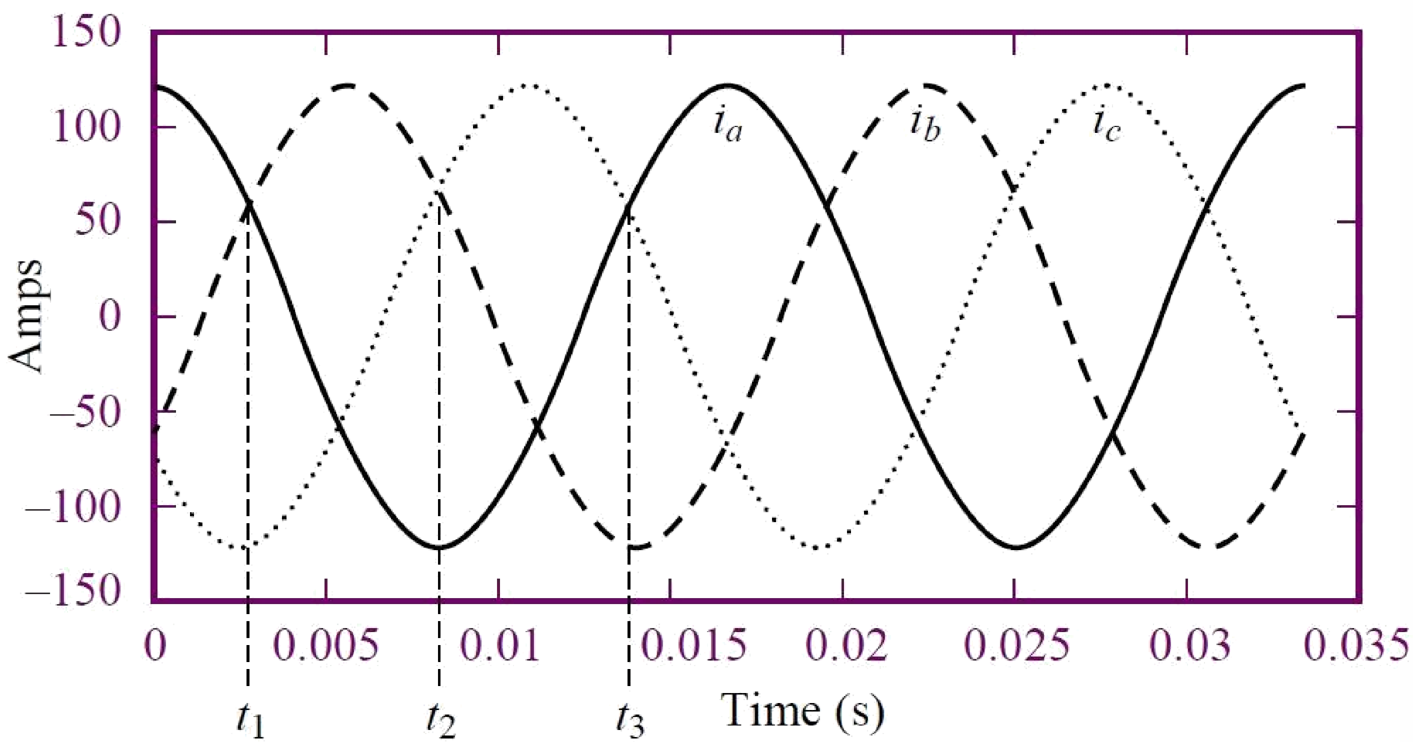
The fundamental principle of operatio
Is:

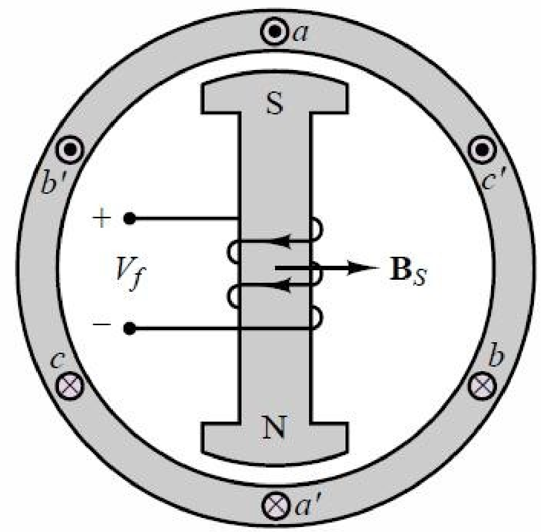
- The generation of a rotating magne field,
- This causes the rotor to turn at speed that depends on the speed rotation of the magnetic field

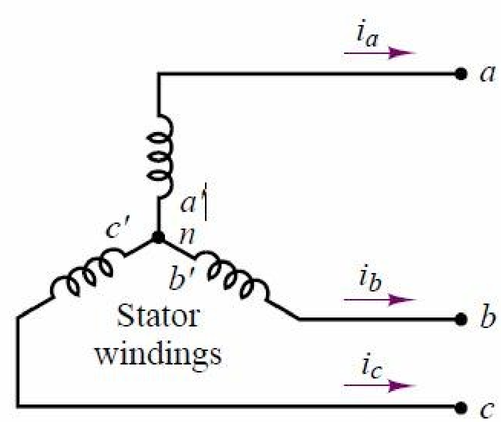
A uniform rotating magnetic field is produced in the air gap between the roto and stator by applying balanced 3 phase supply.

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◦.







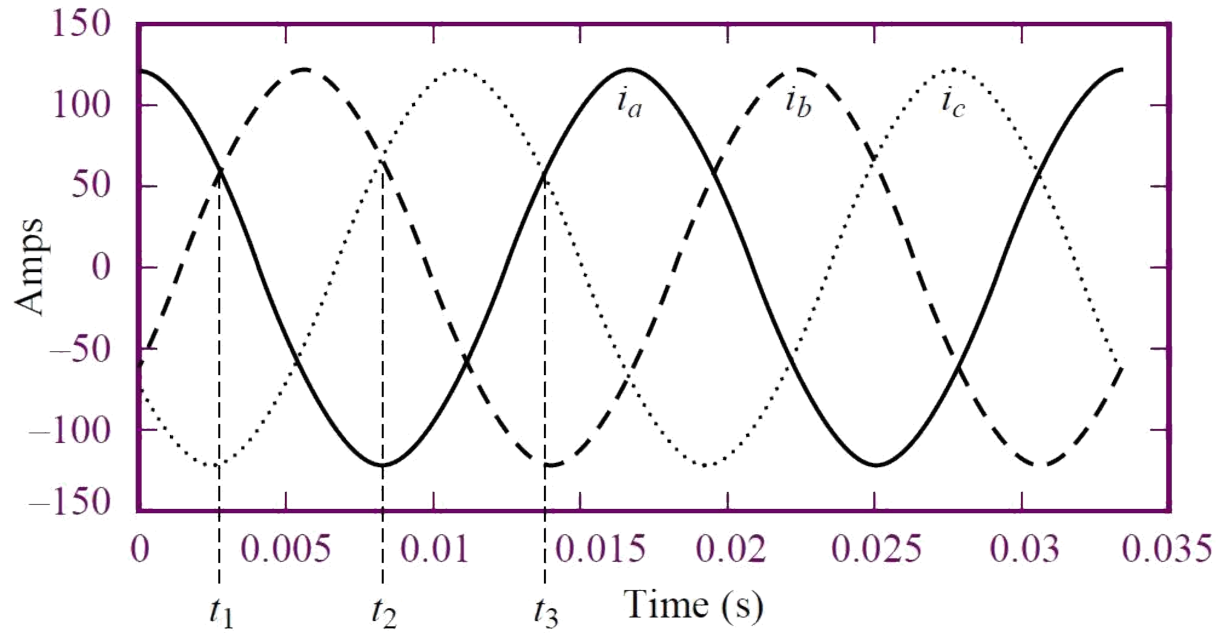
PRINCIPLE OF OPERATION

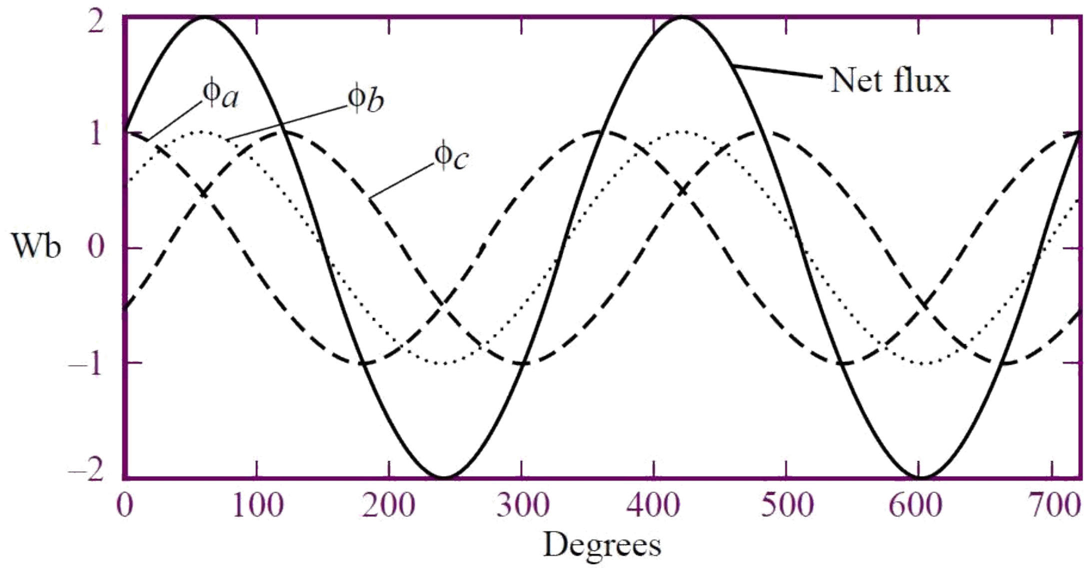
The phase voltages referenced to the neutral terminal, would then be given by the expressions

