Module-3
Synchronous Generators
and
Synchronous Generator Analysis

Prepared By,
Sowmyashree K S
Assistant Professor
Department of EEE
ATMECE, Mysuru

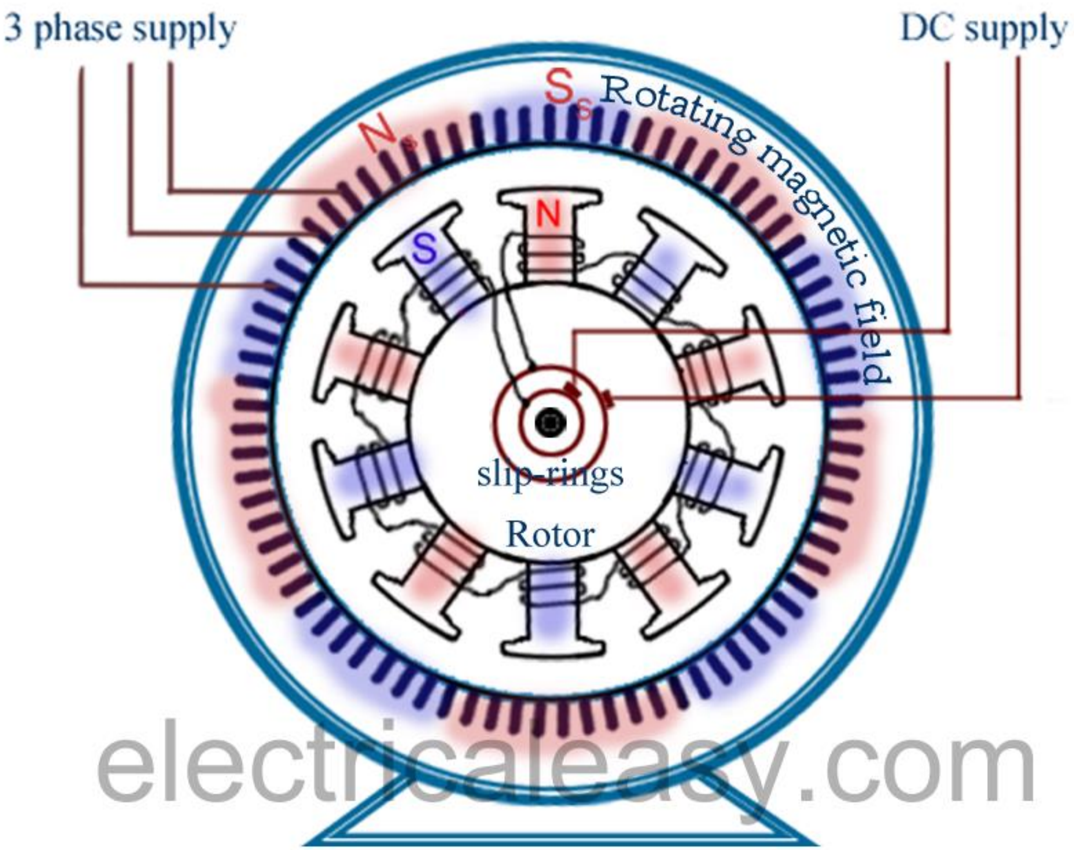
Module-3

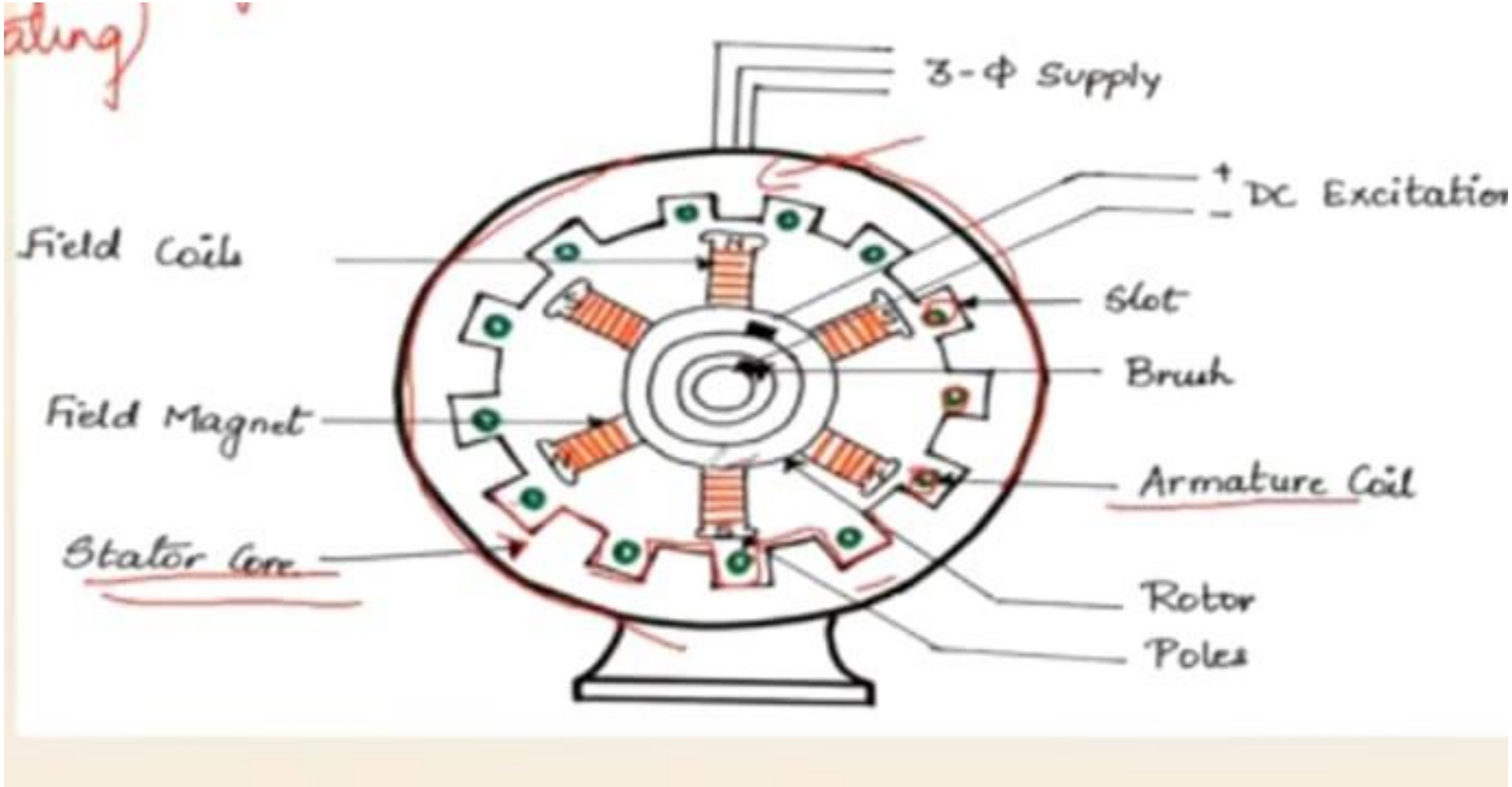
Synchronous Generators: Construction, working, Armature windings, winding factors, EMF equation. Harmonics–causes, reduction, and elimination. Armature reaction, Synchronous reactance, Equivalent circuit.

