ADVANCED ELECTRICAL MACHINES

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- **Course Objectives:**
- 1. Learn construction & working principle of three phase synchronous machines.
- 2. Define regulation of alternator & calculate it by direct and indirect methods.
- 3. Explain operation and performance of synchronous reluctance motors.
- 4. Familiarize with operation and performance of permanent magnet brushless D.C.
- 5. Learn operation and performance of permanent magnet synchronous motors.

Course Outcomes: After completion of this course students will be able to

- 1 Explain construction & working principle of three phase synchronous machines
- 2. Estimate regulation of alternator by direct and indirect methods.
- 3. Interpret the principal of operation of PMSM, Switch reluctance and linear motors

Class Continuous Assessment (CCA) (50 Marks)

- **Assignments –** 10 (20%)
- **Test -** 15 (30%)
- **Presentations -**10 (20%)
- **Case study -**Nil
- **MCQ** 10 (20%)
- **Oral** Nil
- **Attendance & Initiative -**05 (10%)

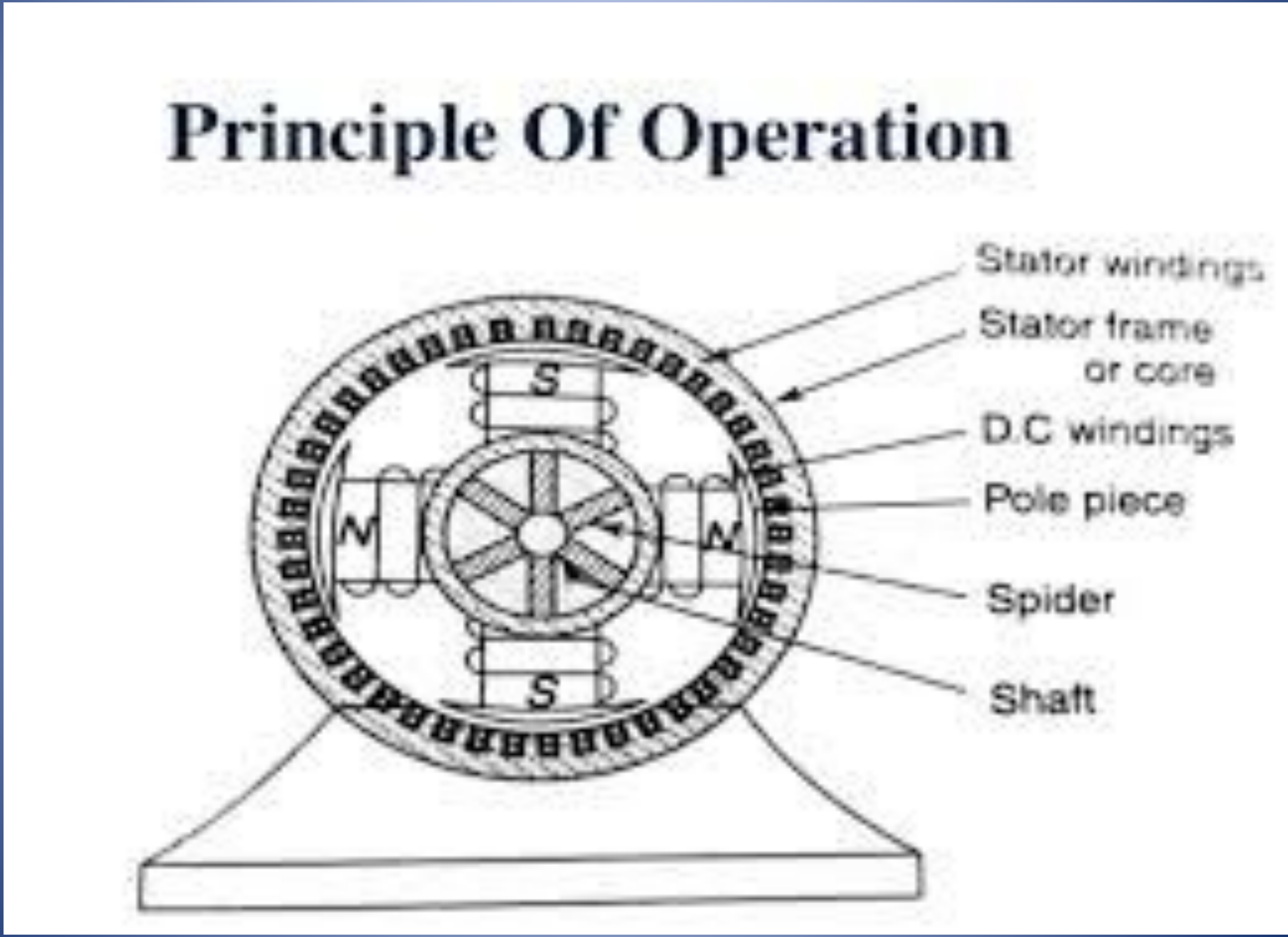
Laboratory Continuous Assessment (LCA) (50 Marks)

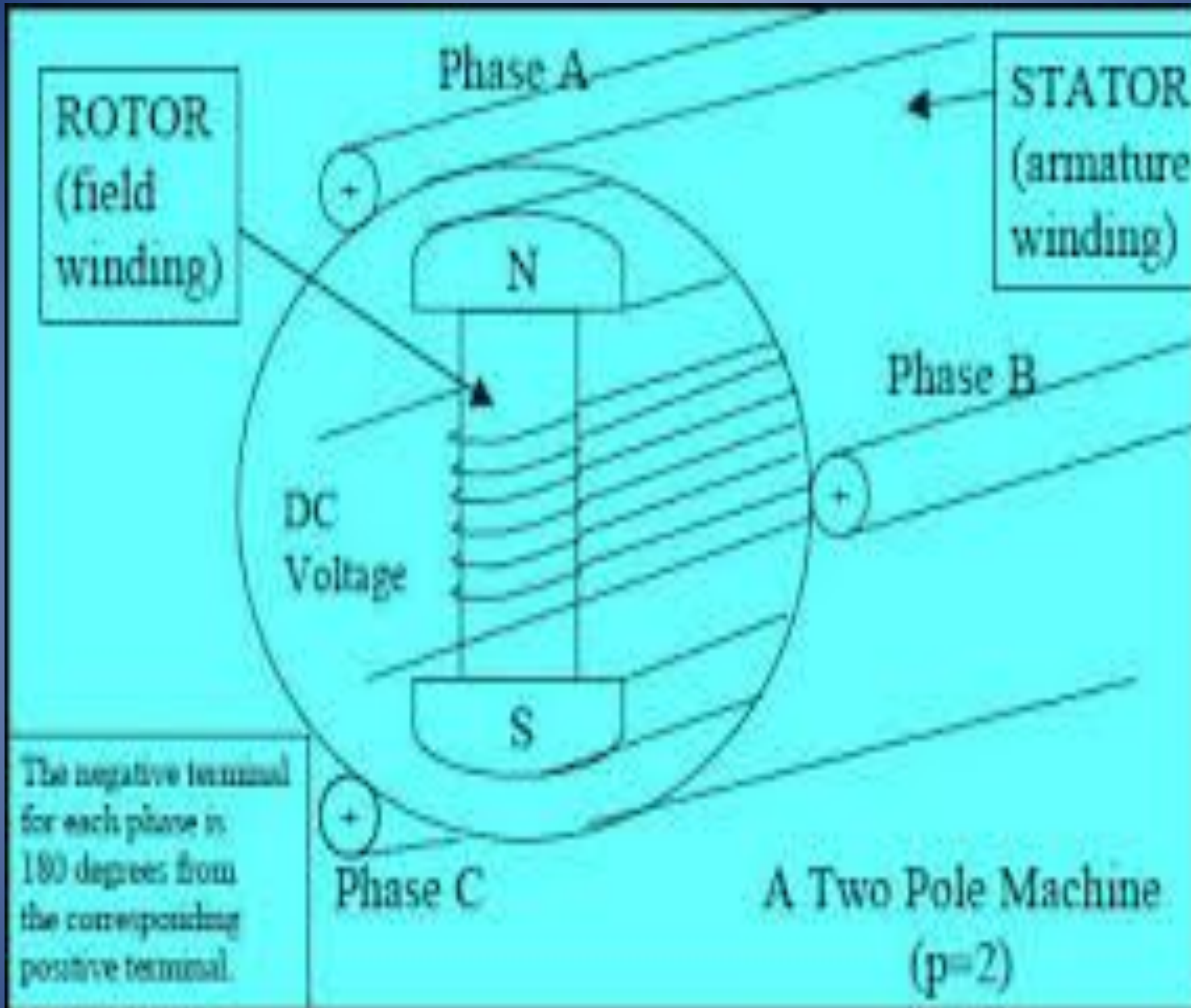
- **Regularity and punctuality -**10 (20%)
- **Understanding the Objective -**10 (20%)
- **Understanding of procedure -**10 (20%)
- **Experiment Skills-**10 (20%)
-
- **Ethics-**10 (20%)
- **Term End Examination:**
  Term end exam of 50 Marks will be based on entire syllabus

Three phase Synchronous machines.

- Construction,
- rotating-field type and
- rotating-armature type
- salient-pole type and
- non-salient-pole type and their comparison.
- Excitation Methods

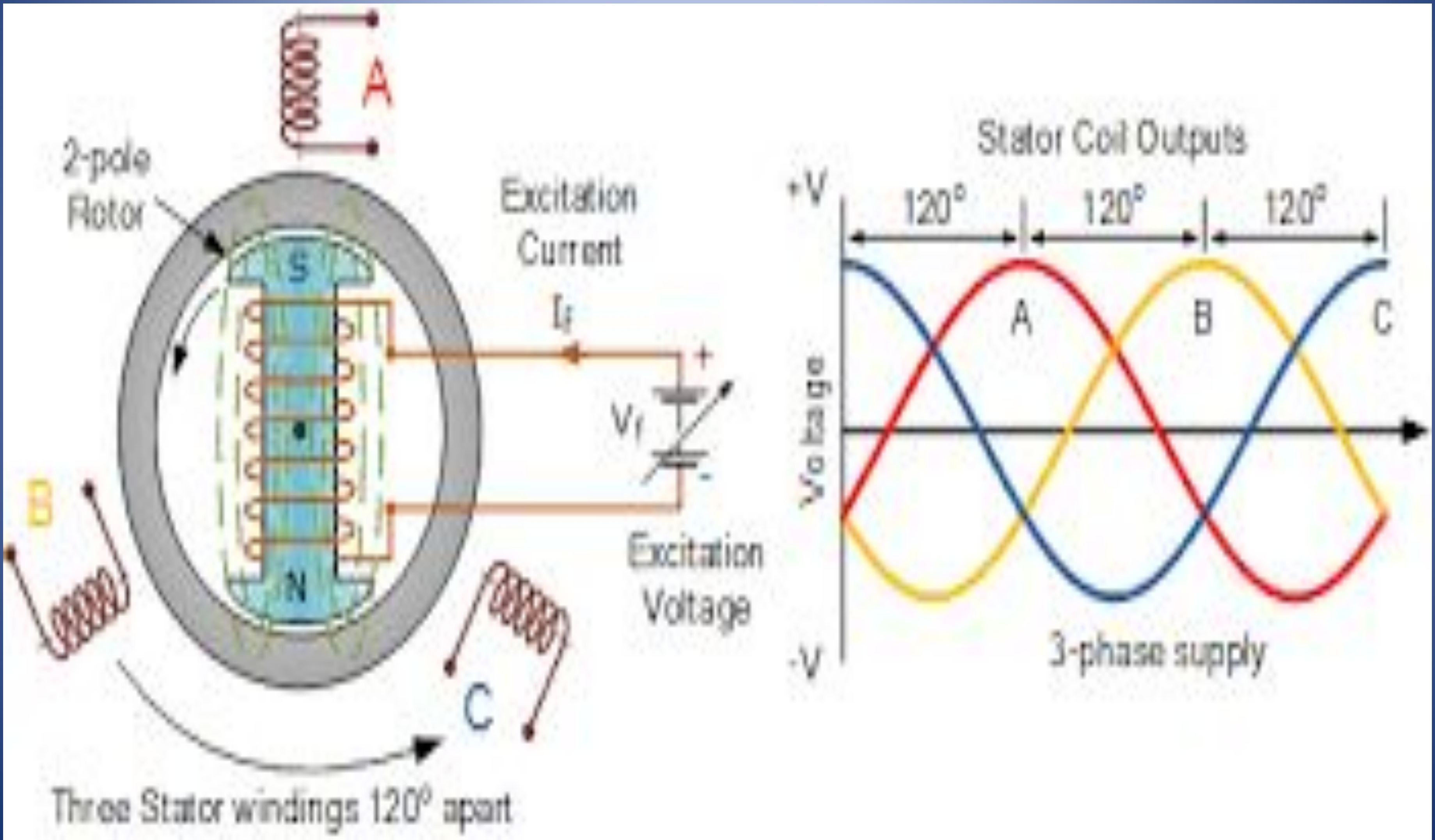
CONSTRUCTION





Phase A
ROTOR (field winding)
STATOR (armature winding)
N
Phase B
DC Voltage
S
The negative terminal for each phase in 180 degrees from the corresponding positive terminal.
Phase C
A Two Pole Machine (p=2)