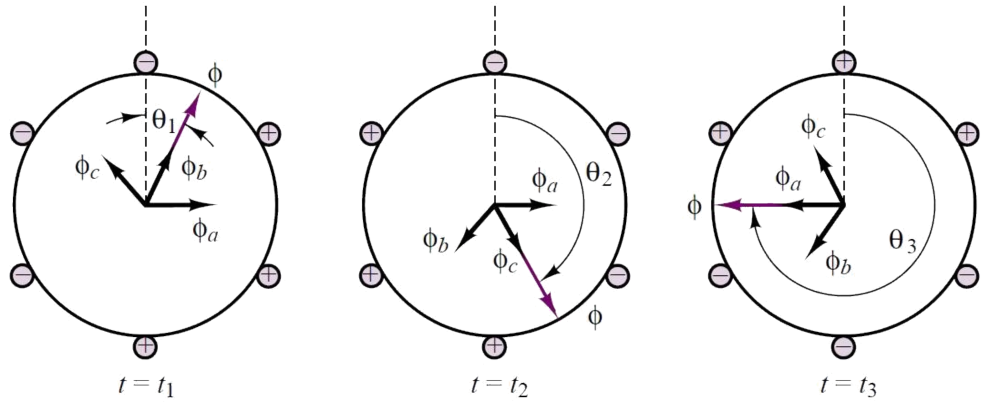
$$v_a = A\cos(\omega_e t)$$

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

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





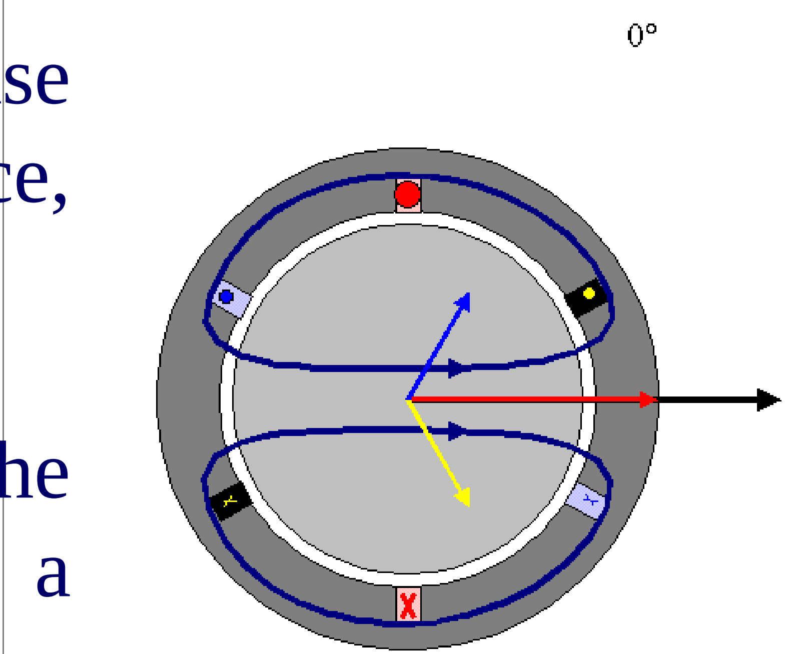


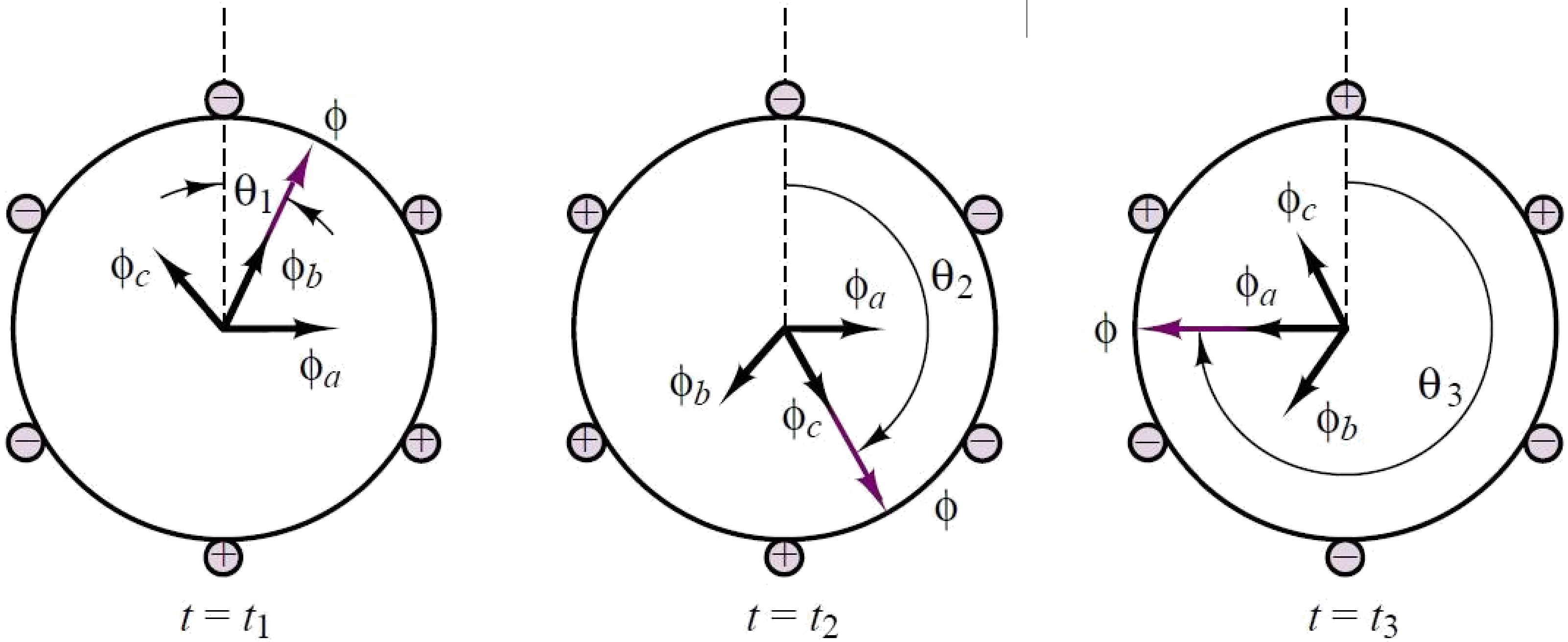
- The coils are arranged so that the flux distribution generated by any one winding is approximately sinusoidal.

- 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.

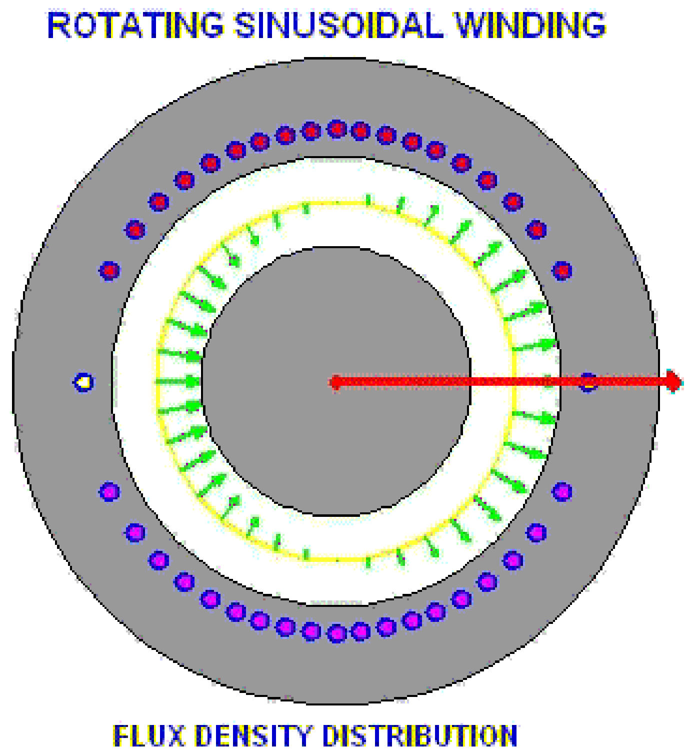
- Hence, A stationary observer on the machine's stator would see a sinusoidally varying flux distribution.





- 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.

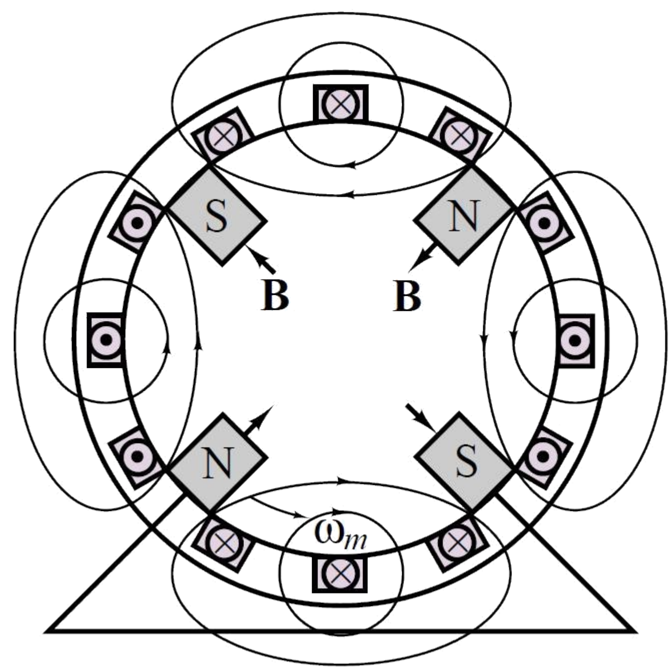
- The number of magnetic poles resulting from the stator winding configuration is two. However, it is possible to configure the windings so that they have more poles.