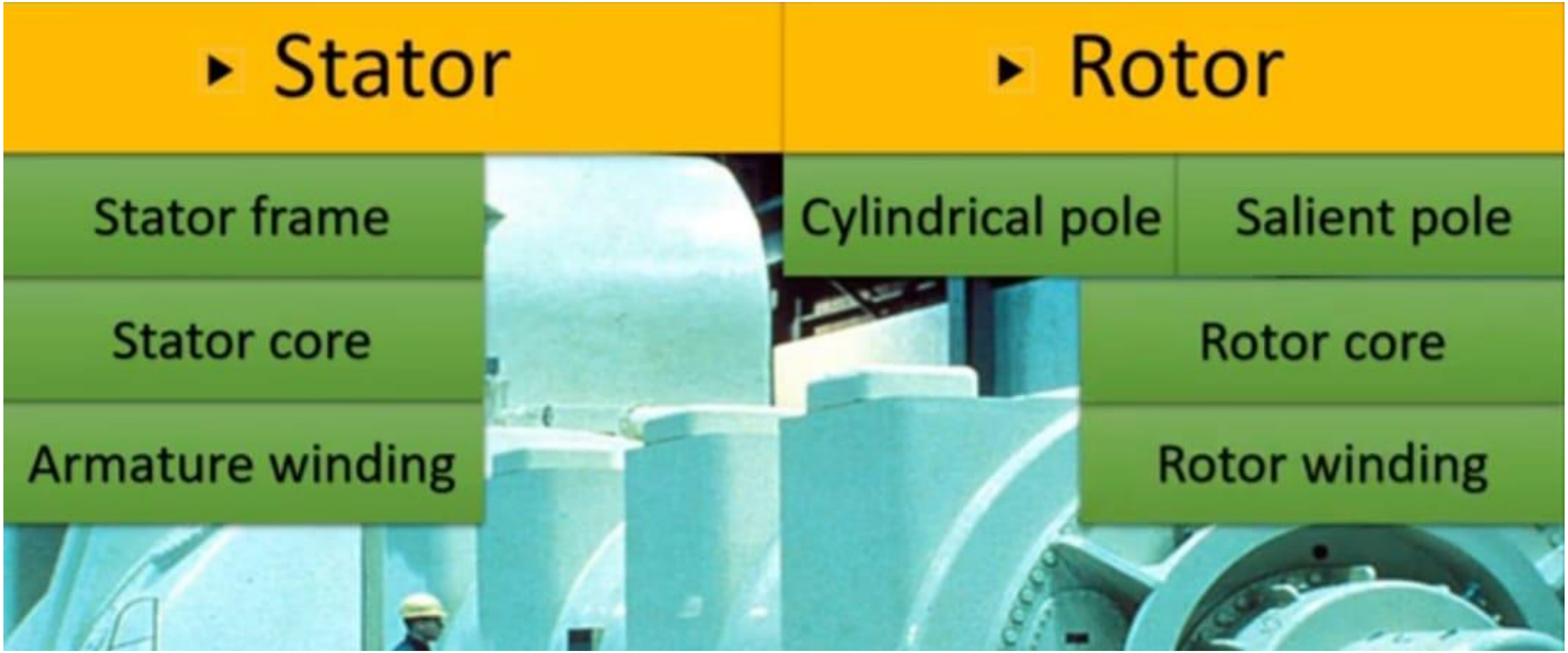
Synchronous Generators Analysis: Open circuit and short circuit characteristics, Assessment of reactance-short circuit ratio, Alternator on load. Voltage regulation. Voltage regulation by EMF and MMF methods. Excitation control for constant terminal voltage. Numerical.

Introduction: An alternator is an alternating current voltage generator. It is also called a “Synchronous generator”. In the case of an alternator, the field system is rotating and the armature is stationary.

Construction of Synchronous Generator:




3-Φ Supply
+ DC Excitation
−
Field Coils
Slot
Brush
Field Magnet
Armature Coil
Stator Core
Rotor
Poles


Stator
Rotor
Stator frame
Stator core
Armature winding
Cylindrical pole
Salient pole
Rotor core
Rotor winding

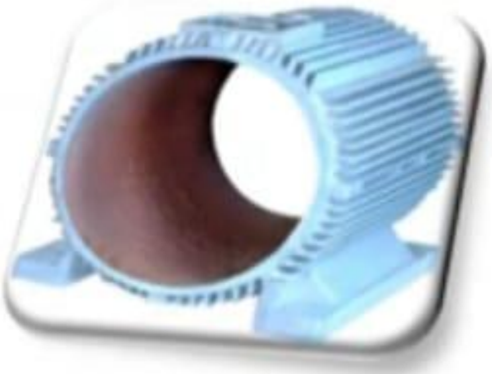
Stator Core

Silicon Steel

Thin lamination

Eddy current loss
Hysteresis loss

Stator frame



Cast Iron

To provide support to stator core

Armature Winding

Copper/Aluminium

Rectangular bar and
Round conductor

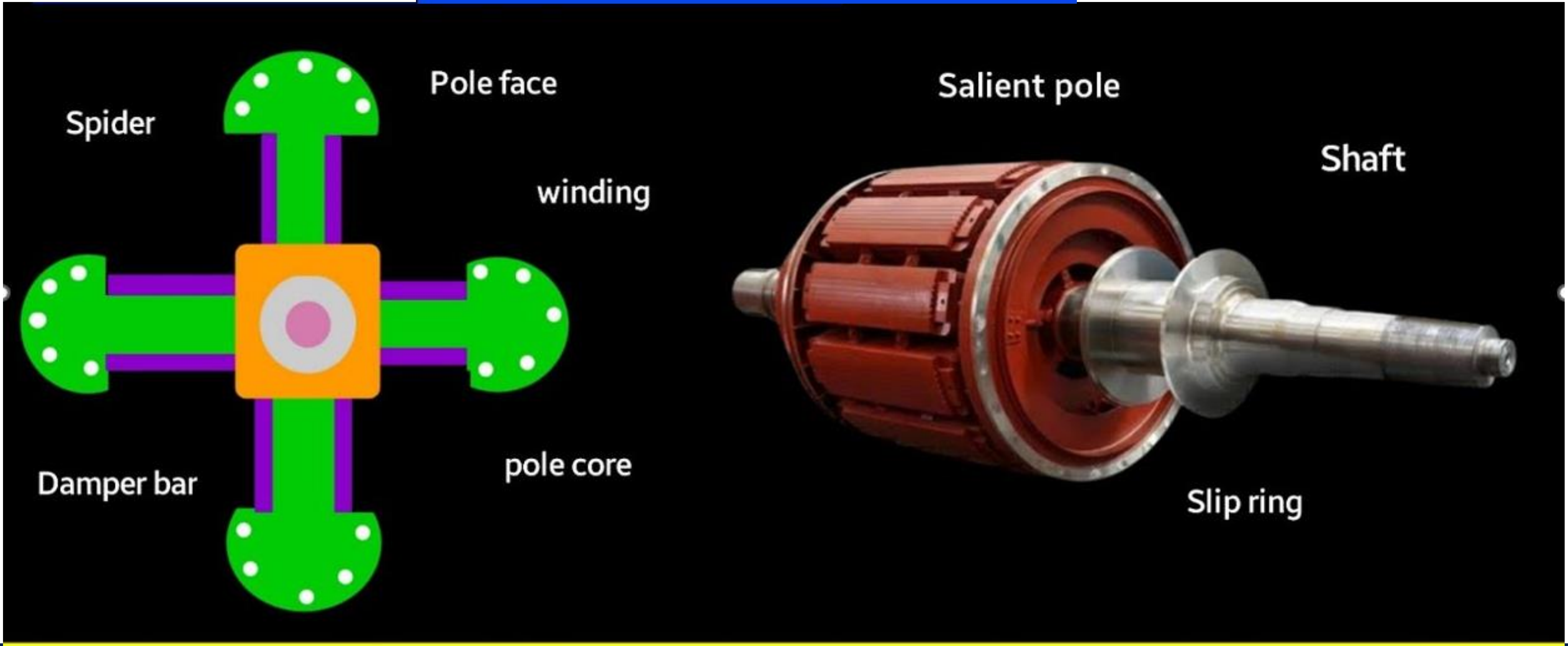
Salient Pole	Cylindrical
	
Projected pole	Non-salient pole
Large diameter & small length	Small diameter & long length
Law speed, nonuniform airgap	High speed, uniform airgap