WORKING



A
2-pole
Rotor
S
N
Excitation
Current
I_f
+
V_f
-
Excitation
Voltage
B
C
Three Stator windings 120° apart
Stator Coil Outputs
+V
120°
120°
120°
A
B
C
Voltage
-V
3-phase supply

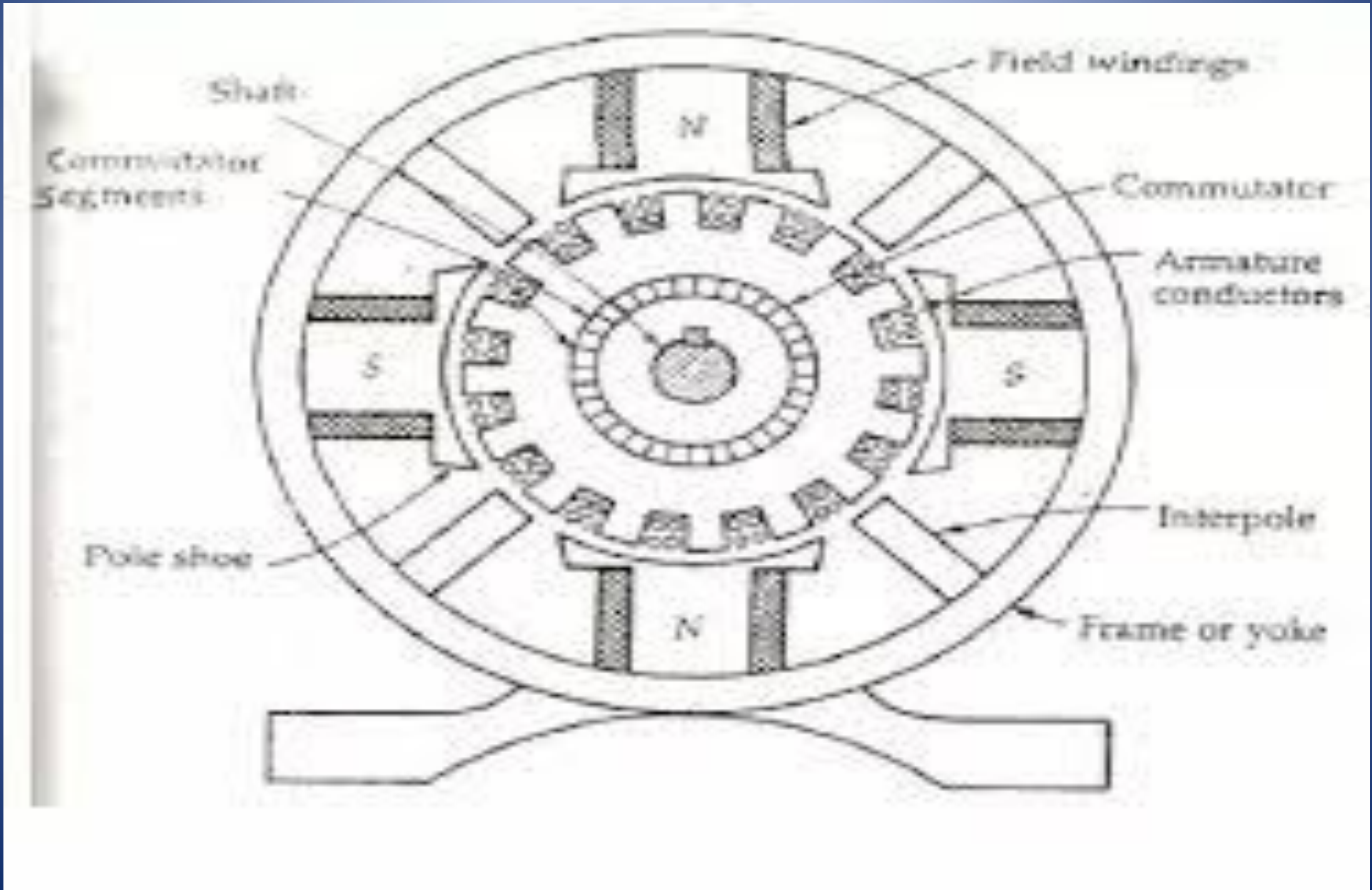
Working principal

- Rotor of generator is rotated by prime mover
- Excitation to the rotor is provided
- RMF is produced
- RMF induces 3 phase voltage in the stator winding

Advantages of Stationary Armature

- At high voltage ,easier to insulate stationary armature winding
- Not subjected to vibrations
- Output can be directly taken
- For field winding low D.C. can be used easily
- Rotating field –light-constructed for high speed rotation.

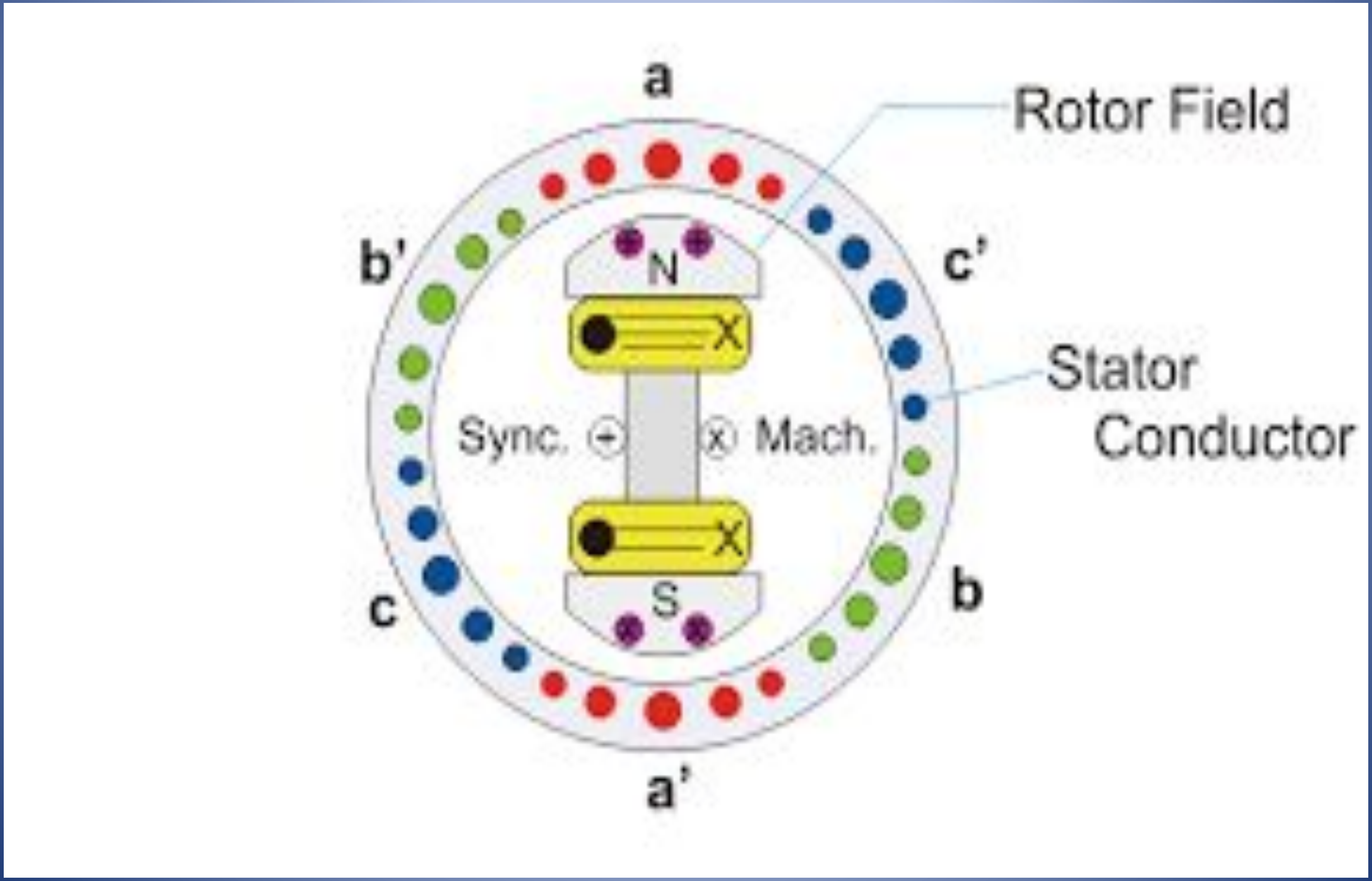
Alternator with field stationary



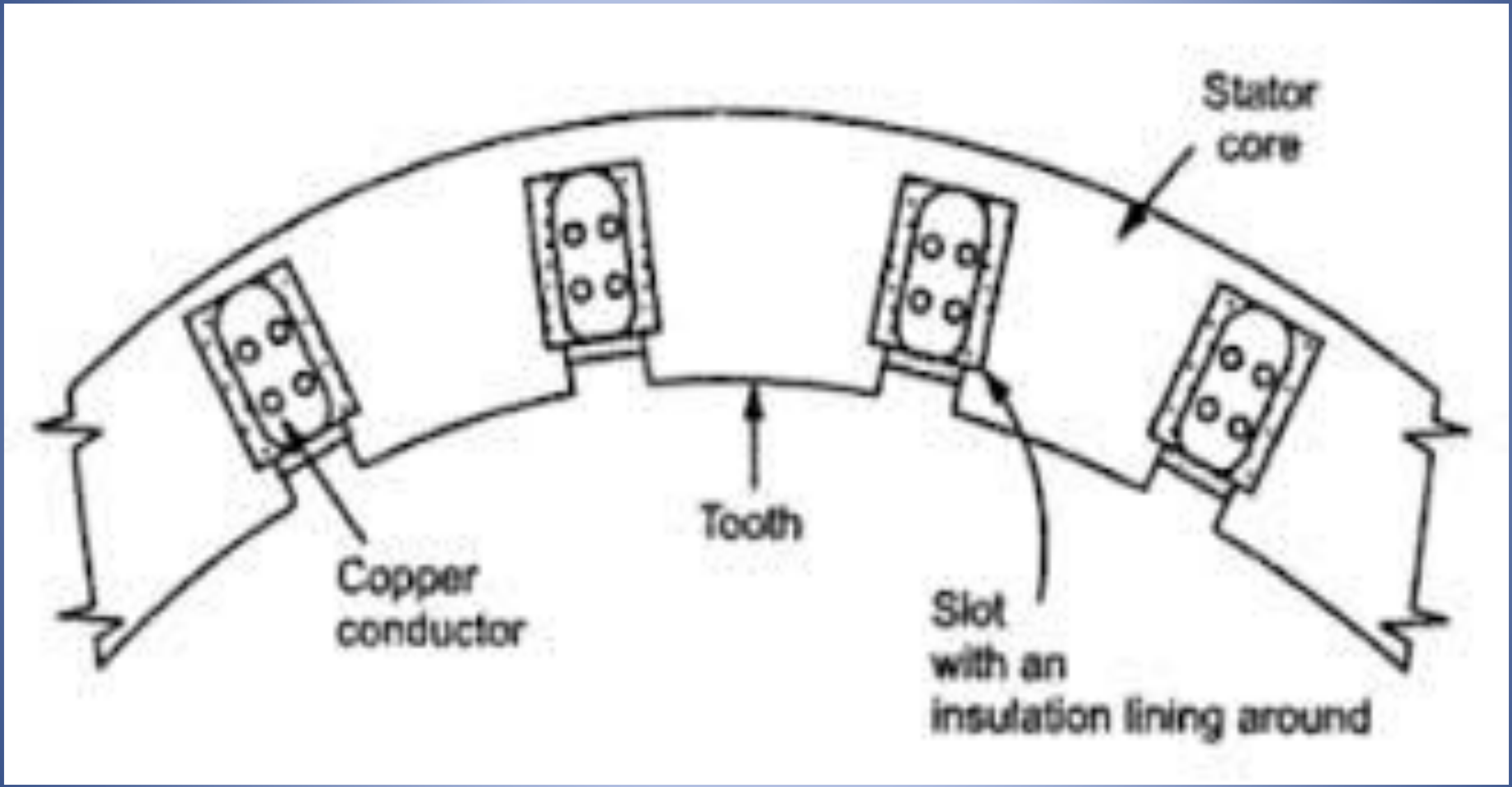
CONSTRUCTIONAL FEATURE

- Main two parts
- Stator or Armature –made up of
  - cast steel for small size
  - Welded steel for large size
  - With high grade silicon content steel laminations
- Rotor –field
  - Two types-
    - Salient pole type Rotor
    - Smooth Cylindrical type - Non - salient pole type