In general,

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

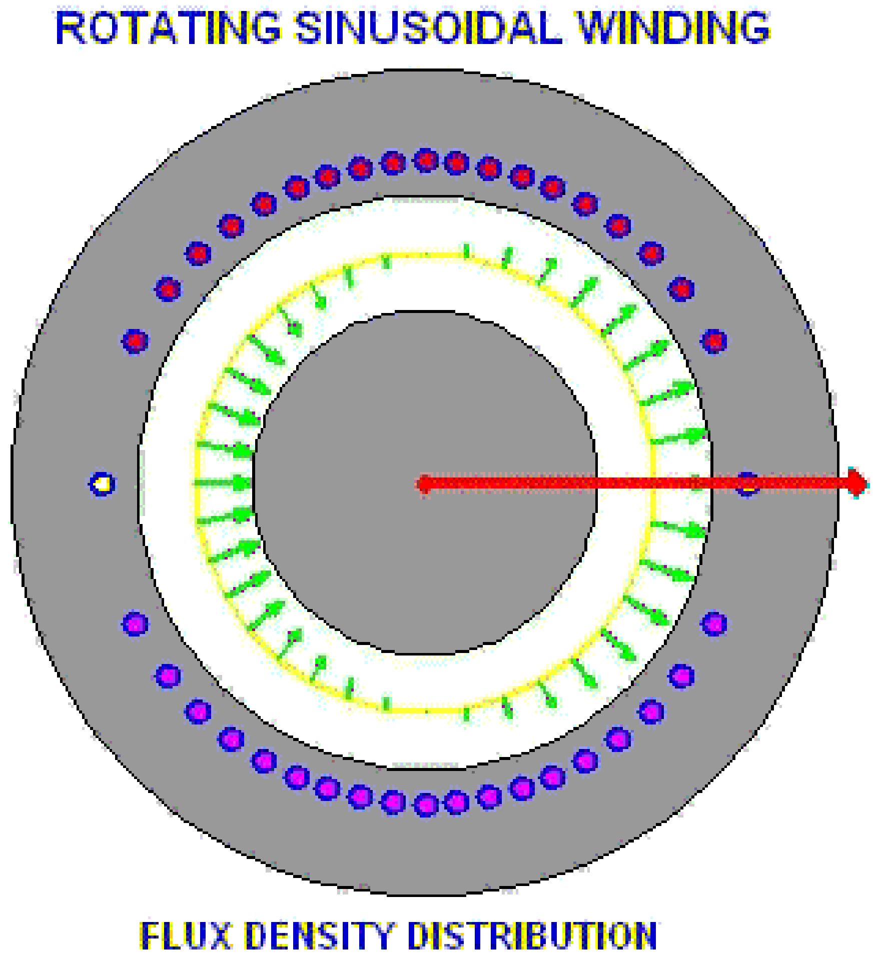
- By the number of poles present in the stator, **p**, according to the equation



$$\left.\begin{aligned} n_s &= \frac{120}{p} f \quad \text{rev/min} \\ \omega_s &= \frac{2\pi n_s}{60} = \frac{2\pi f}{p} \quad \text{rev/min} \end{aligned}\right\}$$

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

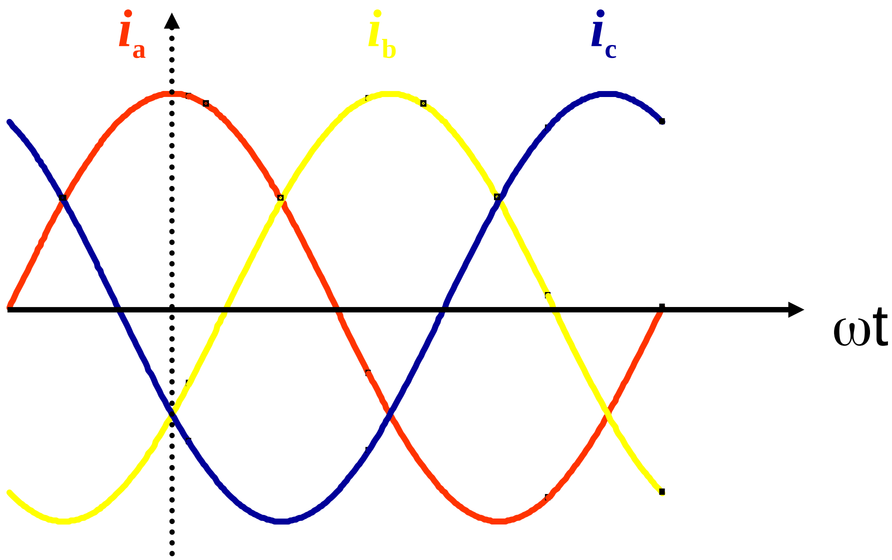
- The stator magnetic field rotates in an AC machine, and
  - therefore the rotor cannot "catch up" with the stator field and is in constant pursuit of it.
  - The speed of rotation of the rotor will therefore depend on the number of magnetic poles present in the stator and in the rotor.
- The magnitude 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.



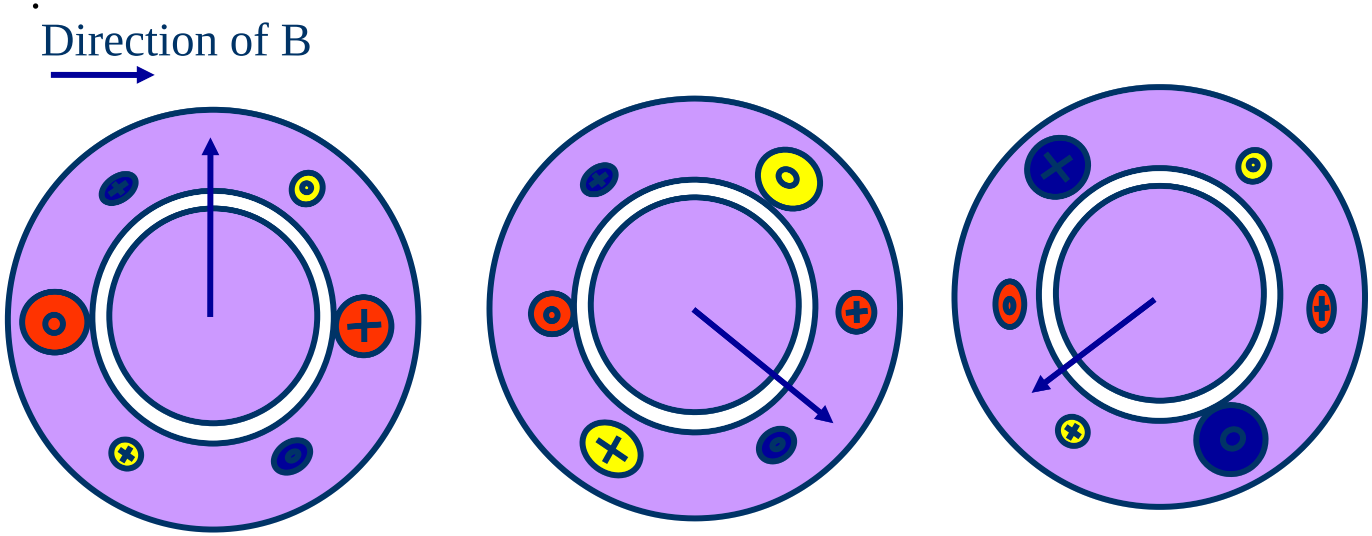
It is important to generate a constant electromagnetic torque to avoid torque pulsations

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



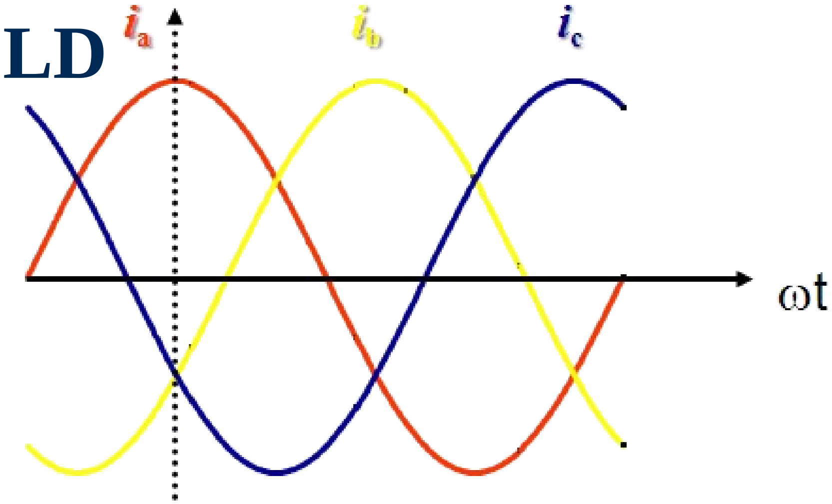
$$i_a = I_m \cos\omega o$$
$$i_b = I_m \cos(\omega o - 120^\circ)$$
$$i_c = I_m \cos(\omega o + 120^\circ)$$



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

Time

Rotating Magnetic Field

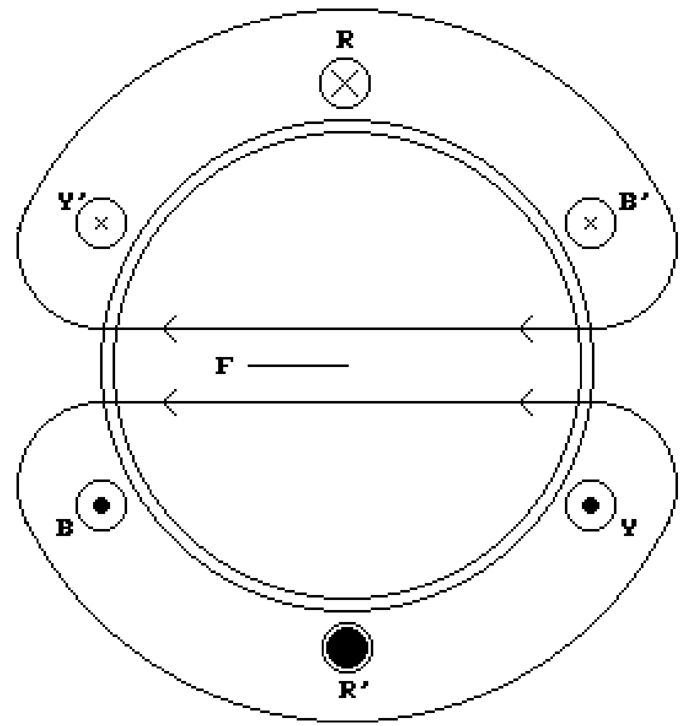


Assume that the current waveforms are as in the top Figure.

- At the moment t = 0:
  - Red phase current is at positive maximum
  - Yellow and Blue phase currents are both at negative half-maximum.