Rotor Winding

Copper / Aluminium

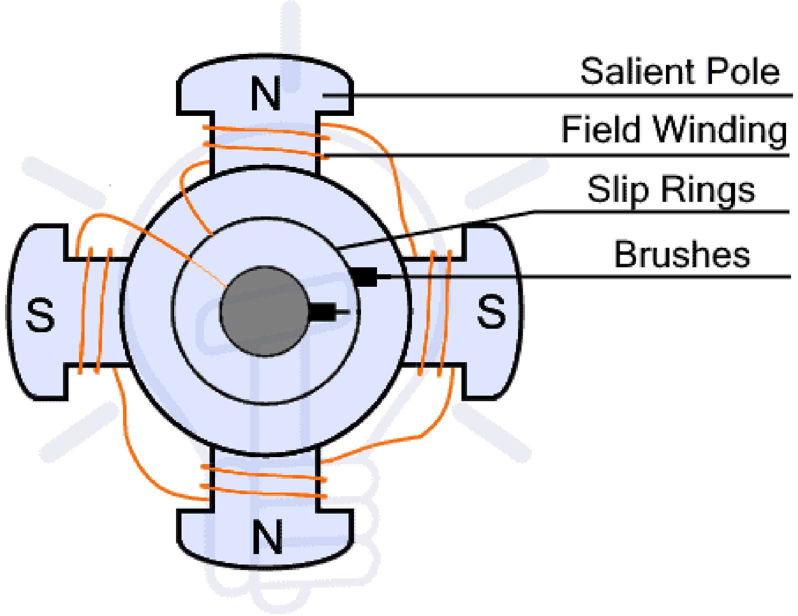
Rectangular bar / Round conductor

Salient Pole Rotor



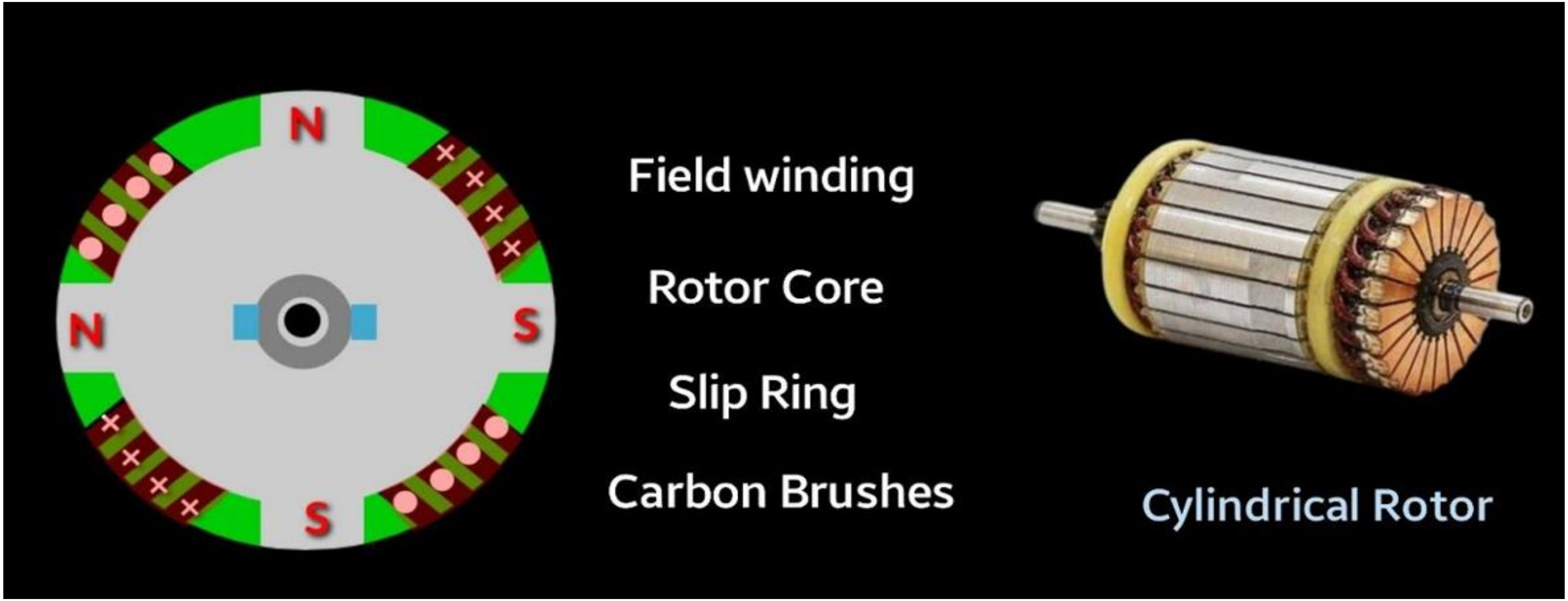
Salient Pole Rotor

- Projecting poles
- Large Diameter
- Small axial length
- Non-uniform air gap
- Mechanically weak
- Preferred for low speed (100-1500rpm)
- Damper windings



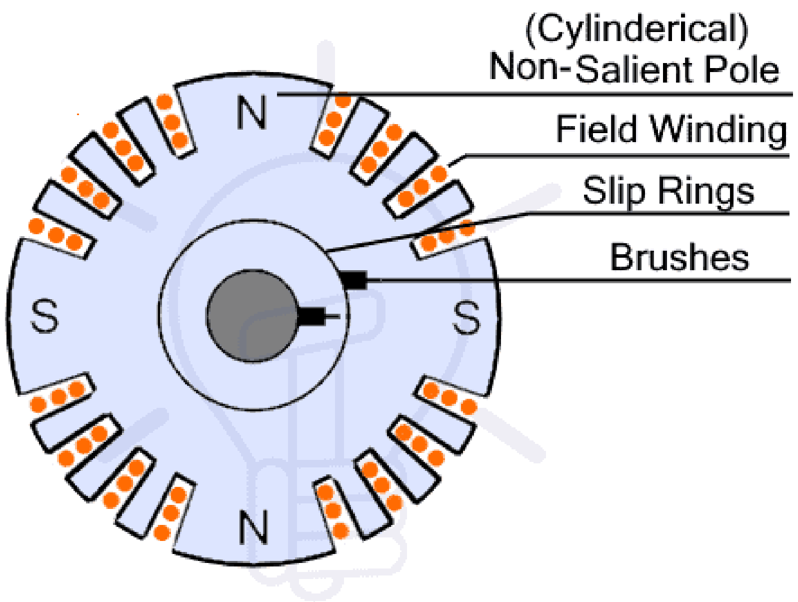
Salient Pole Rotor

Cylindrical Rotor Construction



Cylindrical Rotor Construction

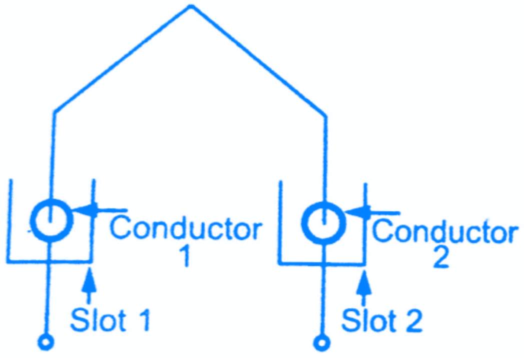
- Non-Projecting poles
- Small Diameter
- Large Axial Length
- Uniform air-gap
- Mechanically Strong
- Preferred for high speed 1500-3000 rpm
- No damper windings



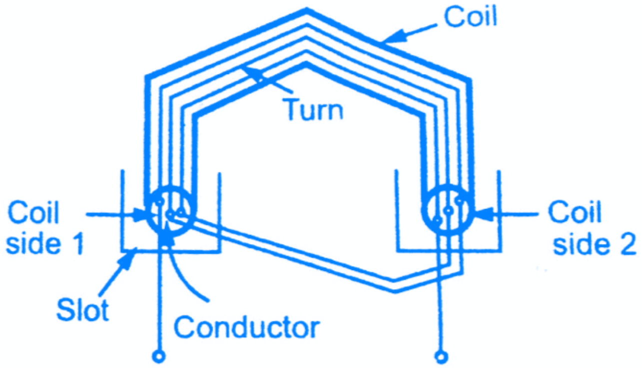
Non-Salient (Cylinderical) Pole Rotor

Winding Terminology:

1. **Conductor:** The part of the wire, which is under the influence of the magnetic field and responsible for the induced e.m.f. is called the active length of the conductor. The conductors are placed in the armature slots.
2. **Turn:** A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.