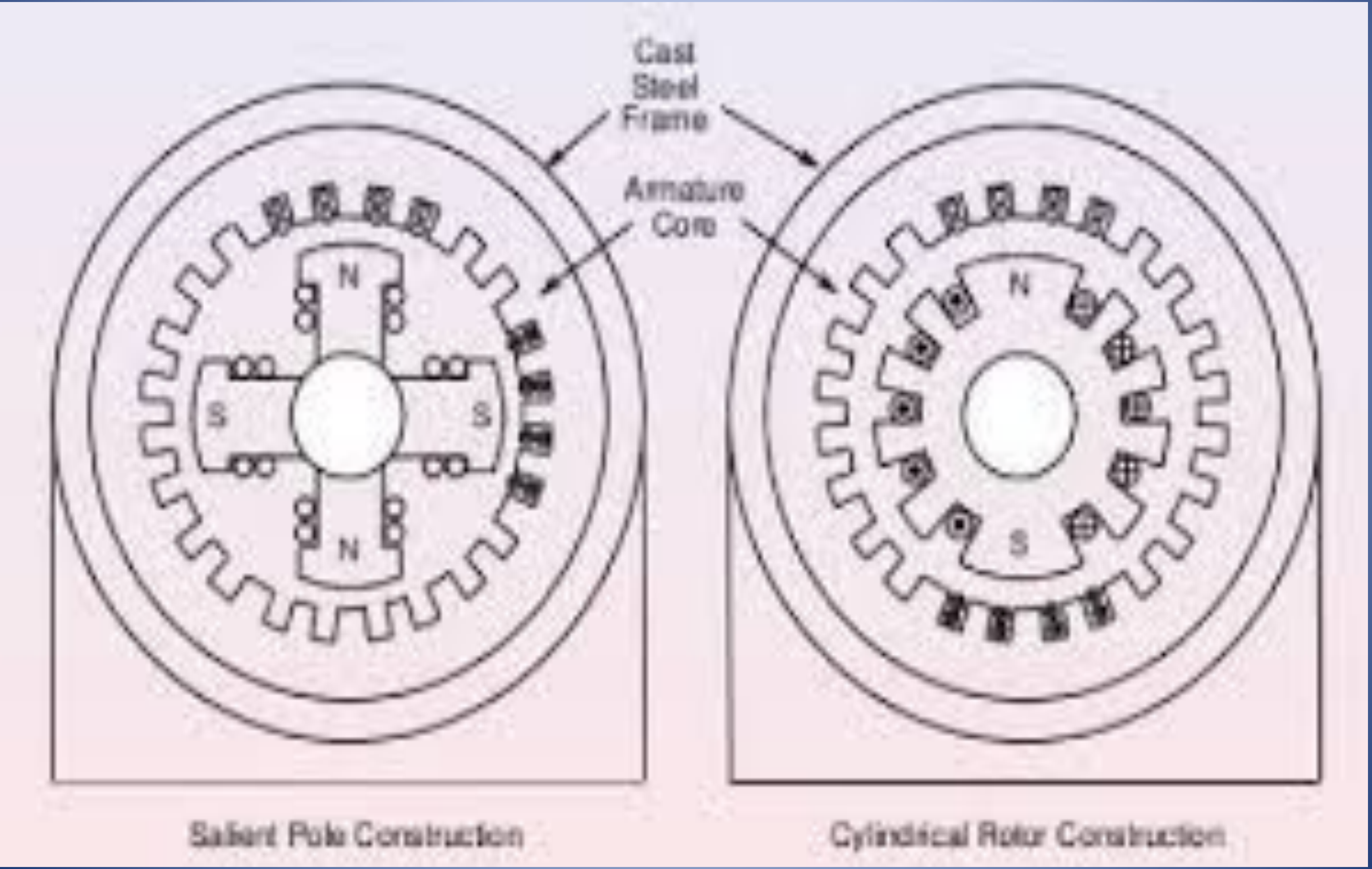
Stator and Rotor

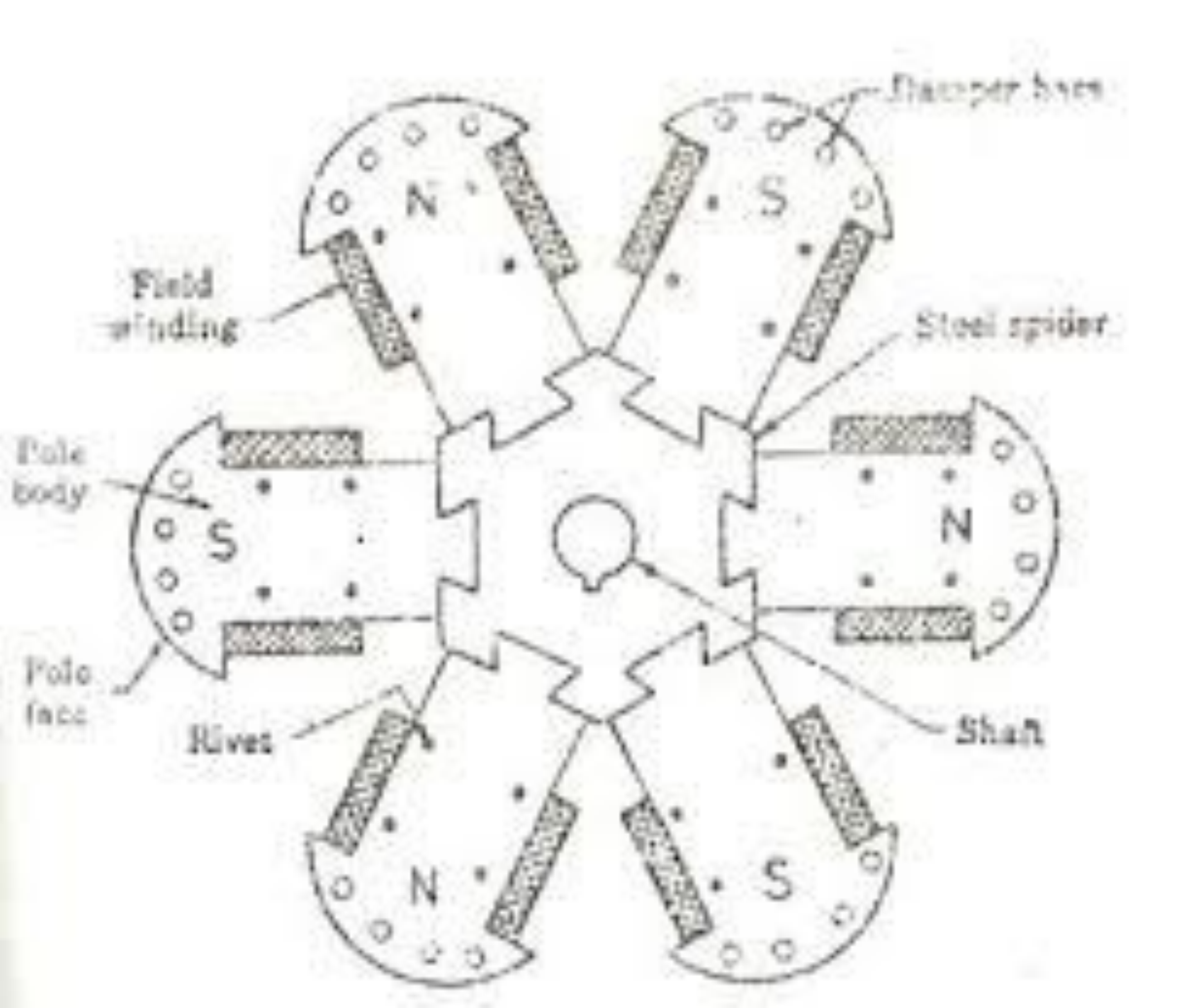


Stator construction

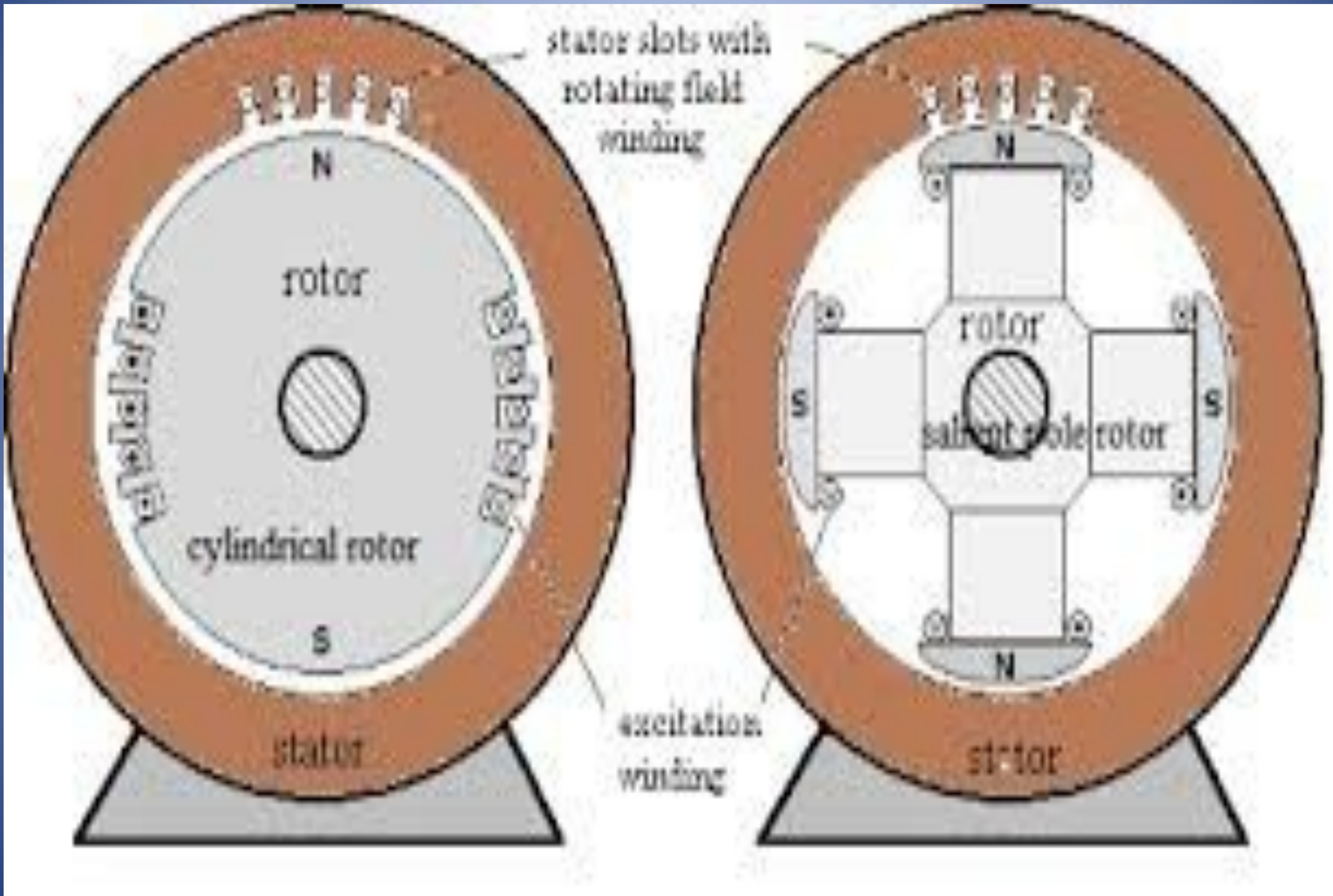


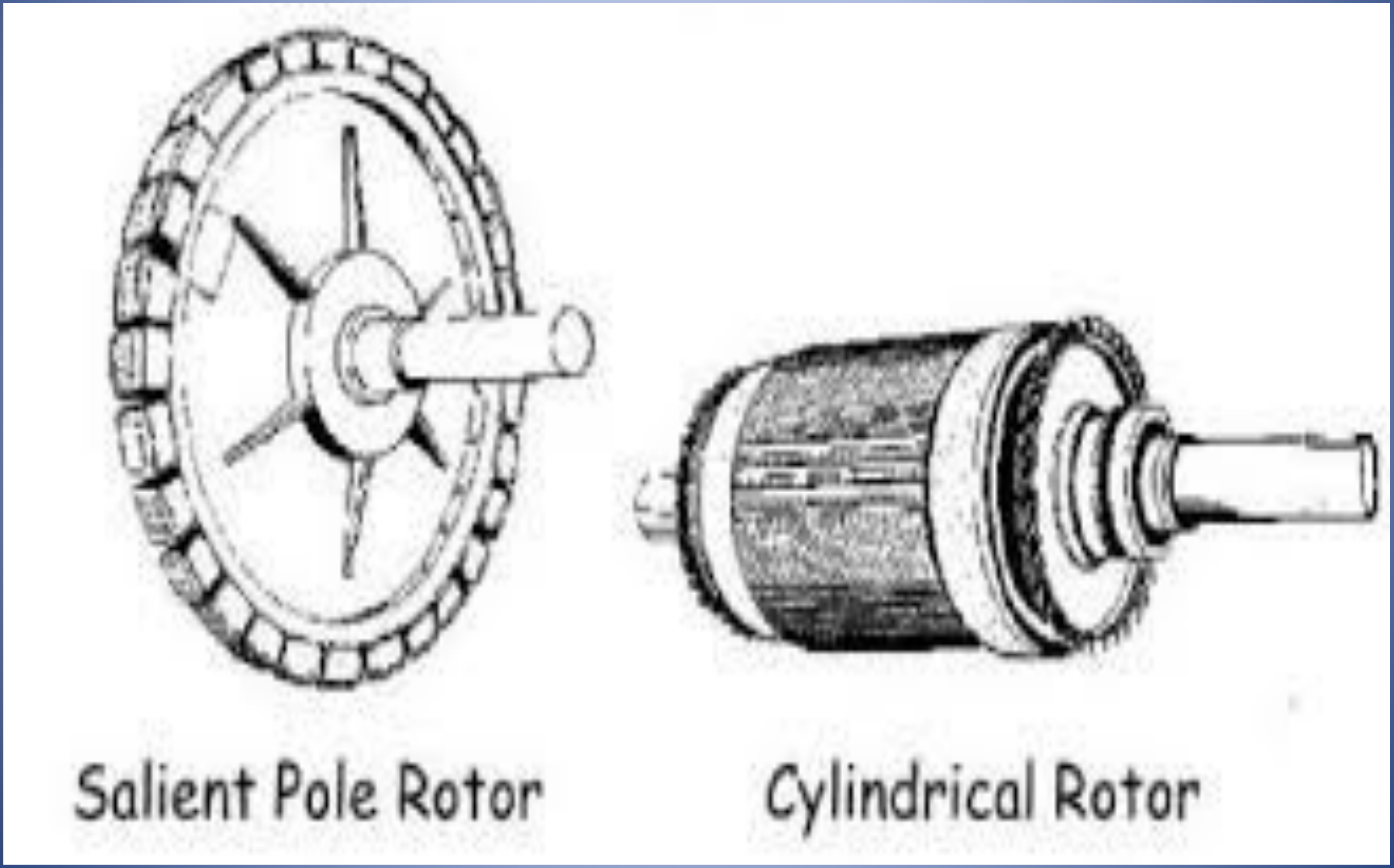
Salient pole and cylindrical pole rotor





Damper bars
N
S
Field winding
Steel spider
Pole body
S
N
Pole face
Rivet
Shaft
N
S


stator slots with
rotating field
winding
N
rotor
cylindrical rotor
S
stator
excitation
winding
N
rotor
S
S
N
stator


Salient Pole Rotor
Cylindrical Rotor

Comparison

- Salient pole rotor
  - –Large no of poles ,operate at lower speed

–Hydro alternator

-air gap is non uniform

-large diameter ,short axial length

Cylindrical rotor

-less no. of poles, operate at high speed

-turbo alternator

-air gap is uniform

-small diameter ,large axial length

Excitation method

- Small machines – dc supply by dc generator(pilot exciter)
- Medium machines-ac exciter -3 phase ac generator rectified &supplied through brushes and slip rings.
- Large machines –brushless excitation system

  -Solid state rectifies are used

  - power loss is less

Concentrated winding

- If all the coil sides of any one phase under one pole are placed in one slot, the winding obtained is known as concentrated winding. Such winding give maximum induced emfs for a given number of conductors but the waveform is not exactly of sinusoidal waveform.

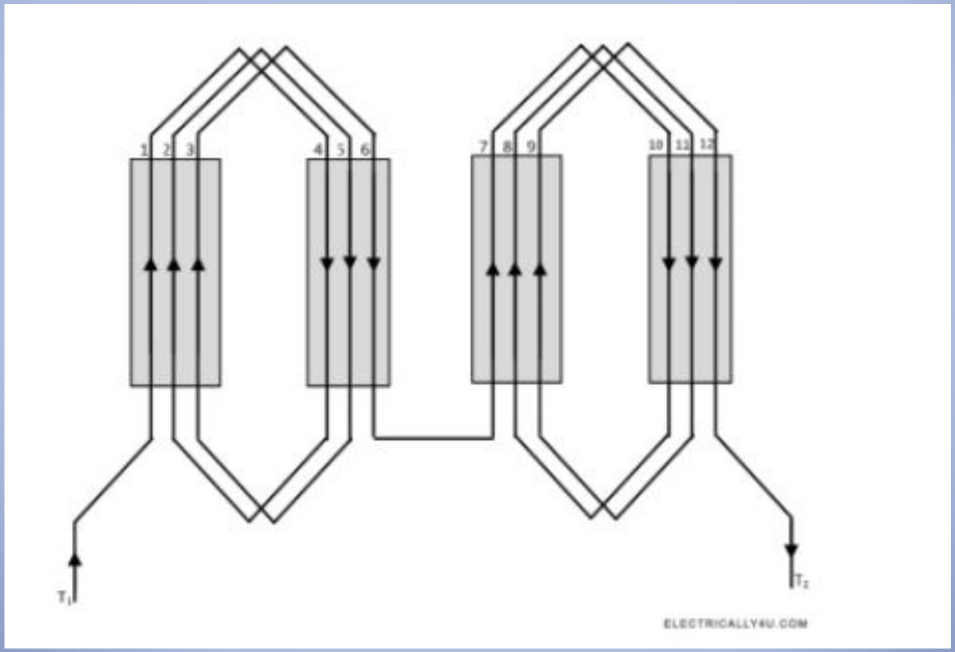
Distributed winding

- If the conductors are placed in several slots under one pole, then the winding is known as distributed winding. The winding may be partially distributed or completely distributed, depending on the slots, which may be spread over only a portion of the surface or over the entire surface.