  Each of these currents produces a magnetic field. These fields interact to form the net field shown in the first sequence in the Figure.

t = 0, red at positive maximum



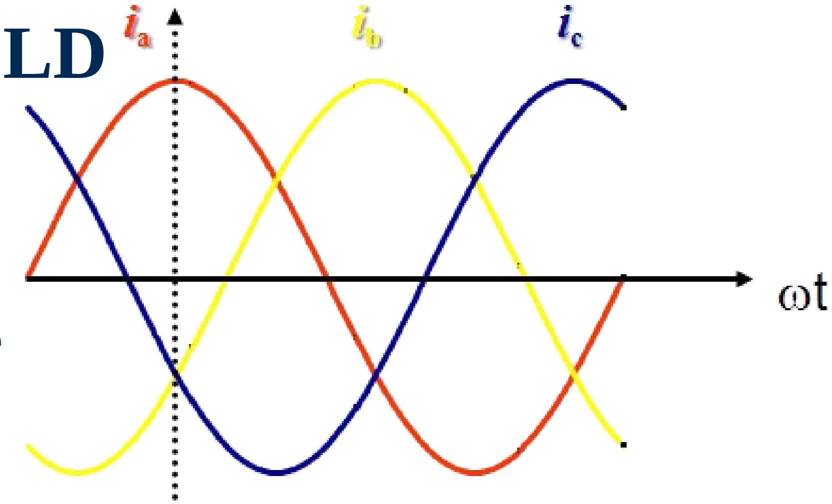
The magnetic field resembles that associated with a two pole bar magnet. As a consequence the machine is called a <u>2-pole</u> motor.

ROTATING MAGNETIC FIELD

As time increases the current distribution changes:

- ❑The red current falls;
- ❑The yellow current becomes less negative eventually becoming positive and
- ❑The blue current approaches negative maximum.

As these changes take place the net field, which maintains a constant magnitude, rotates clockwise

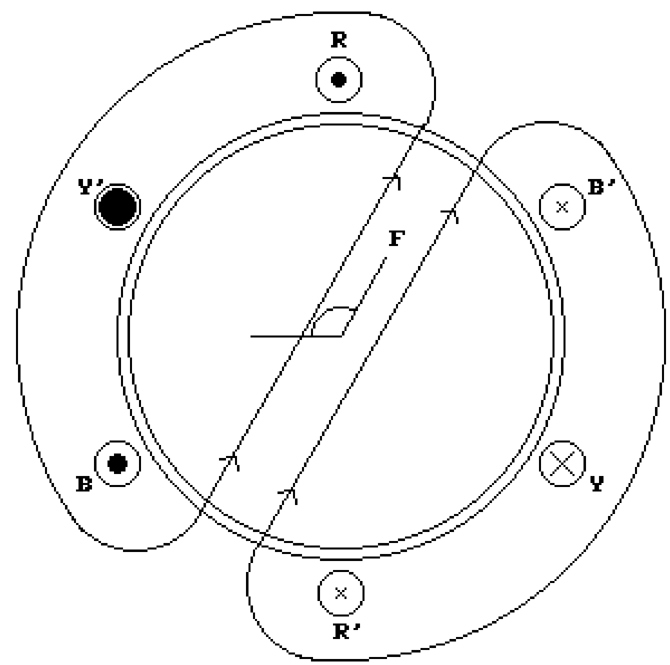


t = 1/3f, (1/3rd of a cycle later)
yellow at
positive maximum

Hence, the second sequence shows the position after 1/3rd cycle (120 electrical degrees):

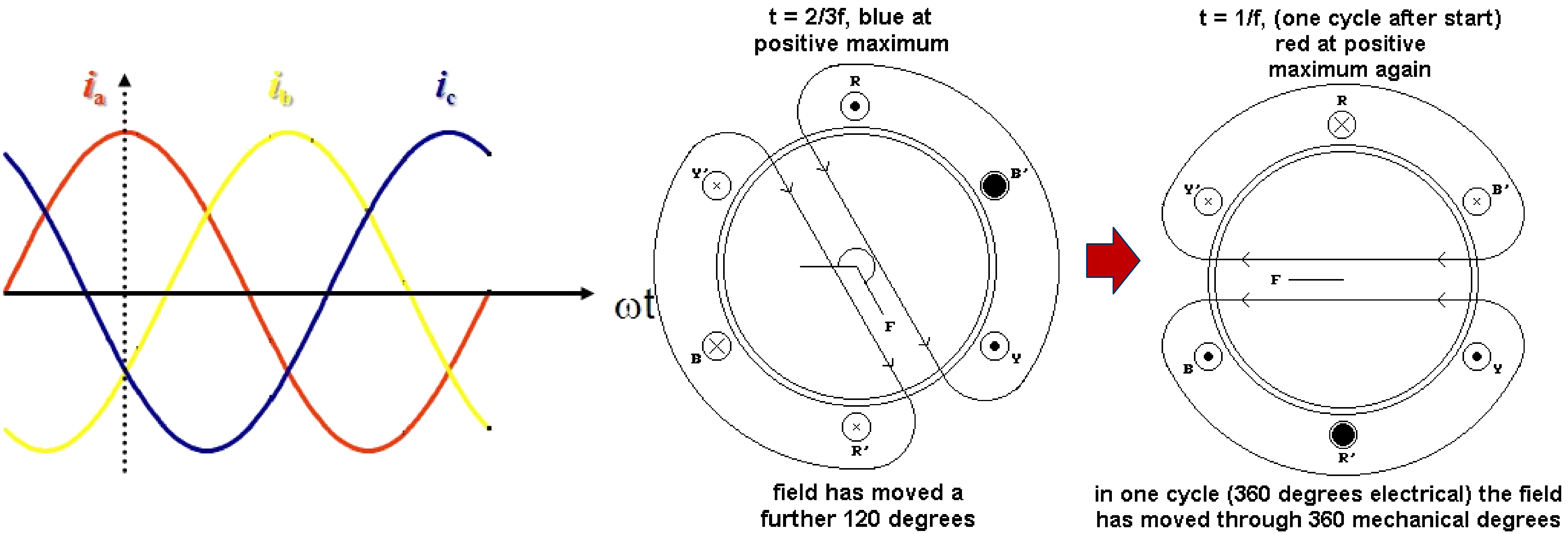
- ❑The yellow current is at positive maximum and
- ❑Red and Blue current are both at negative half-maximum.

At this time, the field has rotated 120° from its original position.



field in the air gap has moved
clockwise through 120 degrees

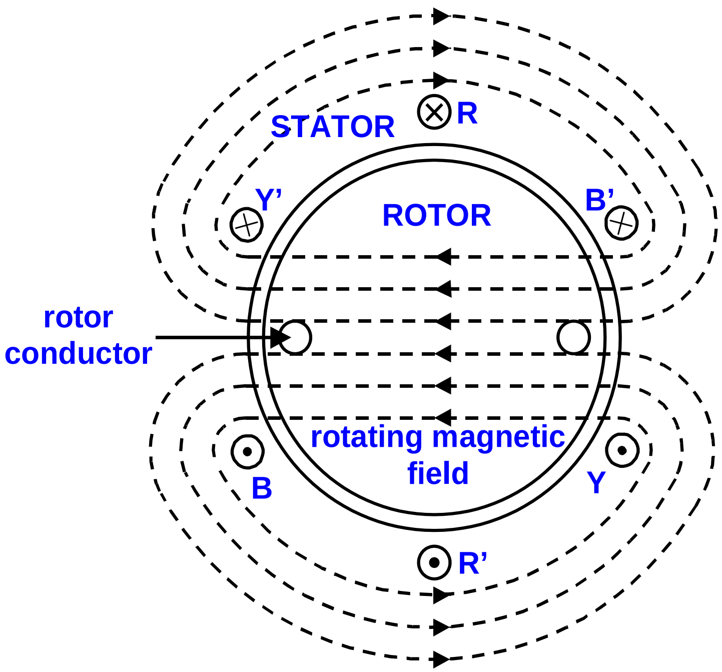
ROTATING MAGNETIC FIELD

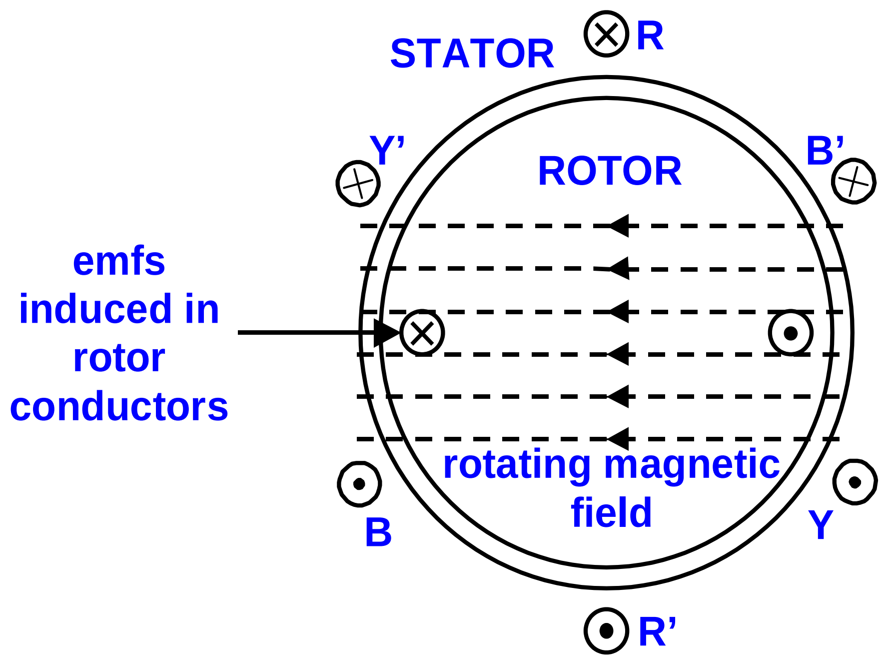


- After 2/3rd cycle (third sequence) the field has moved a total of 240° and after one complete cycle (last sequence) the field has returned to its original position.
- The net field rotates at what is called the synchronous speed, n_s.
- This speed in revolutions per second is equal to the frequency, *f*, in hertz (Hz) or cycles per second, of the stator currents.