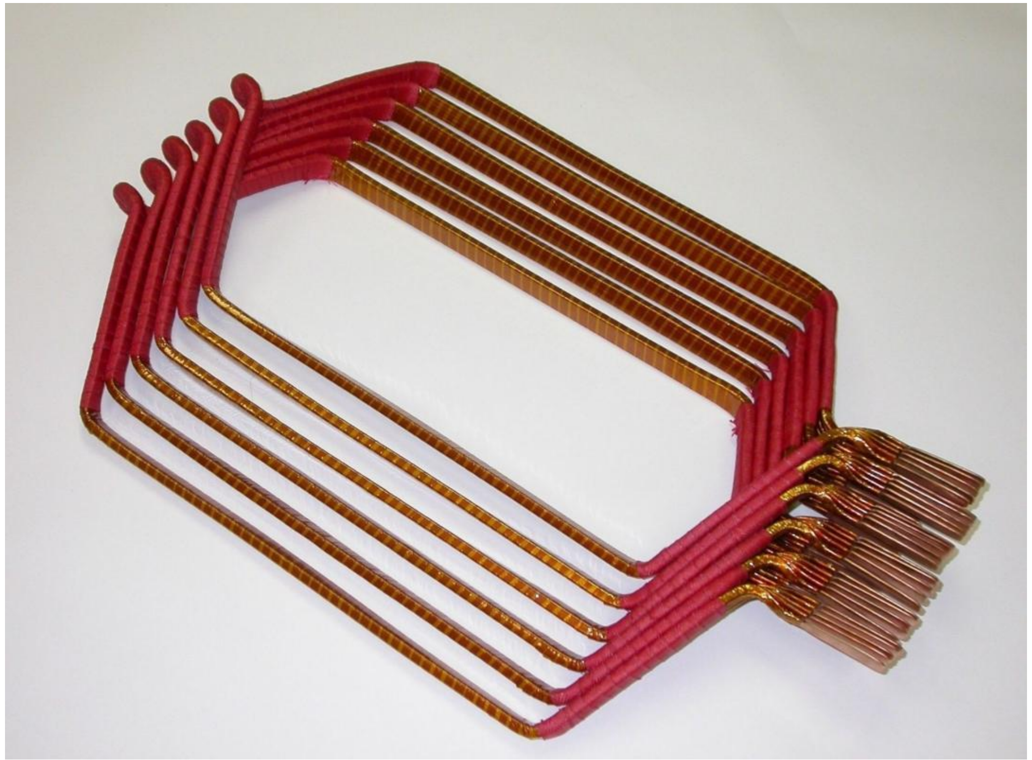


(a)Turn

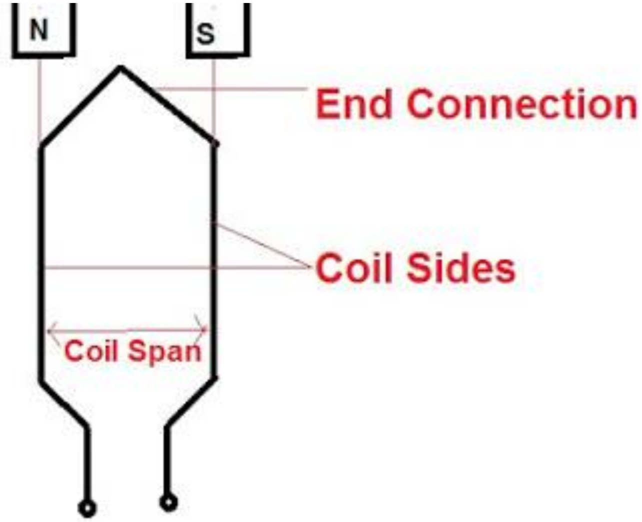


(b)Multiturn coil

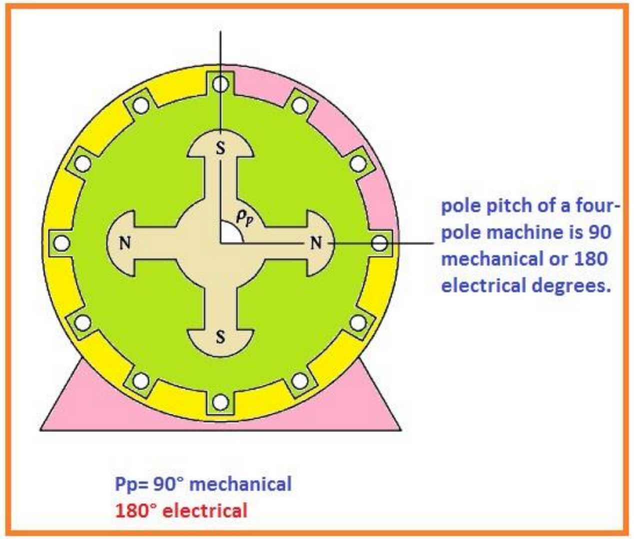
Coil: As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multiturn coil. A coil may consist of a single-turn coil.



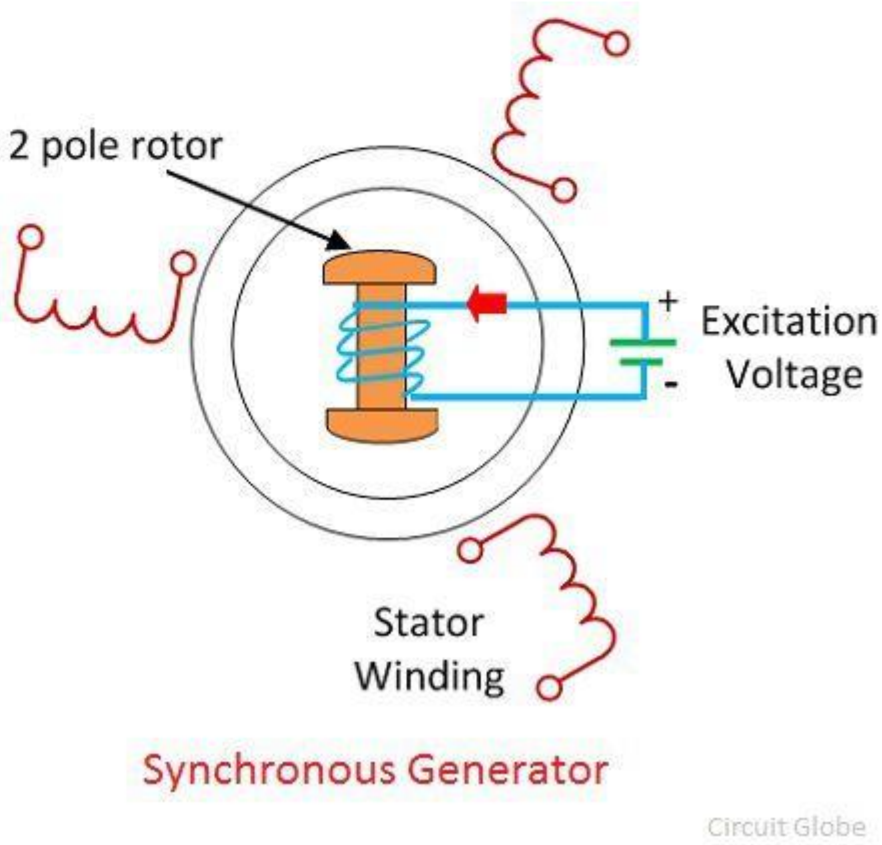
Coil side: Coil consists of many turns. Part of the coil in each slot is called the coil side of a coil.

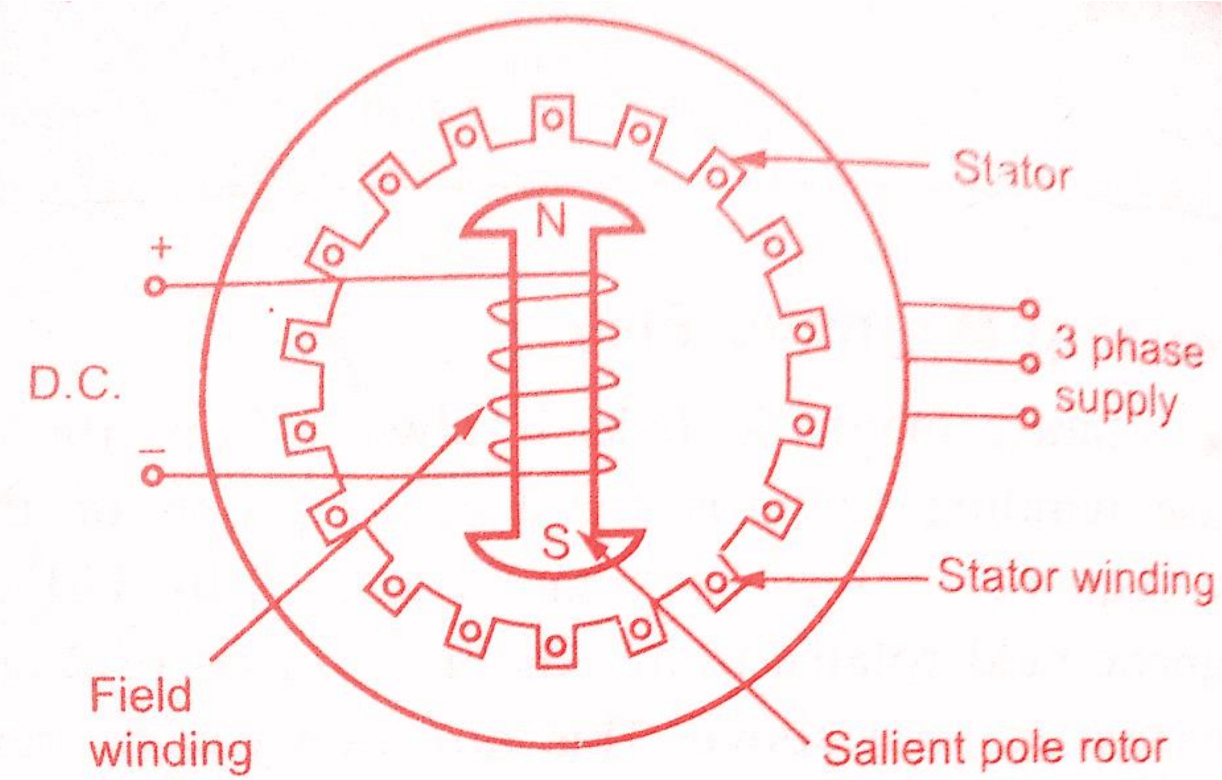


Pole Pitch: It is center to centre distance between the two adjacent poles. We have seen that for one rotation of the conductors, 2 poles are responsible for 360^0 electrical of e.m.f., 4 poles are responsible for 720^0 electrical of e.m.f. and so on. So 1 pole is responsible for 180^0 electrical of induced e.m.f.