- Distributed winding have certain advantages:
- *Harmonic emfs are reduced and so the waveform is improved.*
- *Distorting harmonics can be eliminated.*
- *Armature reaction and armature reactance is reduced to a greater extent.*
- *Efficient cooling is possible for the armature winding due to the distribution of winding.*
- *Core is also better utilised as the slots are evenly spaced.*

- **Lap winding**
- If the conductors are joined in such a way that their parallel paths and poles are equal in number, then it is a lap winding. i.e., A=P, where A is the number of parallel paths of a conductor and P is the number of poles.
- Lap winding is employed in stator of high speed synchronous machine applications.

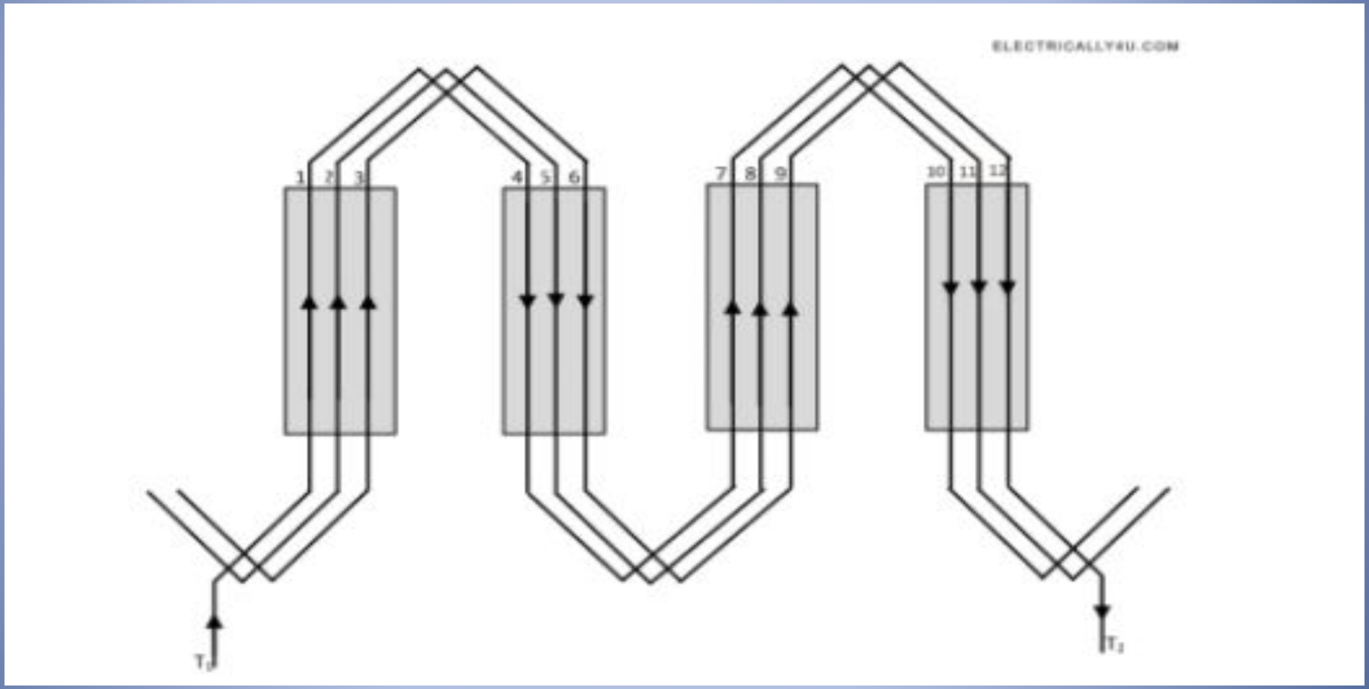
- The below figure shown the structure of lap winding of a 4 pole, 12 slots, 12 conductor alternator.



- *Lap winding*

- **Wave winding**
- In wave winding, the number of parallel paths(A) is always equal to 2. The number of conductors per pole will be equal to the conductors in front end and back ends.
- Wave windings are much suitable for the rotors of induction type motors.

- The below figure shown the structure of wave winding of a 4 pole, 12 slots, 12 conductor alternator.



- *Wave Winding*

Full pitch and short pitch winding

- When the two coil sides forming a complete coil of a winding are 180 electrical degrees apart, the winding is called as full pitch winding.
- When the coil span of the winding is less than 180 electrical degrees, i.e.,the two coil sides forming a complete coil of a winding are less than 180 electrical degrees apart, then the winding is known as short pitch winding or fractional pitch winding.