$$n_s \text{ (rev s}^{-1}) = f \text{ (in Hz)}$$

ROTOR SLIP





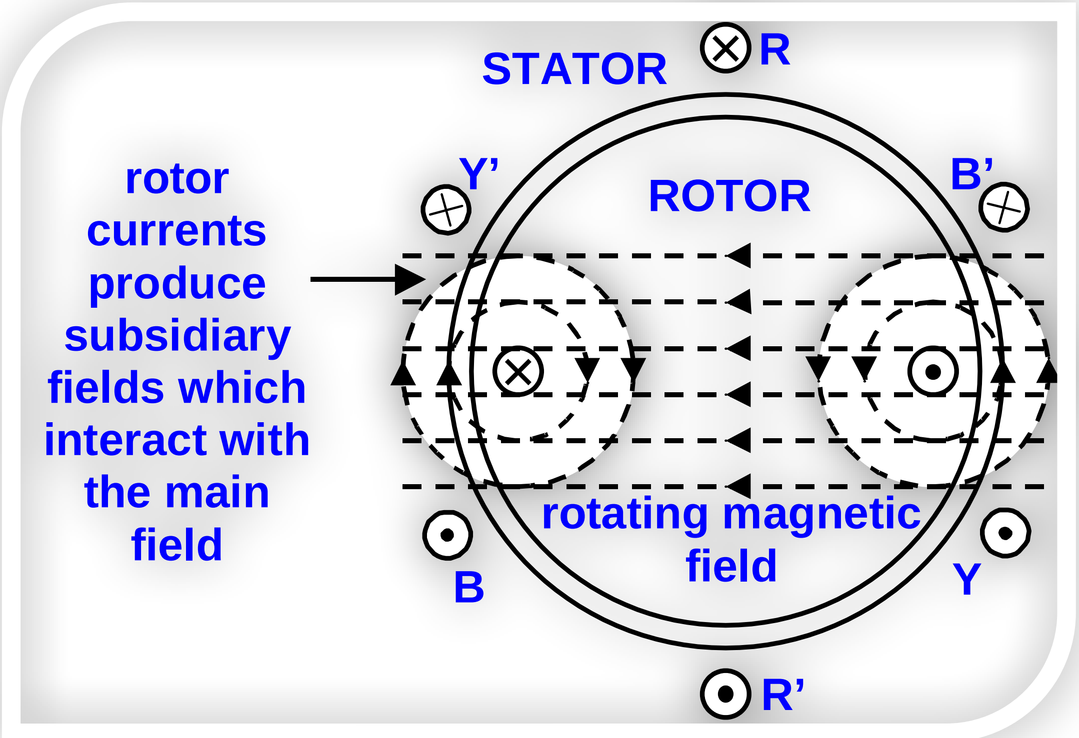
Consider a simple rotor, with one short circuited coil, inserted within the stator:

- Initially, the rotor is stationary.
- The moment the stator supply is switched on currents start to flow and the rotating magnetic field is established.
- The relative motion between the moving field and the stationary rotor conductors induces emf in the stationary rotor conductors (in accordance with Faraday's Law)

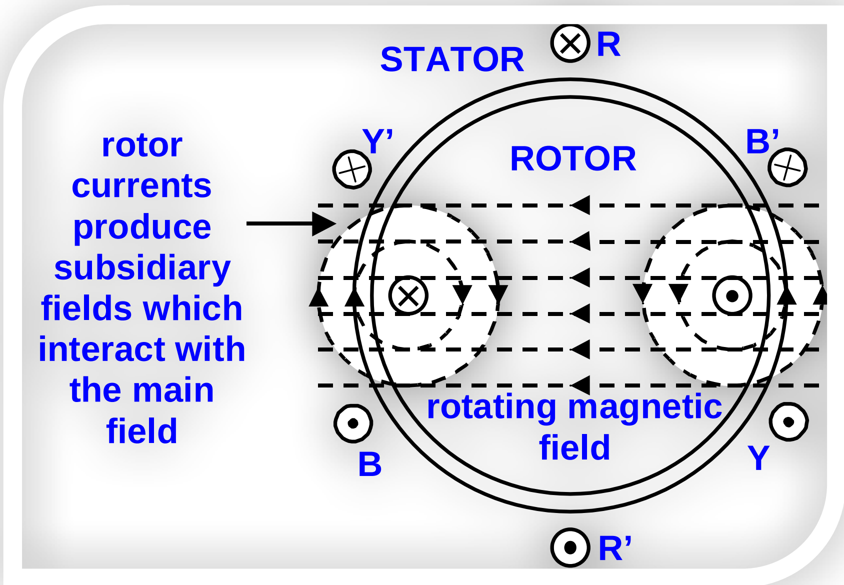
Slip in Induction Motor

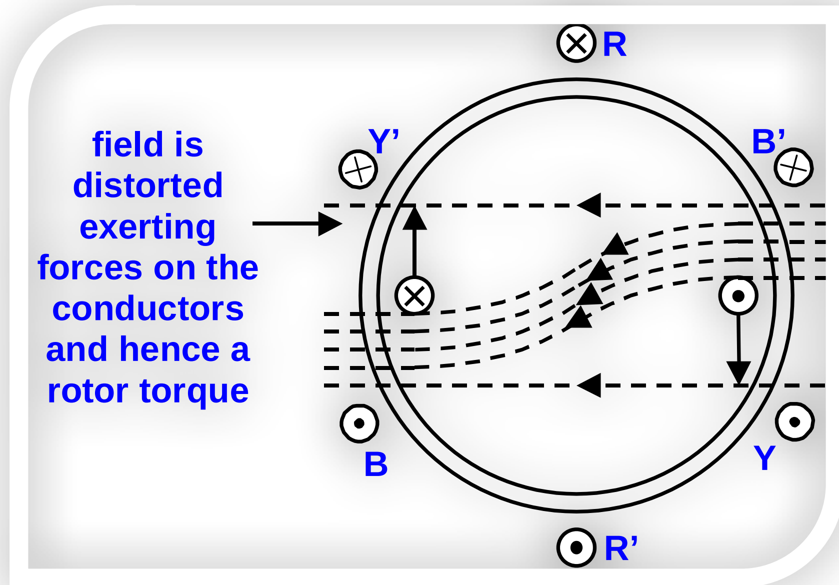
ROTOR SLIP

- ❑ Current start flowing in the conductors as they are short circuited by the end rings.
- ❑ These currents create their own magnetic fields, which interact with the rotating stator field to produce forces on the individual conductors and a net rotor torque



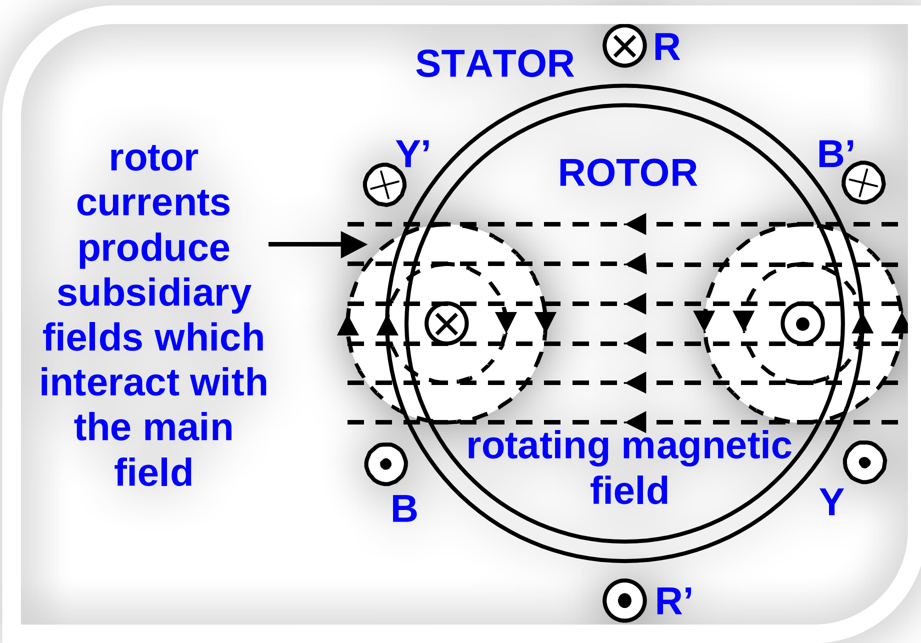
- ❑ The rotor starts to accelerate lowering the relative speed between the rotating field and rotor conductors.
  - ❖ This reduces the induced emfs, conductor currents and subsidiary magnetic fields;
  - ❖ thus decreasing the forces on the conductors and electrical torque on the rotor.

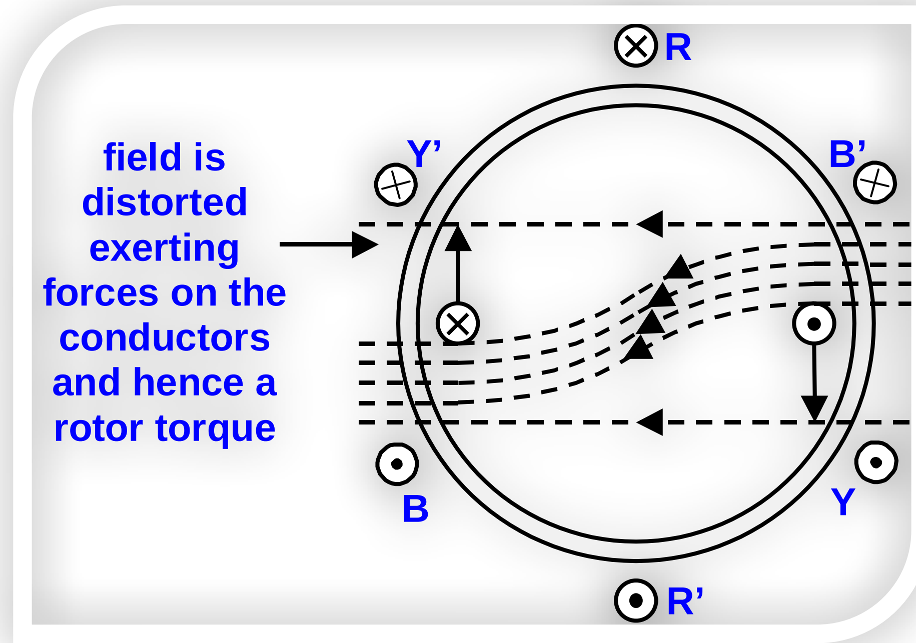




The rotor continues to accelerate until the electrical torque exactly equals the mechanical load torque on the shaft.