Working Principle of Alternator:



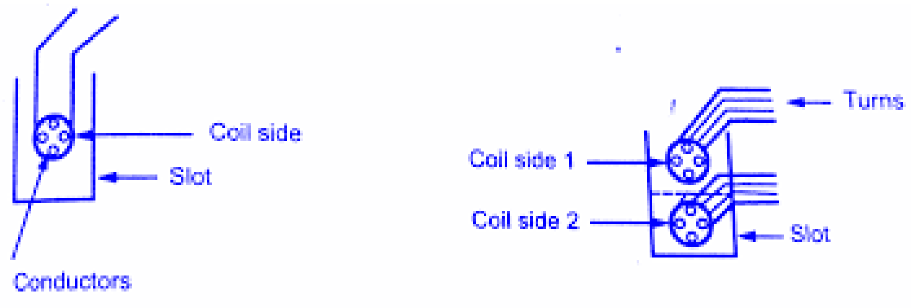


Types of Armature Windings in Alternator:

The different types of armature windings in alternators are,

1. Single-layer and double-layer winding.
2. Full-pitch and short-pitch winding.
3. Concentrated and distributed winding.

Single-layer and double-layer winding:



(a) Single layer (b) Double layer

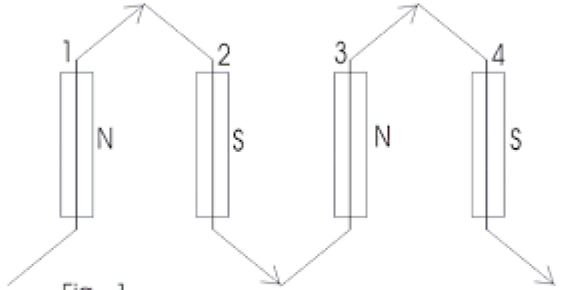
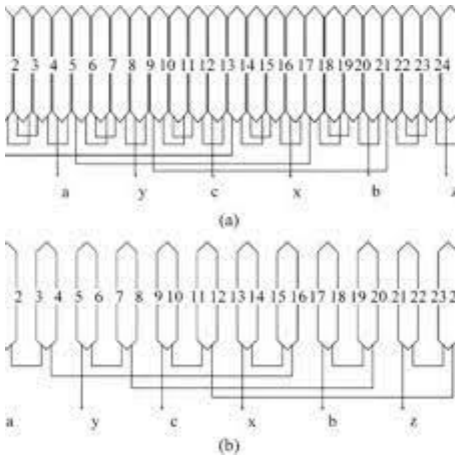


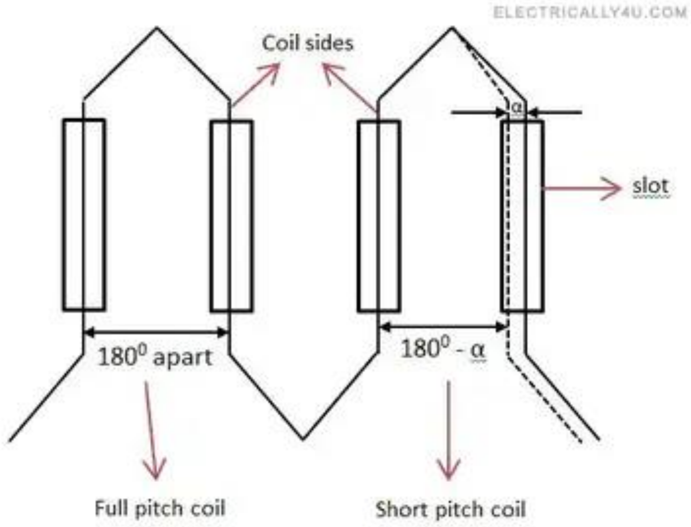
Fig - 1

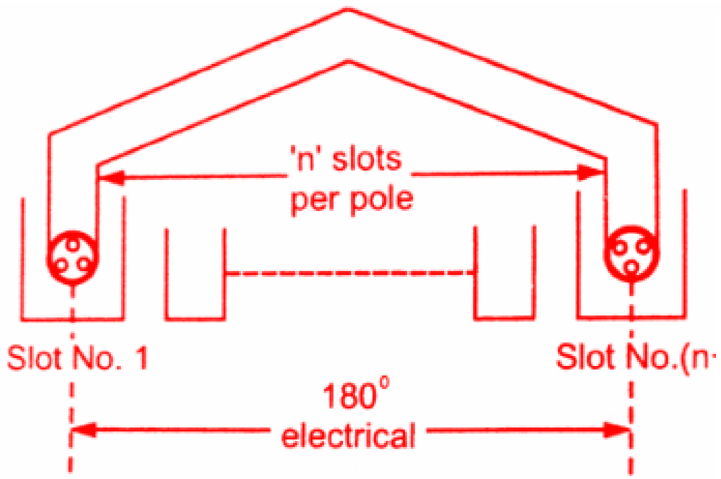


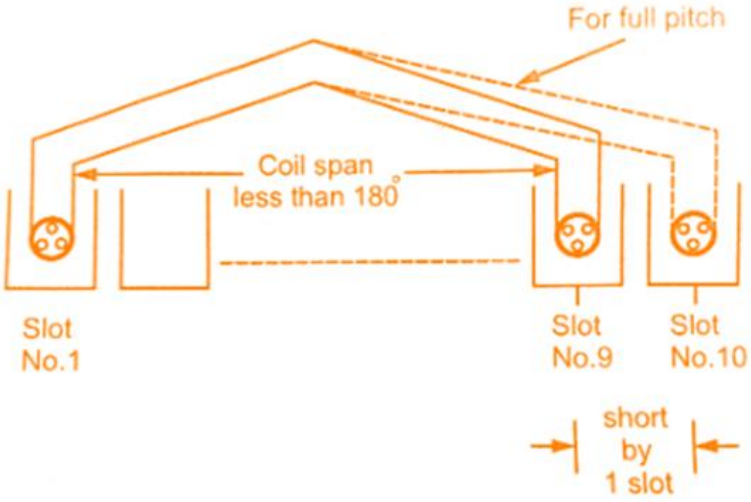
(a) Single layer winding (b) Double layer winding

If a slot consists of only one coil side, winding is said to be a single layer. While there are two coil sides per slot, one, at the bottom and one at the top the winding is called double layer.

Full-pitch and short-pitch winding:







Concentrated and Distributed Winding:

Concentrated

Distributed

EMF Equation of Synchronous Generator or Alternator:

Let Φ = Flux per pole, in Wb

P = Number of poles

N = Synchronous speed in r.p.m

f = Frequency of induced emf in Hz

Z = Total number of conductors

Z_{ph} = Conductors per phase connected in series

$Z_{ph} = Z/3$ as number of phases = 3

Consider a single conductor placed in a slot.

The average value of emf induced in a conductor = $d\Phi/dt$

For one revolution of a conductor,

E_{avg} per conductor = (Flux cut in one revolution /

$$\therefore \quad e_{avg} \text{ per conductor} = \frac{\phi P}{\left(\frac{60}{N_s}\right)} = \phi \frac{PN_s}{60}$$

$$\text{But} \quad f = \frac{PN_s}{120}$$

$$\therefore \quad \frac{PN_s}{60} = 2f$$

E_{avg} per conductor = 2 f Φ volts

Z conductors are connected in series per phase,

$E(avg)/phase = 2fZ\Phi\ volts.$

But Z=2T

$$E(avg)/phase = 2f\Phi 2T$$
$$= 4fT\Phi\ volts.$$

Wkt,

$$Form\ factor = rms\ value/average\ value = 1.11\ for\ sine\ wave.$$

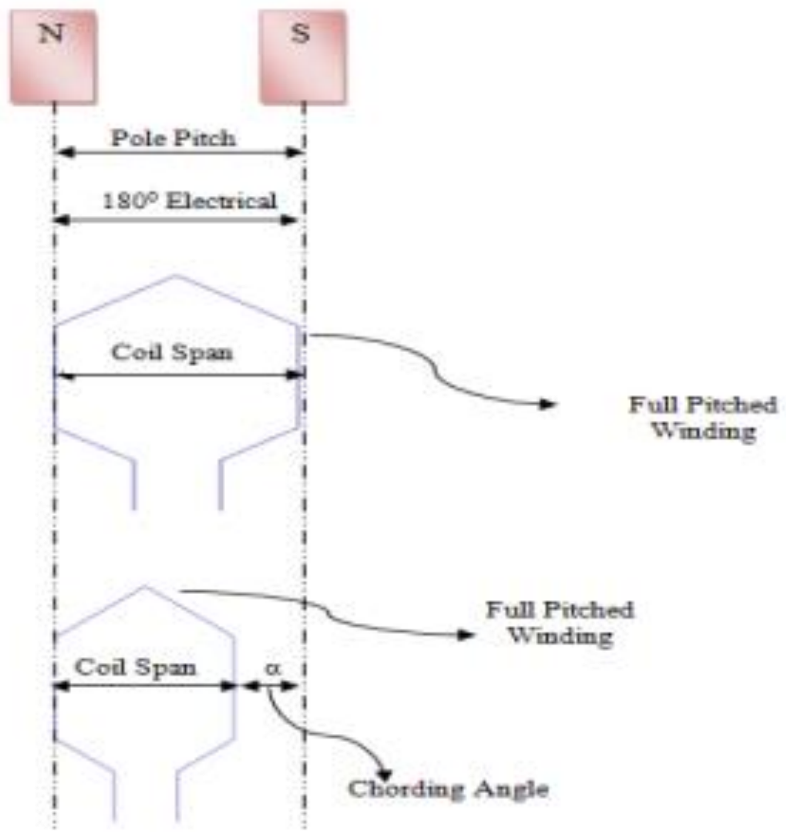
Therefore $E(rms/phase) = 4.44\ fT\Phi\ volts$

$$Eph = 4.44KpKd\ fZ\Phi\ volts$$

Where K_P=pitch factor

K_d= distribution factor

Pitch factor or coil span factor(Kp):



Distribution factor K_d : This is also known as the breadth factor or winding factor. Under the influence of each pole, Z/P conductors belong to one phase. All these conductors can be accommodated in one armature slot and we have to distribute them over two or more slots. This again reduces the induced emf by a factor K_d.

$$K_d = \frac{\sin\left({}^{m\beta}/_{2}\right)}{m \sin\left({}^{\beta}/_{2}\right)}$$

Where m = number of slots/pole/phase.