Kc And Kd

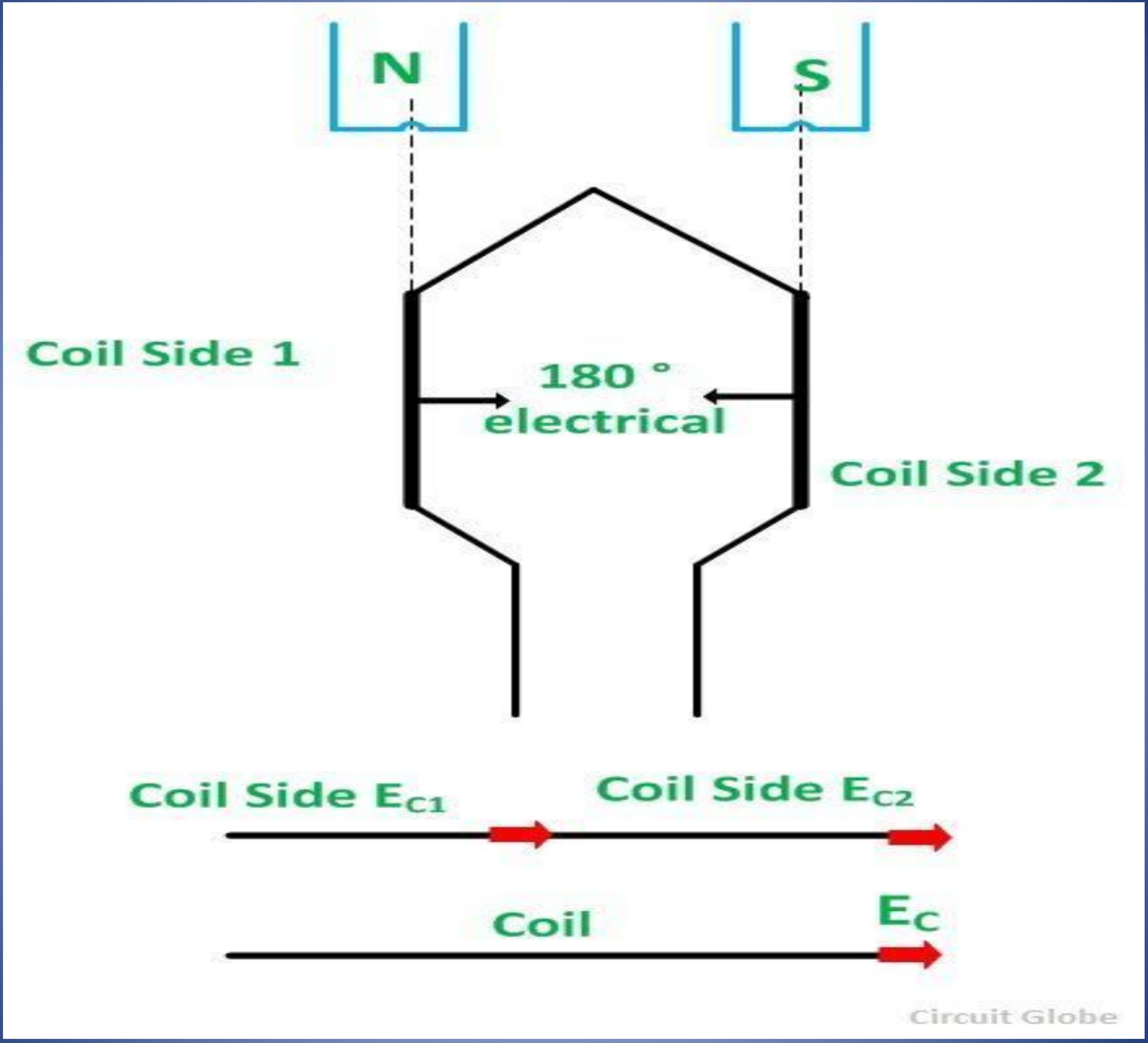
- Coil Span Factor
- The Coil Span Factor is defined as the ratio of the induced emf in a coil when the winding is short-pitched to the induced emf in the same coil when the winding is full pitched.

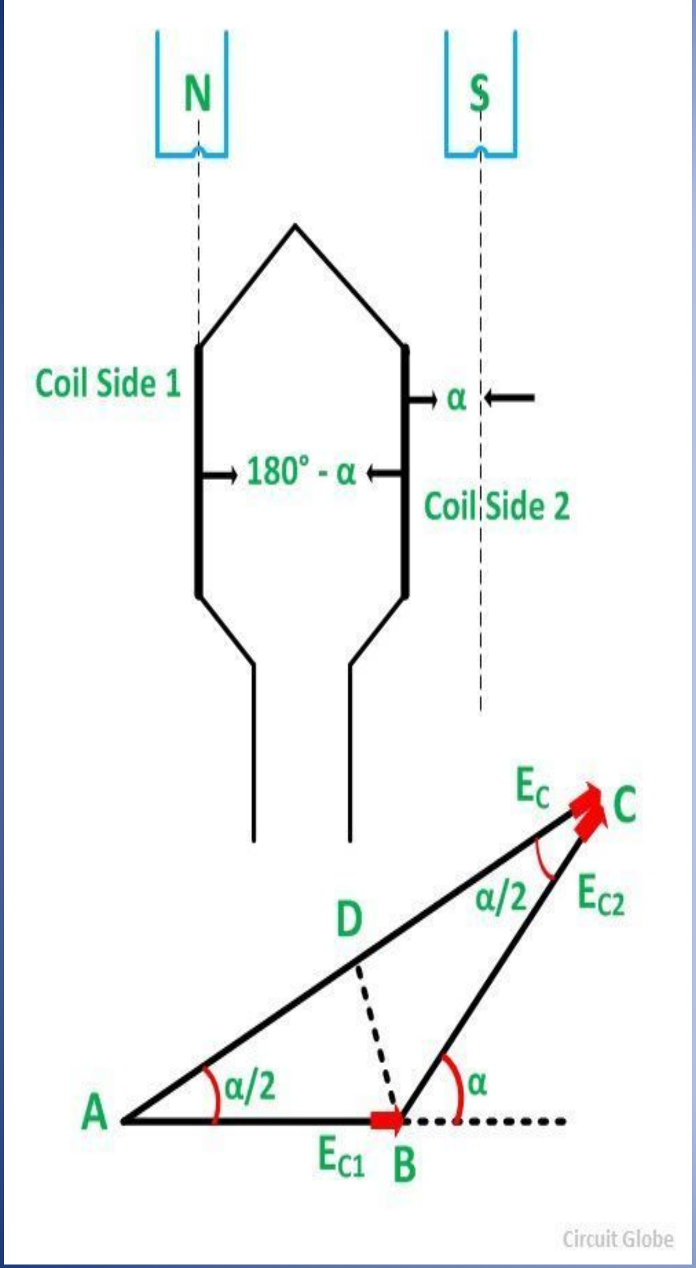
- Distribution Factor
- The distribution factor is defined as the ratio of induced EMF in the coil group when the winding is distributed in a number of slots to the induced EMF in the coil group when the winding is concentrated in one slot.

Coil Span Factor

- The distance between the two sides of a coil is called the **Coil Span** or **Coil Pitch Factor**. It is also known as **Chording Factor.**

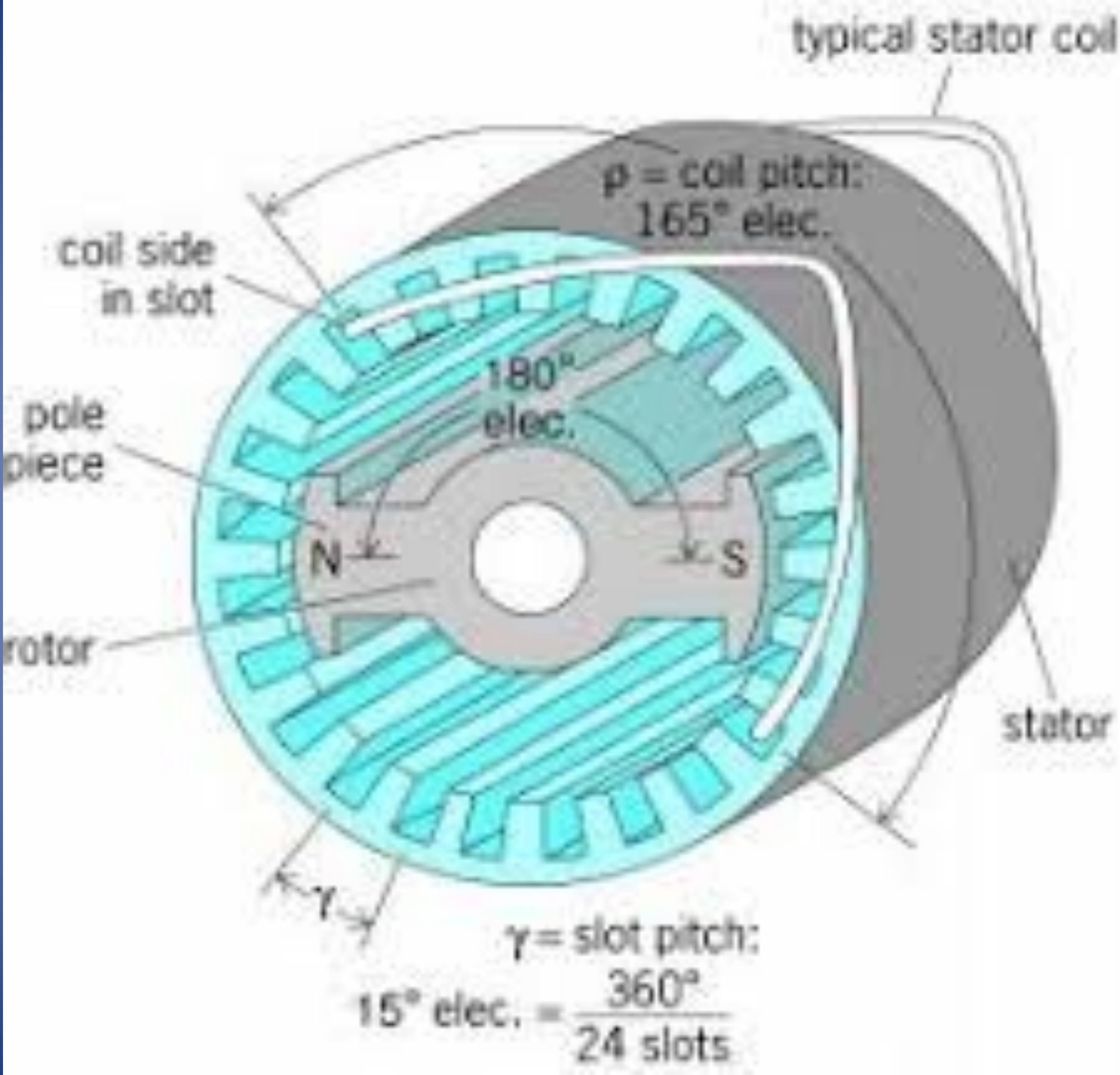
- The angular distance between the central line of one pole to the central line of the next pole is called **Pole Pitch**. A pole pitch is always 180 electrical degrees, regardless of the number of poles on the machine. A coil having a span equal to 180^0 electrical is called a **full pitch coil** as shown in the figure below:
-


N
S
Coil Side 1
180 °
electrical
Coil Side 2
Coil Side E_{C1}
Coil Side E_{C2}
Coil
E_C
Circuit Globe



- A coil having a span less than 180^{0} electrical is called a short pitch coil or fractional pitch coil. It is also called a chorded coil. The short pitch coil factor is shown in the figure below:

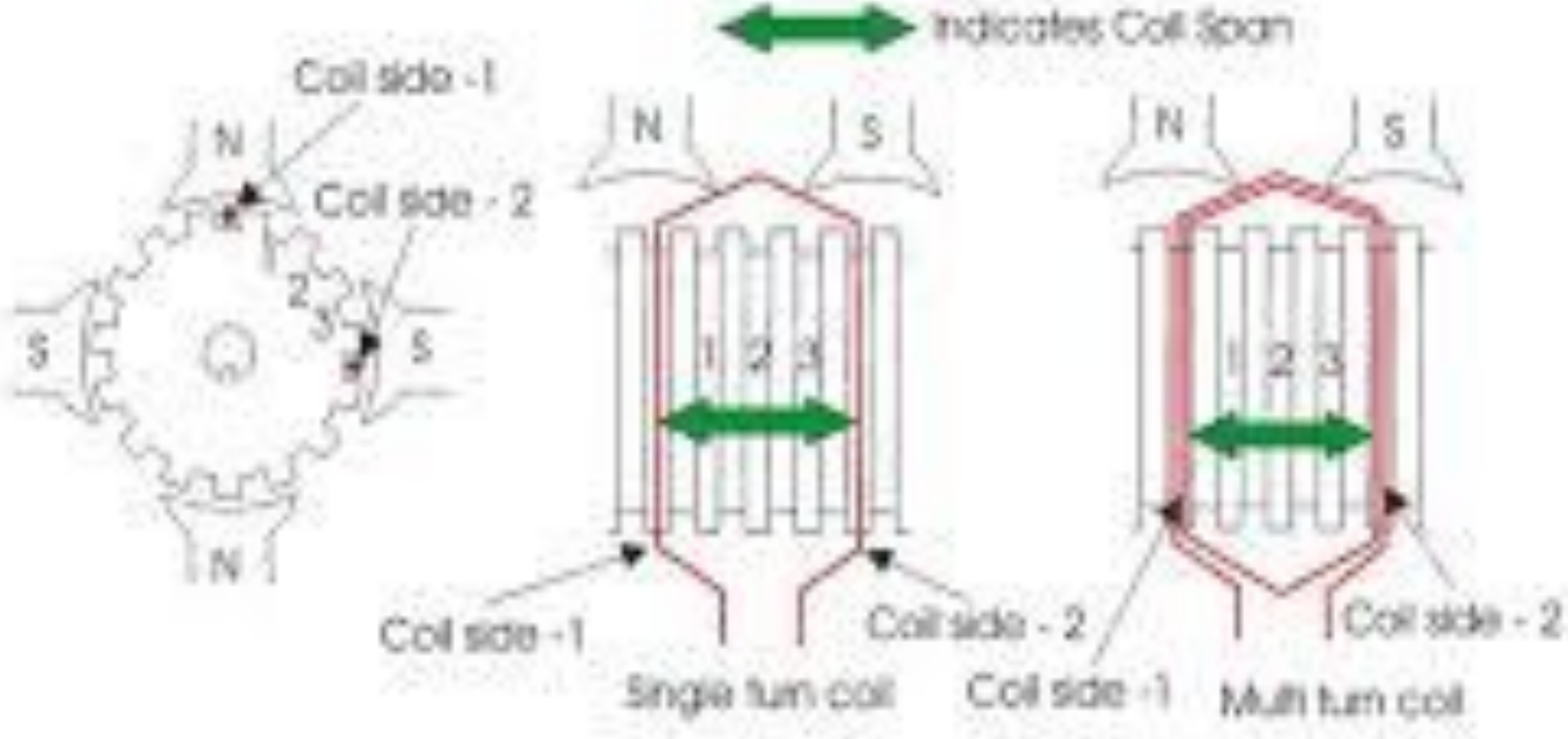
- A stator winding using fractional pitch coil is called a chorded winding. If the span of the coil is reduced by an angle α electrical degrees, the coil span will be (180 – α) electrical degrees.
- In case of a full pitch coil, the distance between the two sides of the coil is exactly equal to the pole pitch of 180^{o} electrical. As a result, the voltage in a full pitch coil is such that the voltage of each side of the coil is in phase.

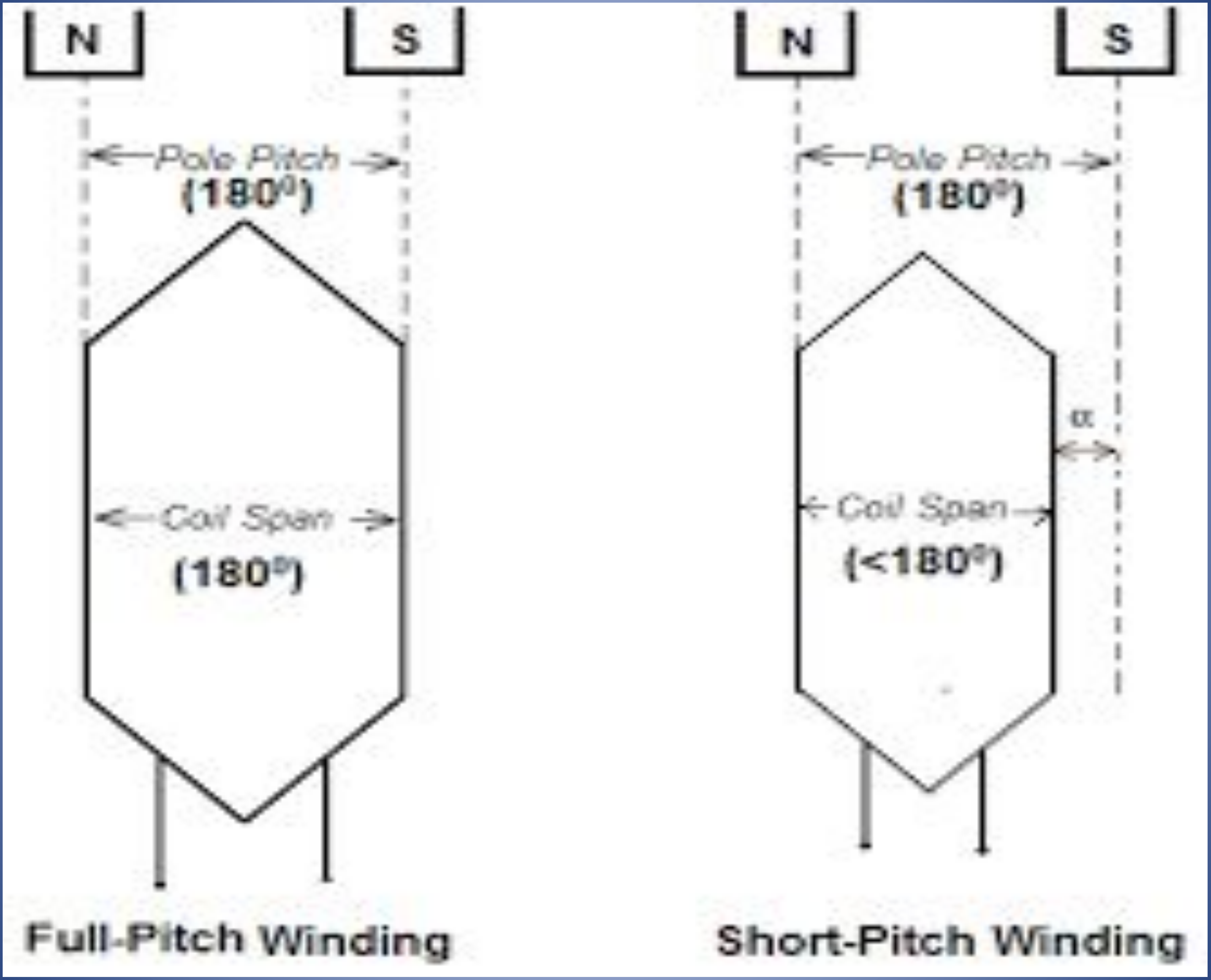


typical stator coil
ρ = coil pitch:
165° elec.
coil side
in slot
180°
elec.
pole
piece
N
S
rotor
stator
γ
γ = slot pitch:
15° elec. = 360° / 24 slots

Coil span or Coil pitch (YS)

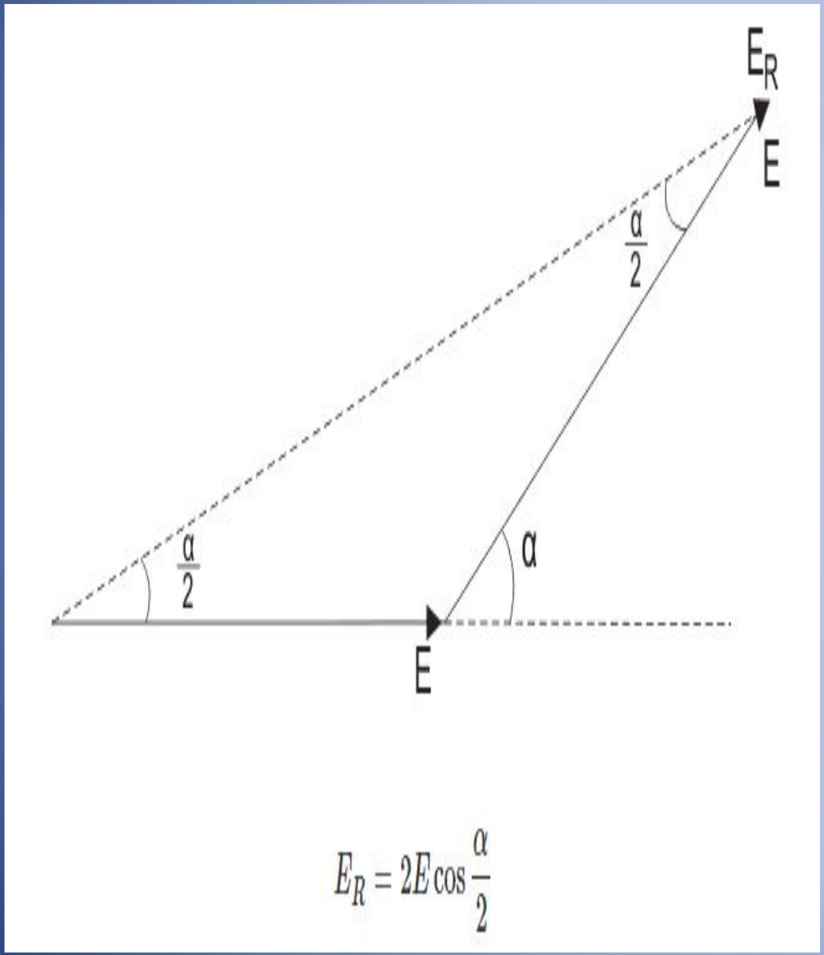
- Coil span is the distance between 2 sides of the coil.




N
S
Pole Pitch
(180⁰)
Coil Span
(180⁰)
Full-Pitch Winding
N
S
Pole Pitch
(180⁰)
α
Coil Span
(<180⁰)
Short-Pitch Winding

- Let us assume that, a coil is short pitched by an angle α (electrical degree). Emf induced per coil side is E. The arithmetic sum of induced emfs is 2E. That means, 2E, is the induced voltage across the coil terminals, if the coil would have been full pitched.
  Now, come to the short pitched coil. From the figure below it is clear that, resultant emf of the short pitched coil