- At this point the rotor is running at a speed slightly slower than the rotating field.
- This small difference in speed is needed.
- In order to create an electrical torque there must be some distortion of the net field, which will only happen when currents flow in the rotor conductors.
- These currents depend on emfs being induced in the conductors, which in turn depend on there being a difference between the speed at which the conductors rotate and that of the rotating magnetic field.





This difference in speed is expressed as a ratio known as the (per unit) slip.

Remembering that the rotational speed of magnetic field is known formally as the synchronous speed, the slip is defined as

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

For most machines the value of the slip varies between around 0.01 on no-load, (when the only torque required is to overcome friction at the bearings) and 0.10 at full load.

Formula

AC Induction Motor Slip

$$\text{Slip (\%)} = \frac{(n_s - n)}{n_s} \times 100$$

slip (%) → AC Induction Motor slip percentage

n → rotor speed in RPM

n_s → synchoronous (stator) speed in RPM

In the induction motor rotor always rotates speed less than synchronous speed. **The difference between the rotor speed (N) and the rotating magnetic flux speed (N_s) is called slip.** The *induction motor slip* is usually expressed as a percentage of synchronous speed (N_s) and is represented by symbol **s**.

Mathematically, Percentage slip, $\% \ s = [(N_s - N)/N_s] \times 100$

or Fractional slip, $s = (N_s - N)/N_s$

The difference between synchronous speed and rotor speed is called slip speed

i.e. Slip speed = $N_s - N$

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

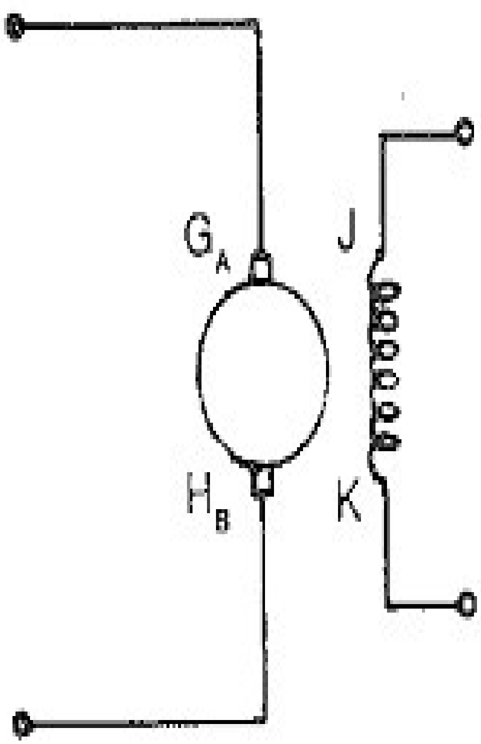
Hence the rotor speed is always less than the stator rotating field speed and the difference is called *"Slip"*

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

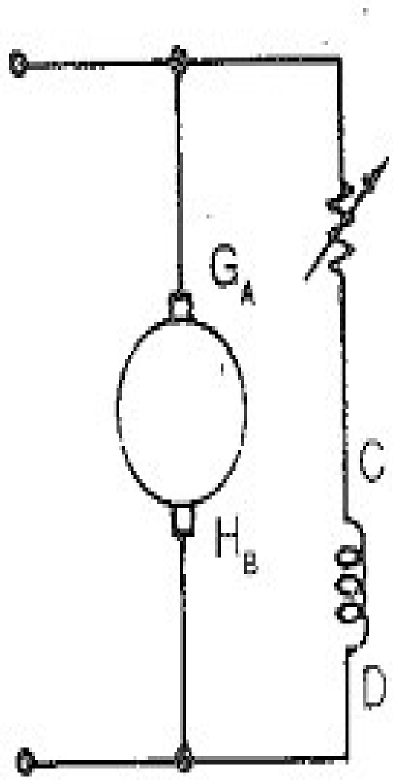
Note: For a stationary rotor the slip is 1; Generally the change in slip from no load to full load is 0.01 to 0.1 so the speed of the motor is constant.

The three types of DC motors

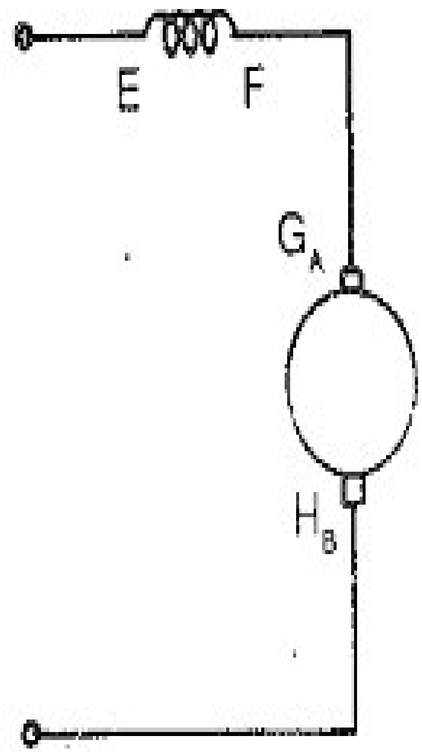
- Shunt wound DC motors
- Series wound DC motors
- Separately excited DC motor



(a) Separately excited dc motor.



(b) Shunt motor

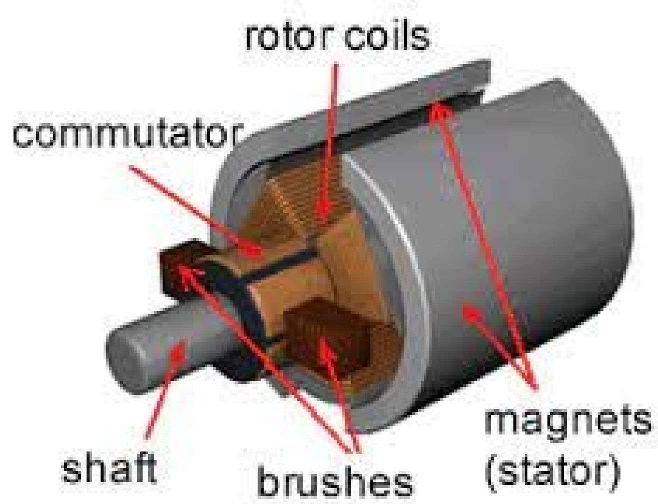


(c) Series motor

ARMATURE

What is an armature in a motor?

An armature is **a device through which electric current is passed for generating torque (rotor)**. The current that passes through the rotor is sometimes called the armature current. The word "armature" refers to a device through which electric current is passed for generating torque.



Speed Control of DC Motor

The **DC motor** is the motor which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that the current carrying conductor placed in a magnetic and electric field experience a force. To learn more about DC motors, visit Working Principle of DC motor and check out the related details.

- Different Types of DC Motor
- Working Principle of DC Motor
- Difference Between AC and DC Motor
- Applications of Dc motor.

Often we want to control the speed of a DC motor on demand. This intentional change of drive speed is known as speed control of a DC motor.
We can control the speed of DC motor manually or through an automatic control device. This is different to speed regulation – where the speed can regulate against the natural change in speed due to a change in the load on the shaft.

The **speed of a DC motor** (N) is equal to

$N = K (V – I_aR_a)/ ø$ Where, K is a constant.

This implies three things:

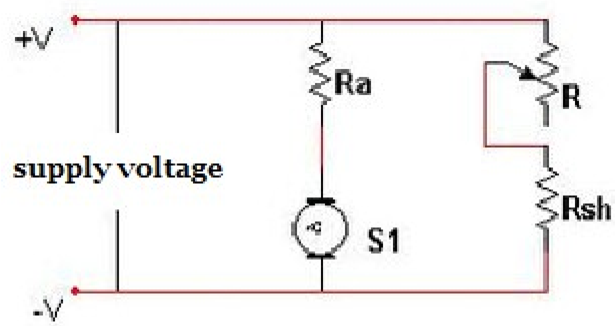
1. Speed of the motor is directly proportional to supply voltage.
2. The Speed of the motor is inversely proportional to armature voltage drop.
3. The motor speed is inversely proportional to the flux due to the field findings

Thus, the speed of a DC motor can control in three ways:

- By varying the flux, and by varying the current through field winding
- By varying the armature voltage, and the armature resistance
- Through the supply voltage

1. Flux Control Method

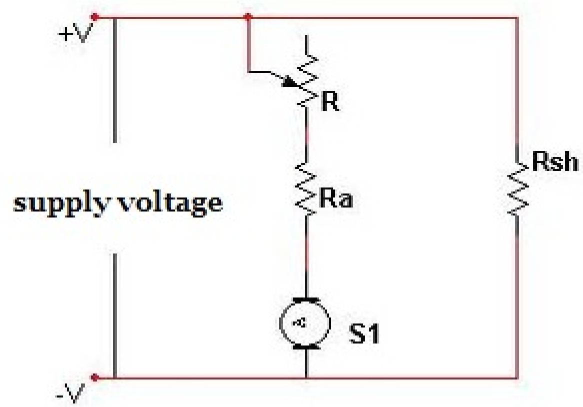
Due to the field winding, the magnetic flux varies in order to vary the speed of the motor. As the magnetic flux depends on the current flowing through the field winding, it changes by varying the current through the field windina. This can achieve using a variable resistor in a series with the



Initially, when the variable resistor keeps at its minimum position, the rated current flows through the field winding due to a rated supply voltage, and as a result, the speed is kept normal. When the resistance increases gradually, the current through the field winding decreases. This in turn decreases the flux produced. Thus, the speed of the motor increases beyond its normal value.