= total no. of armature slots/ (no. of poles x no. of phases)

$$And\ \beta = \frac{180°}{(no.of\ slots \times\ pole)}$$

$$E_{rms/ph} = 4.44\, K_p K_d\, fT\Phi\ volts$$

$$Or\ E_{rms/ph} = 4.44 K_w fT\,\Phi\ volts\ \ldots\ldots\ldots\ldots\ldots..K_w = K_p K_d$$

Voltage Regulation of an Alternator: The total change in terminal voltage of the alternator from no load to full load, at constant speed and field excitation, is termed as voltage regulation.

[OR]

The voltage regulation of an alternator is the change in its terminal voltage when full load is removed keeping the field excitation and speed constant, divided by the rated terminal voltage.

$$\%Regulation = \frac{E_0 - V}{V} \times 100$$

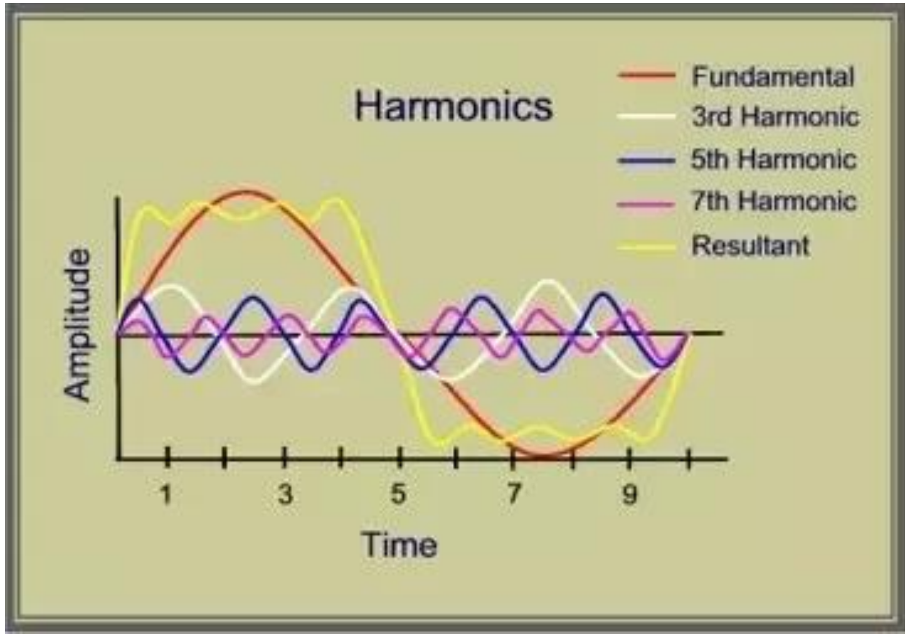
Where E_0= no-load terminal voltage.
V= full load terminal voltage.
The regulation is usually expressed as a % of the voltage drop from no load to full load w.r.t full load terminal voltage.

$$Regulation = \frac{E_0 - V}{V}$$

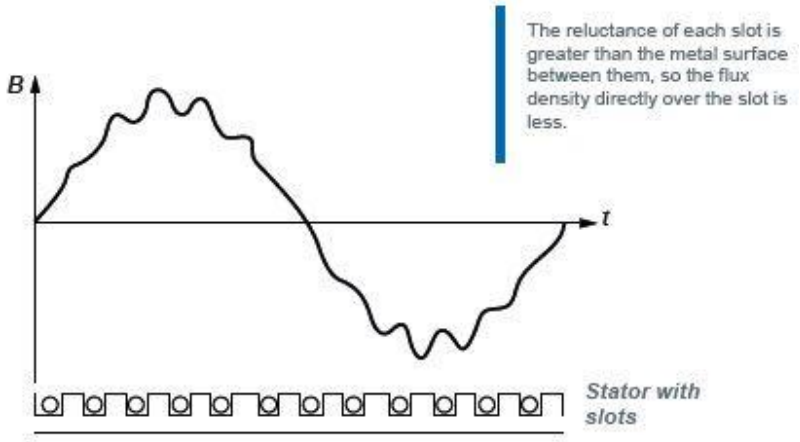
Harmonics

- When the alternator is loaded waveform will not continue to be sinusoidal or becomes non sinusoidal.
- Frequencies are integral multiples of the fundamental wave

Fundamental: $e_1 = Em_1 \sin(\omega t \pm \theta_1)$
2nd Harmonic $e_2 = Em_2 \sin(2\omega t \pm \theta_2)$
3rd Harmonic $e_3 = Em_3 \sin(3\omega t \pm \theta_3)$
5th Harmonic $e_5 = Em_5 \sin(5\omega t \pm \theta_5)$
etc



Slot Harmonics:



As the armature or stator of an alternator is slotted, some harmonics are induced into the emf which is called slot harmonics

Harmonics Minimization

- **Distribution of armature windings:** Instead of having concentrated type of windings, they should be distributed in different slots.

- **Chording:** The e.m.f. generated in the winding is proportional to cos ($x \propto /2$)

- **Fractional slot windings:** The output voltage waveform will be free of harmonics by facilitating the use of fractional slot windings

- **Skewing:** Skewing the pole face will help eliminate the slot harmonics

- **Large length of air gap:** The reluctance will be increased by increasing the air gap and slot harmonics can be reduced.

Effect of Harmonics on induced emf

$B = B_{m1}\sin \omega t + B_{m3} \sin 3\omega t + B_{m5}\sin 5\omega t +$ ....

The emf induced by the above flux density distribution is given by

$e = E_{m1}\sin \omega t + E_{m3} \sin 3\omega t + E_{m5}\sin 5\omega t +$ ....

Effect of Harmonics of pitch and distribution Factor

The pitch factor is given by **$K_p = \cos \alpha/2$,** where α is the chording angle.

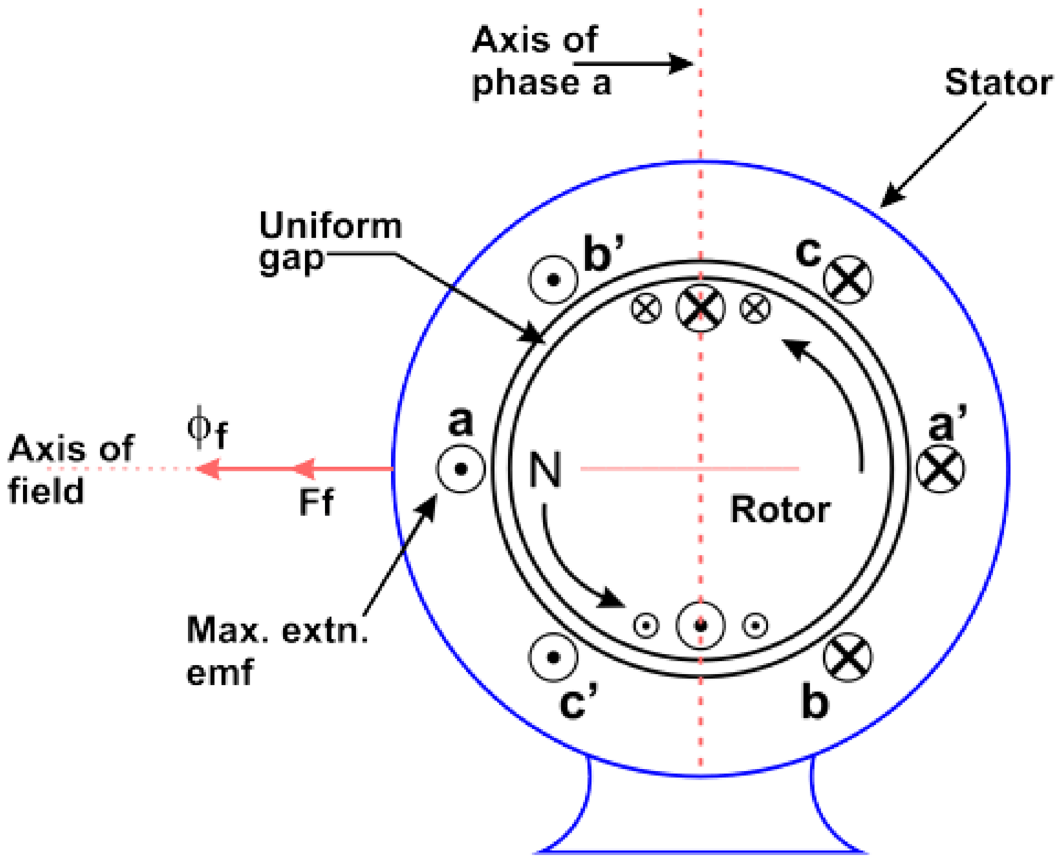
For any harmonic say n^{th} harmonic, the pitch factor is given by $K_{pn} = \cos n\alpha/2$