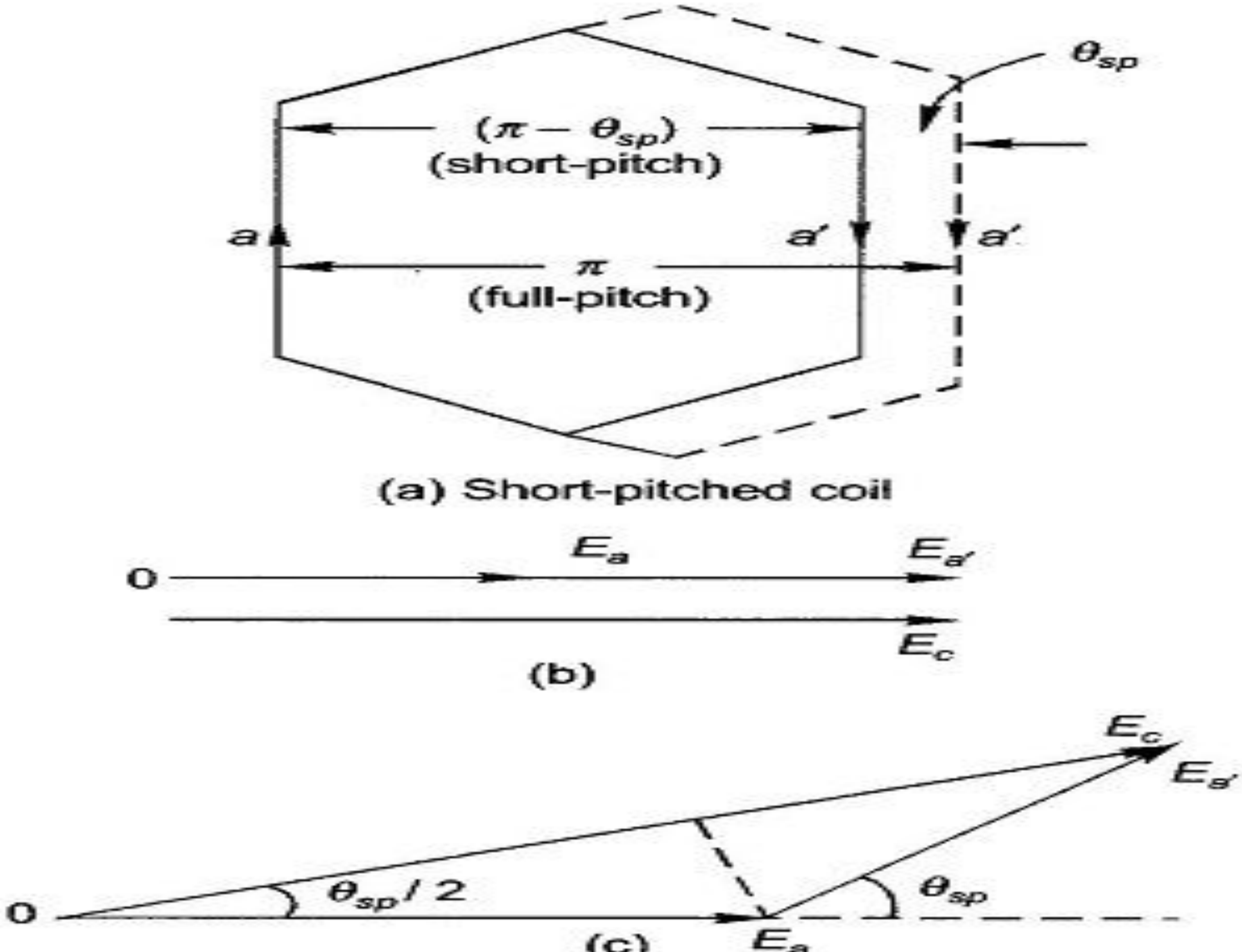
Now, as per definition of pitched factor,



$$K_p = \frac{\text{Resultant emf of short pitched coil}}{\text{Resultant emf of full pitched coil}}$$

$$= \frac{\text{Phasor sum of coil side emfs}}{\text{Arithmetic sum of coil side emfs}}$$

$$= \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$



θ_{sp}
$(\pi - \theta_{sp})$
(short-pitch)
a
a′
a′
π
(full-pitch)
(a) Short-pitched coil
E_a
$E_{a'}$
0
E_c
(b)
E_c
$E_{a'}$
$\theta_{sp}/2$
θ_{sp}
0
(c)
E_a

Fig. 5.20

Distributed factor

- If all the coil sides of any one phase under one pole are bunched in one slot, the winding obtained is known as concentrated winding and the total emf induced is equal to the arithmetic sum of the emfs induced in all the coils of one phase under one pole.
- But in practical cases, for obtaining smooth sinusoidal voltage waveform, armature winding of alternator is not concentrated but distributed among the different slots to form polar groups under each pole.

- As per definition, distribution factor is a measure of resultant emf of a distributed winding in compared to a concentrated winding.
- We express it as the ratio of the phasor sum of the emfs induced in all the coils distributed in some slots under one pole to the arithmetic sum of the emfs induced.

- Distribution factor is,

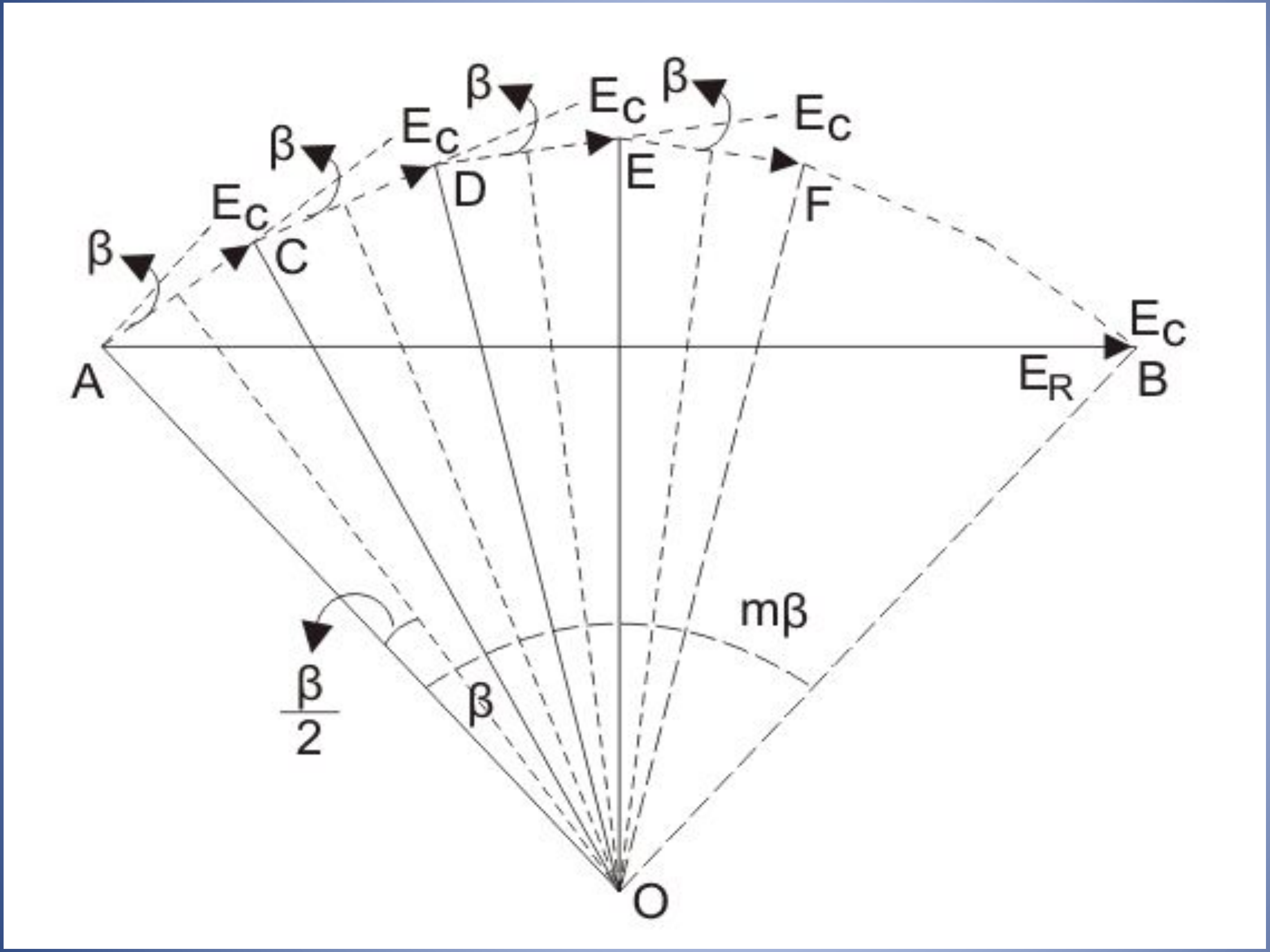
$$k_d = \frac{EMF\ induced\ in\ distributed\ winding}{EMF\ induced\ if\ the\ winding\ would\ have\ been\ concentrated}$$

$$= \frac{Phasor\ sum\ of\ component\ emfs}{Arithmetic\ sum\ of\ component\ emfs}$$

- Let the number of slots per pole is n.
  The number of slots per pole per phase is m.
  Induced emf per coil side is E_c.
  Angular displacement between the slots, $\beta = \frac{180^o}{n}$

- Let us represent the emfs induced in different coils of one phase under one pole as AC, DC, DE, EF and so on. They are equal in magnitude, but they differ from each other by an angle β.
  If we draw bisectors on AC, CD, DE, EF ——–. They would meet at common point O.
  Emf induced in each coil side,

$$E = AC = 2 \cdot OAsin\frac{\beta}{2}$$



β
E c
β
E c
β
E c
β
E c
β
E c
E
D
C
F
A
E R
B
mβ
β
β/2
O

As the slot per pole per phase is m, the total arithmetic sum of all induced emfs per coil sides per pole per phase,

$$Arithmetic\ sum\ =\ m \times 2 \times OAsin\frac{\beta}{2}$$

The resultant emf would be AB, as represented by the figure,

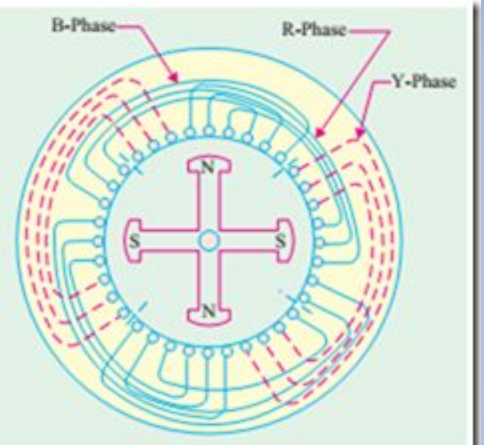
Hence, the resultant emf

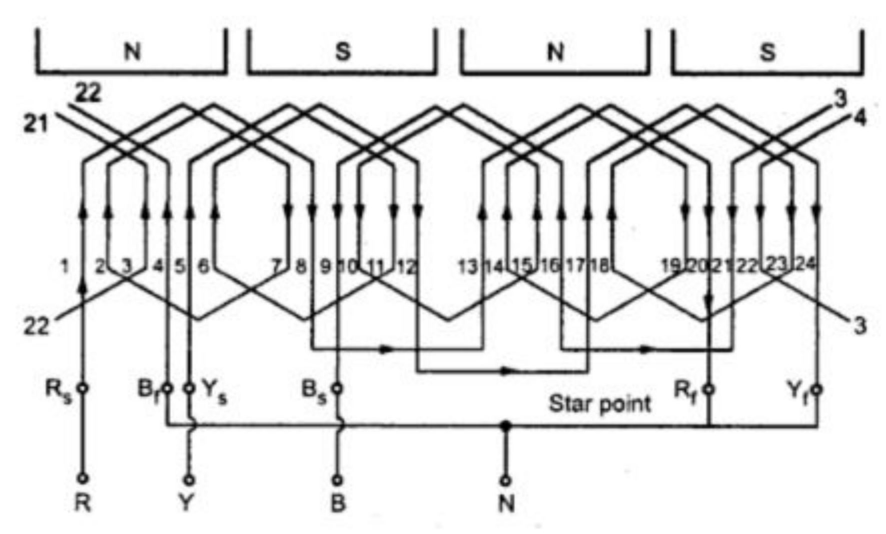
$$E_R = AB = 2 \times OA\sin\frac{\angle AOB}{2} = 2 \times OA\sin\frac{m\beta}{2}$$