2. **Armature Control Method**

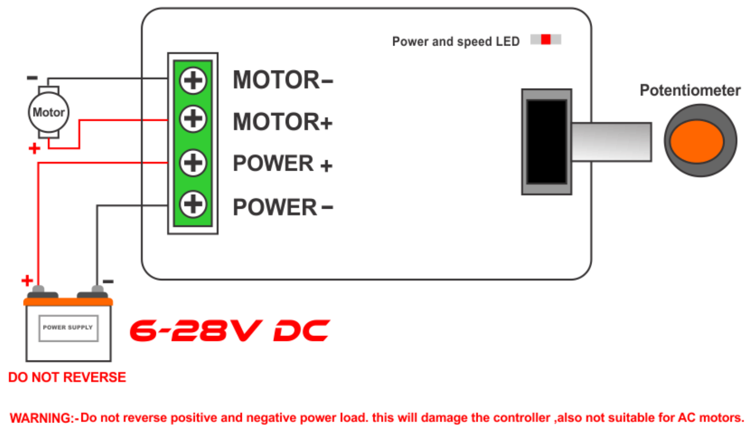
The controlling of armature resistance controls the voltage drop across the armature. With this method, the speed of the DC motor can control. This method also uses a variable resistor in series with the armature.



When the variable resistor reaches its minimum value, the armature resistance is at normal one. Therefore, the armature voltage drops. When the resistance value gradually increases, the voltage across the armature decreases. This in turn leads to decrease in the speed of the motor. In this way, this method achieves the speed of the motor below its normal range.

3. Voltage Control Method

Both the above mentioned methods cannot provide speed control in the desirable range. Moreover, the flux control method can affect commutation. Whereas the armature control method involves huge power loss due to its usage of resistor in series with the armature. Therefore, a different method is often desirable – the one that controls the supply voltage to control the motor speed.
In such a method, the field winding receives a fixed voltage, and the armature gets a variable voltage. One such technique of voltage control method involves the use of a switch gear mechanism to provide a variable voltage to the armature. Another one uses an AC motor driven Generator to provide variable voltage to the armature (named as Ward-Leonard System).



Rheostatic Control Method :

In this method, **a variable resistance (rheostat) is connected in series with the armature winding**. This reduces the voltage across the armature and hence speed falls.

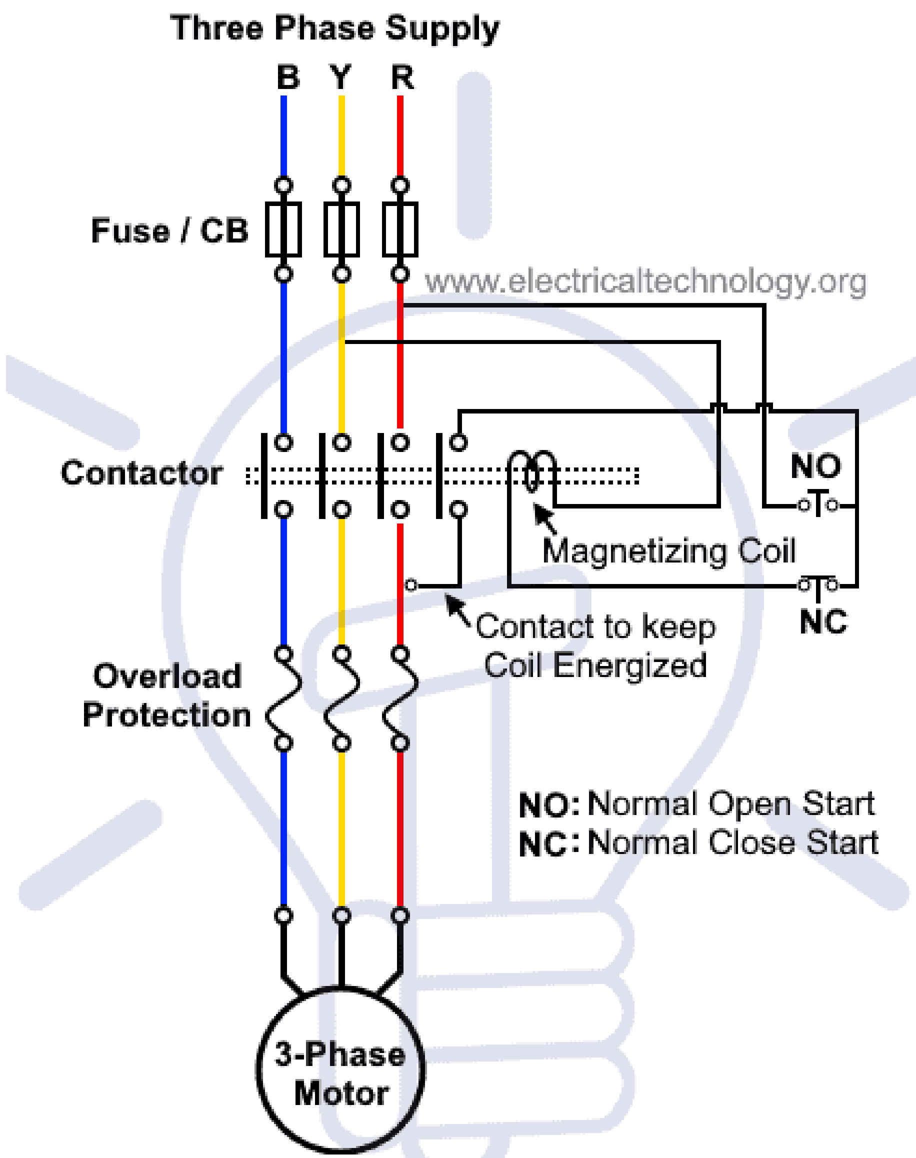
Apart from these techniques, the most widely used technique is the use of pulse width modulation to achieve speed control of a DC motor. PWM involves application of varying width of pulses to the motor driver to control the voltage applied to the motor. This method proves to be very efficient as the power loss keeps at minimum, and it doesn't involve the use of any complex equipment.

PWM is achieved by varying the pulses applied to the enable pin of the motor driver IC to control the applied voltage of the motor. The variation of pulses is done by the micro controller, with the input signal from the push buttons.

What Is The Difference Between DOL and Star-Delta Starter?

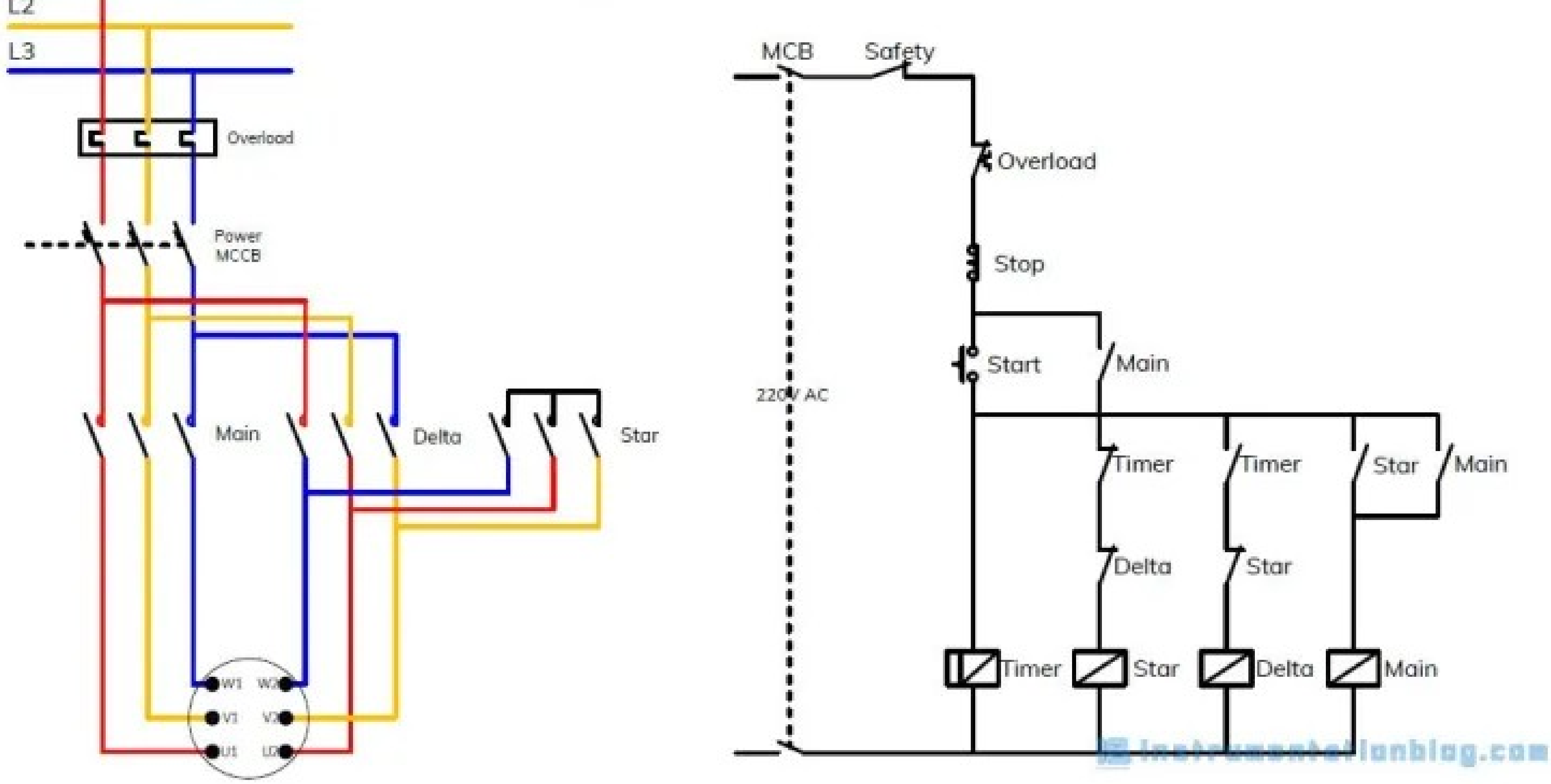
DOL means the motor is connected **Directly ON Line** using one contactor with no starting circuit to lower the high starting current. Typically the Delta part of Star-Delta.

Star-Delta uses two contactors, one to start at a lower voltage in Star and one to run at a higher voltage in Delta configuration.



Direct Online Starter (DOL)

Star-Delta Starter



Salient difference between DOL and Star-Delta starter

D.O.L(Direct On Line)Starter

1. It does not decrease the starting current.
2. It is cheap.
3. It connects directly the motor with supply for starting as well as for running.