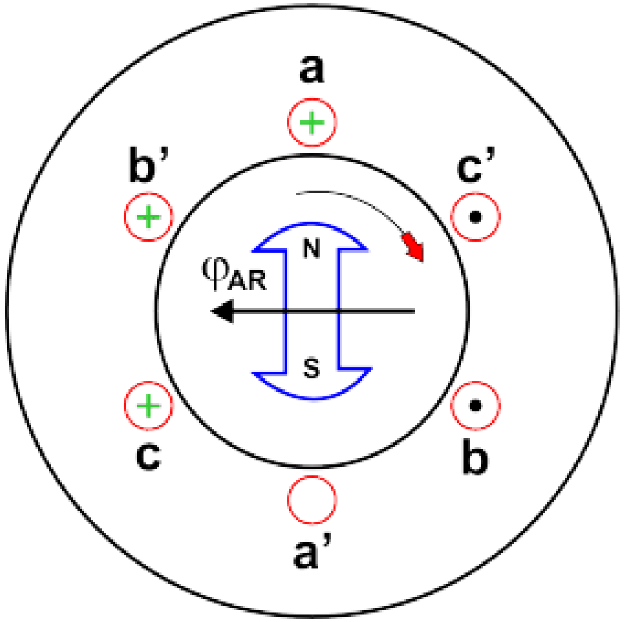
The distribution factor is given by **$K_d = (\sin m\beta/2) / (m \sin \beta/2)$**

For any harmonic say n^{th} harmonic, the distribution factor is given by

$K_{dn} = \sin m\, n\beta/2) / (m \sin n\beta/2)$

Armature Reaction in Alternators





Armature Reaction:

Magnetic fluxes in alternators

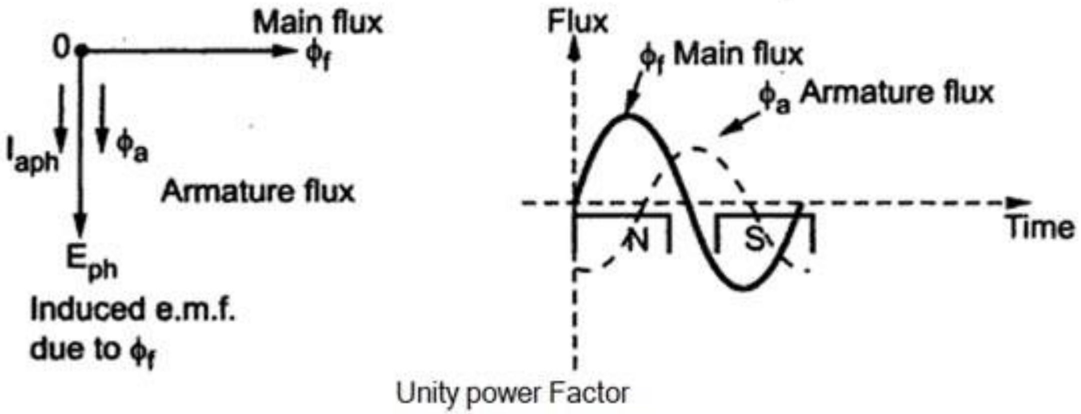
There are three main fluxes associated with an alternator:

1. **Main useful flux linked with both field & armature winding.**

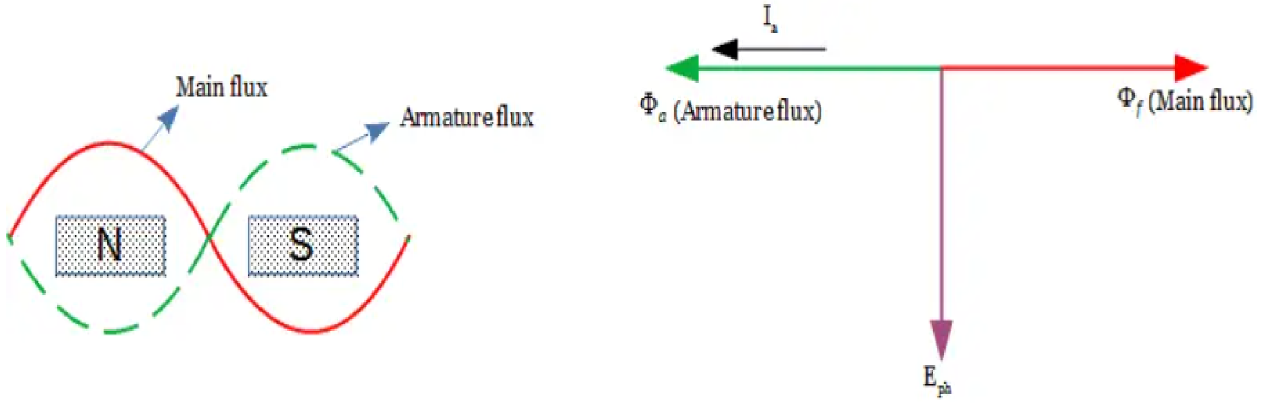
2. **Leakage flux linked only with armature winding.**

3. **Leakage flux linked only with field winding.**

Unity power factor load

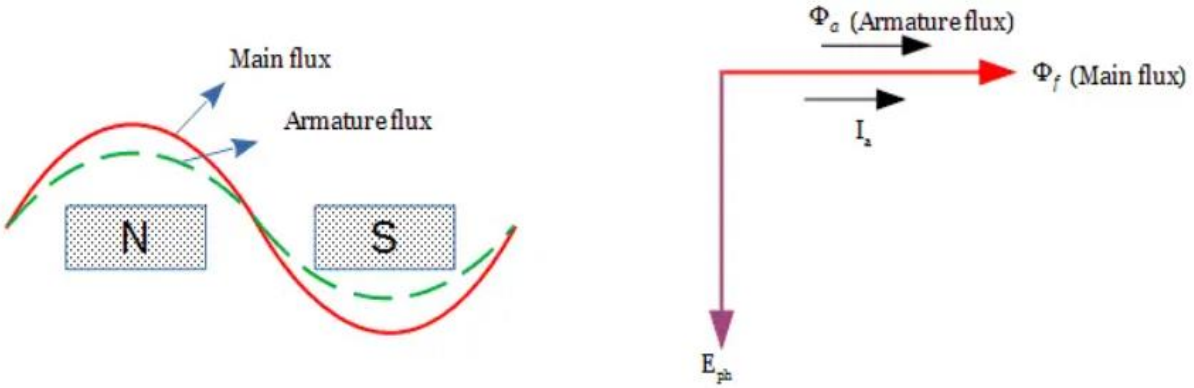


Zero power factor lagging load



Waveform and phasor diagram for demagnetizing effect

Zero power factor leading load



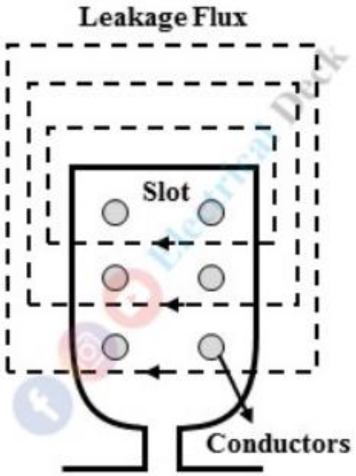
Waveform and phasor diagram for magnetizing effect

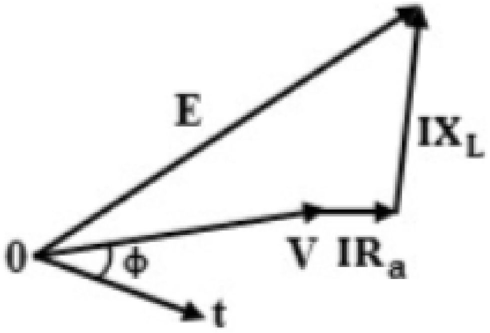
Synchronous Reactance and Impedance:

When an alternator is loaded, there will be a circulation of load current in the armature winding. Once the load on the alternator is increased, the terminal voltage changes (for constant excitation) due to the following reasons,
Voltage drop due to armature resistance, IRa.
Voltage drop due to synchronous reactance.