Star-Delta Starter

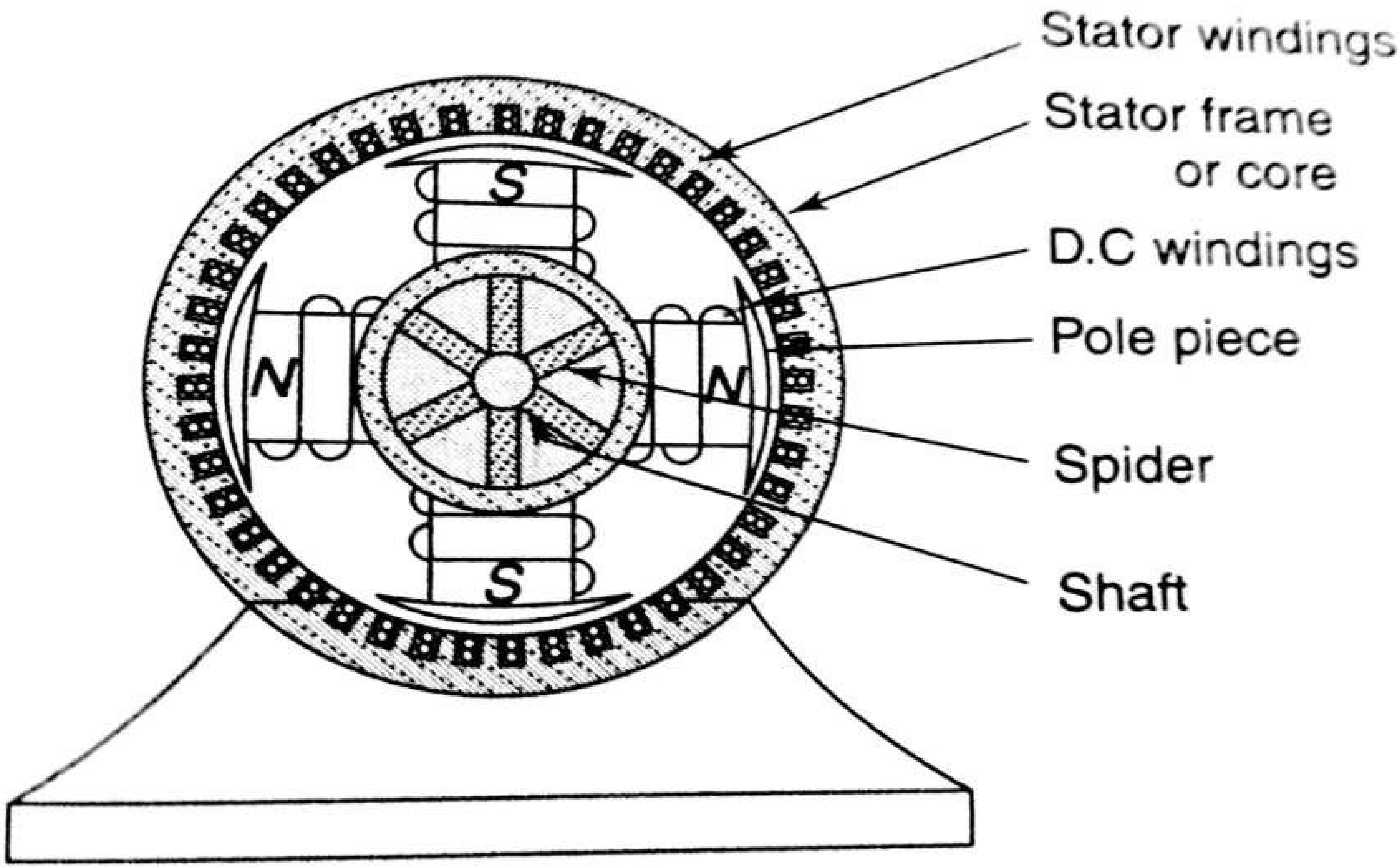
1. It decrease the starting current to 1/3 times.
2. It is costly.
3. It connects motor first in star at the time of starting then in delta for running.

SYNCHRONOUS GENERATORS

Synchronous generators are the **majority source of commercial electrical energy**. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid.

The synchronous generator or alternator is an electrical machine that converts the mechanical power from a prime mover into an AC electrical power at a particular voltage and frequency. The synchronous motor always runs at a constant speed called synchronous speed.

Principle Of Operation



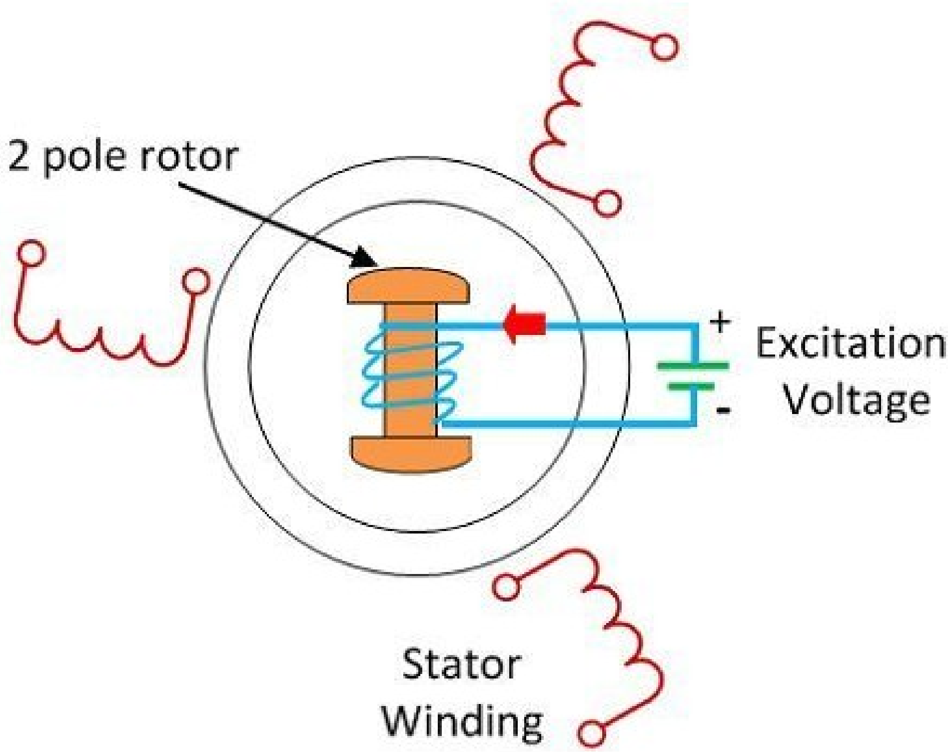
- The synchronous generator works on the principle of Faraday laws of electromagnetic induction. Electromagnetic induction states that electromotive force induced in the armature coil if it is rotating in the uniform magnetic field.

  The EMF will also be generated if the field rotates and the conductor becomes stationary. Thus, the relative motion between the conductor and the field induces the EMF in the conductor. The wave shape of the induced voltage is always a sinusoidal curve.

- Operate on principle of electromagnetic induction
- Stationary armature and rotating field
- Rotor is rotated using a prime mover
- When the rotor rotates, the stationary conductors are cut by the magnetic flux
- Hence emf is induced
- In three phase alternators, the rotor flux will induce 3 voltages displaced in time by 120 degree
- Emf induced is AC in nature
- AC voltage will give rise to AC current when a load is connected to stator

Construction of Synchronous Generator

The rotor and stator are the rotating and the stationary part of the synchronous generator. They are the power generating components of the synchronous generator. The rotor has the field pole, and the stator consists of the armature conductor. The relative motion between the rotor and the stator induces the voltage between the conductor.



Applications of Synchronous Generator

The three-phase synchronous generators have many advantages in generation, transmission, and distribution. The large synchronous generators use in the nuclear, thermal, and hydropower system for generating the voltages.

The synchronous generator with 100MVA power rating uses in the generating station. The 500MVA power rating transformer use in the super thermal power stations. The synchronous generators are the primary source of electrical power. For the heavy power generation, the stator of the synchronous generator design for voltage ratings between **6.6 kV** to **33 kV**.

Formula for Voltage Regulation of Alternator

Voltage Regulation is usually expressed as a fraction or percentage of the terminal voltage on load. Hence in general, if V is the terminal voltage per phase for a given load and E_0 is the open-circuit voltage (i.e. no-load terminal voltage) per phase, then

$$\text{Voltage Regulation} = \frac{E_0 - V}{V} \text{ per unit}$$

Electrical Engineering MCQ

$$Voltage\ Regulation = \frac{V_{NL} - V_{FL}}{V_{FL}}$$

$$\%age\ Voltage\ Regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\%$$

$V_{FL} = Full\ load\ terminal\ voltage\ of\ machine$

$V_{FL} = No\ load\ terminal\ voltage\ of\ machine$

Three-phase Voltage and Current

Connection	Phase Voltage	Line Voltage	Phase Current	Line Current
Star	$V_P = V_L \div \sqrt{3}$	$V_L = \sqrt{3} \times V_P$	$I_P = I_L$	$I_L = I_P$
Delta	$V_P = V_L$	$V_L = V_P$	$I_P = I_L \div \sqrt{3}$	$I_L = \sqrt{3} \times I_P$

Vp = Phase Voltage
VL = Line Voltage
Ip = Phase Current
I_L= Line Current

Example 1

When a three-phase, star-connected alternator is fully loaded at 0.8 lagging power factor, the terminal voltage (line value) is 440 V. On throwing of this load, with speed and field excitation being maintained constant, the voltage rises to 519.6 V. Calculate its voltage regulation.

Solution :

Full-load terminal voltage (phase value),

$$V = \frac{440}{\sqrt{3}} = 254.03 \text{ volts}$$

No-load terminal voltage (phase value),

$$E_0 = \frac{519.6}{\sqrt{3}} = 300 \text{ volts.}$$

$$\therefore \quad \text{Regulation} = \frac{(E_0 - V)}{V} \times 100 = \frac{(300 - 254.03)}{254.03} \times 100$$

$$= \mathbf{18.1 \text{ per cent}}$$

THANK YOU