- Armature Resistance
- Synchronous Reactance
- Armature Leakage Reactance (X_L)

Armature Leakage Reactance (X_L) :





Generated emf, E will be,

$$E = V + IR_a + j\,IX_L$$
$$= V + I\,(R_a + jX_L)$$

Where, X_L = Armature leakage reactance = $2\pi\, f\, L\ \Omega$/ph.

Armature Reaction Reactance (Xa) :

$$i.e.,\ X_s = X_L + X_{ar}$$

$$Z_s = \sqrt{R_a^2 + X_s^2}$$

- R_a = Armature resistance
- X_s = Synchronous reactance ($X_L + X_a$)

$$E = V + IR_a + jI(X_a + X_L)$$

$$E = V + IR_a + j\,IX_s$$

$$E = V + I(R_a + X_s)$$

$$E = V + IZ_s$$

Synchronous Impedance :

The synchronous impedance may be defined as the vector sum of the armature resistance and synchronous reactance. It is denoted as Zs.

$$Z_s = \sqrt{R_a^2 + X_s^2}$$

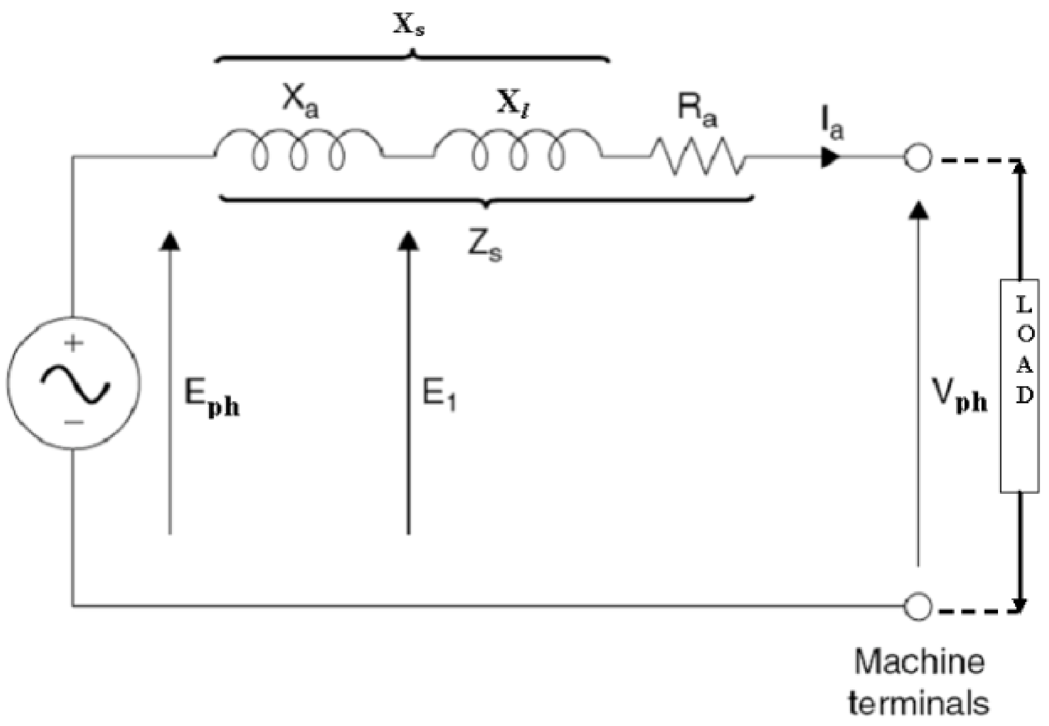
$$E = V + IR_a + jI(X_a + X_L)$$

$$E = V + IR_a + j\,IX_s$$

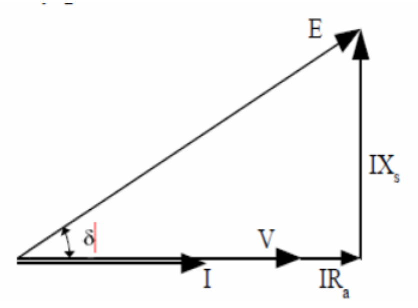
$$E = V + I(R_a + X_s)$$

$$E = V + IZ_s$$

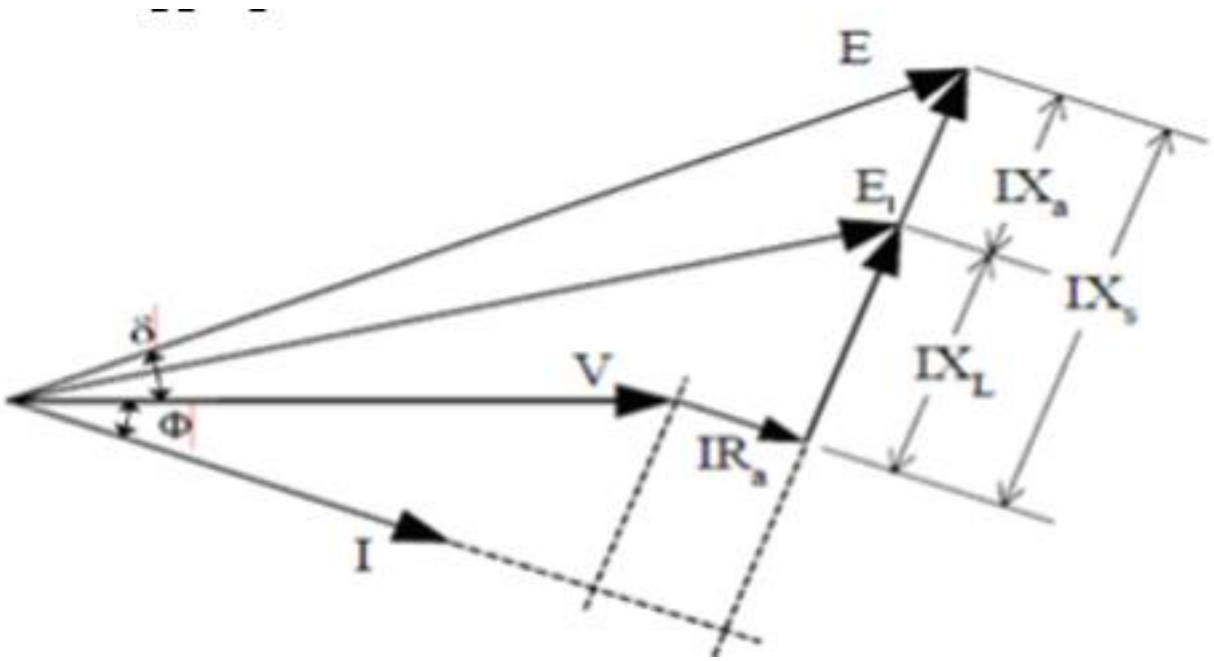
Equivalent Circuit of Synchronous Generator:



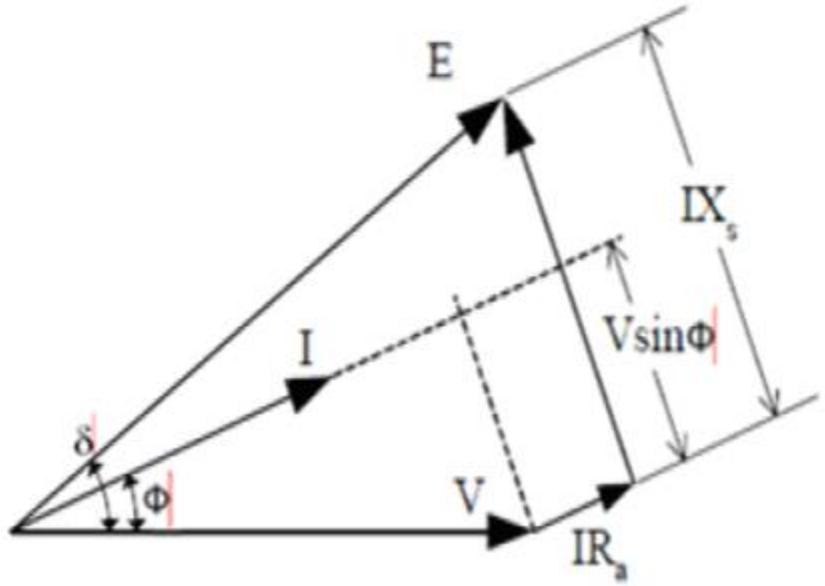
Unity power factor load



Zero power factor lagging



Zero power factor leading




thank
you