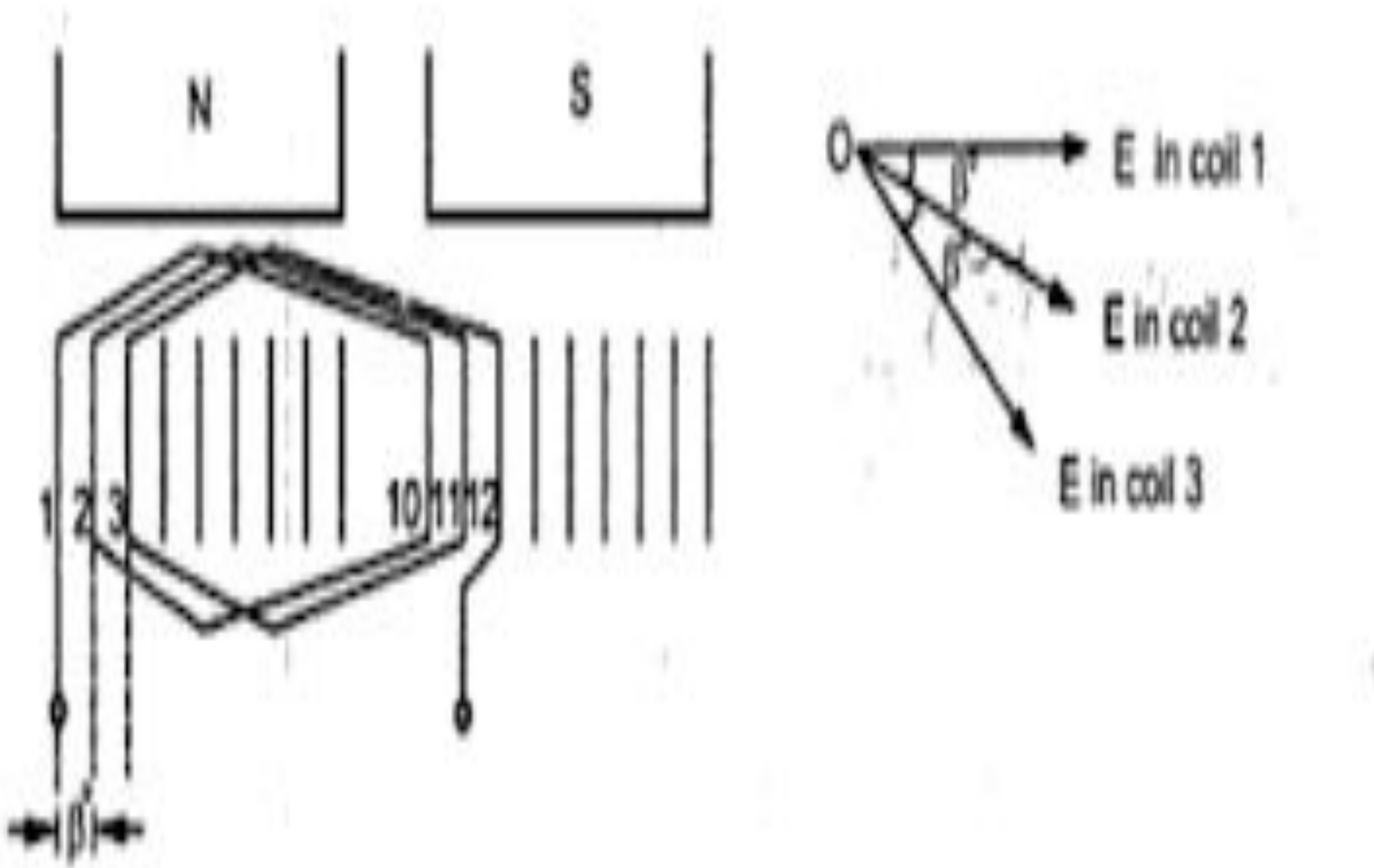
$$Therefore,\ Distribution\ Factor$$

$$K_d = \frac{Phasor\ sum\ of\ component\ emfs}{Arithmetic\ sum\ of\ component\ emfs}$$

$$= \frac{2 \times OA\sin\frac{m\beta}{2}}{m \times 2 \times OA\sin\frac{\beta}{2}} = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$


B-Phase
R-Phase
Y-Phase
N
S
S
N
Fig. 37.19


N
S
N
S
21
22
3
4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
22
3
R_s
B_f
Y_s
B_s
Star point
R_f
Y_f
R
Y
B
N



(a) Distributed winding (b) Phase difference between induced e.m.f.

EXAMPLE 3.2. *A 3-phase, 50 Hz, 8-pole alternator has a star-connected winding with 120 slots and 8 conductors per slot. The flux per pole is 0.05 Wb, sinusoidally distributed. Determine the phase and line voltages.*

SOLUTION. Let us take the full-pitch coil.

$\therefore\ \alpha = 0^\circ,\ k_c = \cos \alpha/2 = \cos 0^\circ = 1$

$$m = \frac{\text{slots}}{\text{poles} \times \text{phases}} = \frac{120}{8 \times 3} = 5$$

$$\beta = \frac{180^\circ \times \text{poles}}{\text{slots}} = \frac{180^\circ \times 8}{120} = 12^\circ$$

$$k_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{5 \times 12^\circ}{2}}{5 \sin \frac{12^\circ}{2}} = 0.9567$$

Total number of conductors

$$= \text{conductor per slot} \times \text{number of slots}$$

$$= 8 \times 120 = 960$$

Conductors per phase, $Z_p = \frac{960}{3} = 320$

Generated voltage per phase

$$E_p = 2.22\, k_c k_d f \Phi Z_p$$

$$= 2.22 \times 1 \times 0.9567 \times 50 \times 0.05 \times 320 = 1699 \text{ V}$$

Generated line voltage $\quad E_L = \sqrt{3} E_p = \sqrt{3} \times 1699 = 2942.8 \text{ V}$

EXAMPLE 3.6. *A 4-pole, 3-phase, 50 Hz, star-connected alternator has 60 slots, with 2 conductors per slot and having armature winding of the two-layer type. Coils are short-pitched in such a way that if one coil side lies in slot number 1, the other lies in slot number 13. Determine the useful flux per pole required to generate a line voltage of 6000 V.*

SOLUTION. Slot angle $\beta = \dfrac{180^\circ \times \text{poles}}{\text{slots}} = \dfrac{180 \times 4}{60} = 12^\circ$

Coil span $= 12\,\beta = 12 \times 12 = 144^\circ$

$$\alpha = 180^\circ - 144^\circ = 36^\circ$$

$$k_c = \cos\frac{\alpha}{2} = \cos\frac{36^\circ}{2} = 0.951$$

$$m = \frac{\text{slots}}{\text{poles} \times \text{phase}} = \frac{60}{4 \times 3} = 5$$

$$k_d = \frac{\sin\dfrac{m\beta}{2}}{m\sin\dfrac{\beta}{2}} = \frac{\sin\dfrac{5 \times 12^\circ}{2}}{5\sin\dfrac{12^\circ}{2}} = 0.9567$$

$$Z_p = \frac{60 \times 2}{3} = 40$$

$$E_p = 2.22\,k_c k_d f \Phi Z_p$$

$$\frac{6000}{\sqrt{3}} = 2.22 \times 0.951 \times 0.9567 \times 50 \times \Phi \times 40$$

$$\Phi = 0.8576 \text{ Wb}$$

Synchronous Generator Rating

- The purpose of ratings is to protect the machine from damage.
- Typical ratings of synchronous machines are voltage, speed, apparent power (kVA), power factor, field current and service factor
- . – The rated frequency of a synchronous machine depends on the power system to which it is connected. Once the operation frequency is determined, only one rotational speed in possible for the given number of poles.
- – For a given design, the rated voltage is limited by the flux that is capped by the field current. The rated voltage is also limited by the windings insulation breakdown limit.
- –

- The maximum acceptable armature current sets the apparent power rating for a generator. The power factor of the armature current is irrelevant for heating the armature windings.
- Allowable heating sets the maximum field current, which determines the maximum acceptable armature voltage EA . – These translate to restrictions on the lowest acceptable power factor: • For some angles the required EA exceeds its maximum value. • The angle of IA that requires maximum possible EA specifies the rated power factor of the generator.

Rating of Alternator

- **Why Alternator / Generator Rated in kVA. Not in kW**

As we already know that why transformer rated in kVA inst ead of kW, same reason here i.e. the power **$\sqrt{3}$ V_L I_L Cos θ** delivered by the alternator and generator for the same value of current, depends upon p.f. (**Power Factor = Cos θ**) of the load.

- But the alternator conductors are calculated for a definite current and the insulation at magnetic system are designed for a definite voltage independent of p.f. (Cos θ) of the load. *For this reason apparent power measured in kVA is regarded as the rated power of the alternator.*

Alternator at NO LOAD

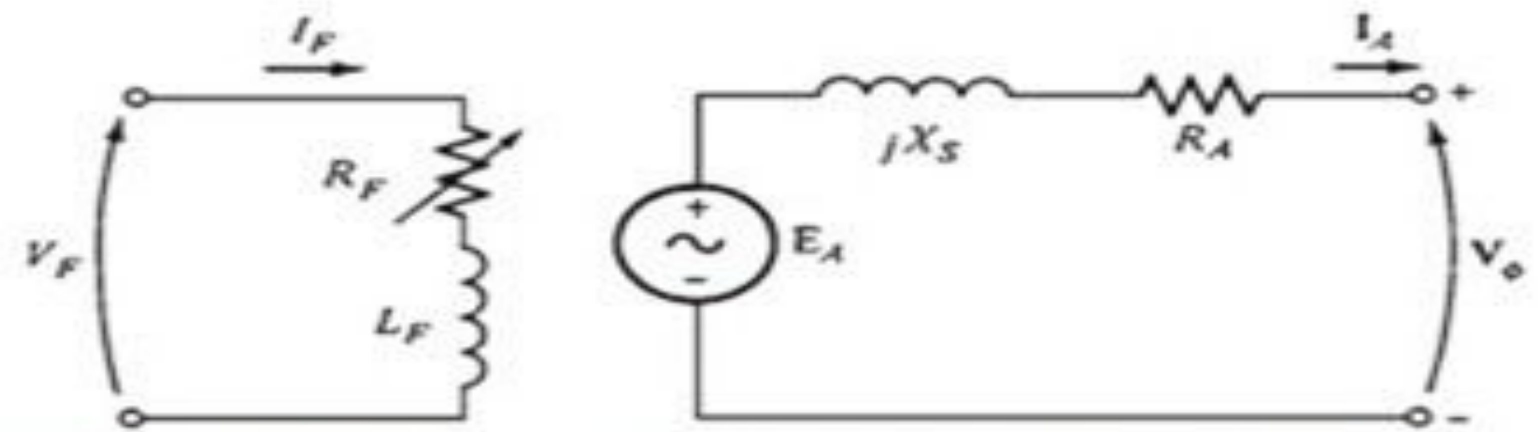


FIGURE 12.12 The per-phase equivalent circuit of a synchronous generator. The internal field circuit resistance and the external variable resistance have been combined into a single resistor R_F.

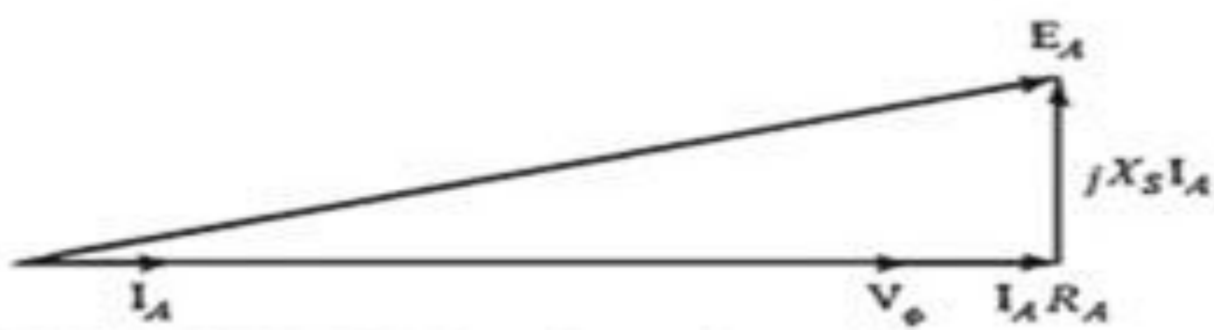
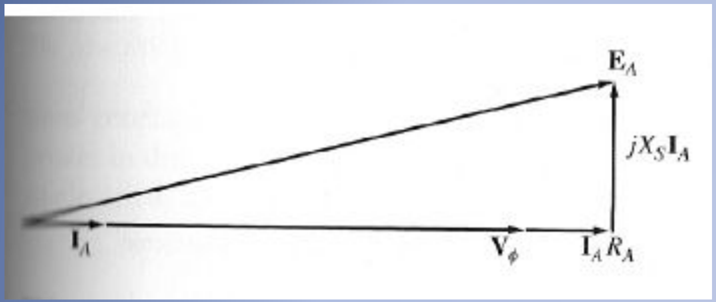


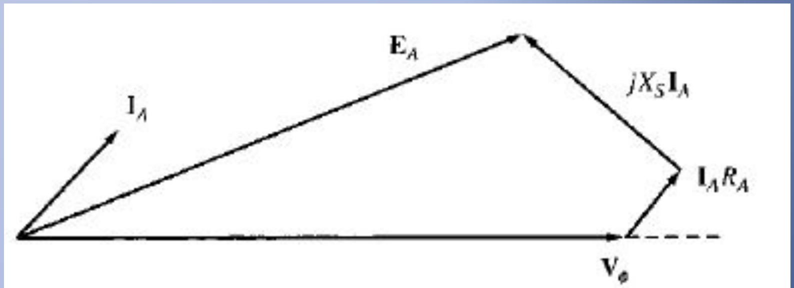
FIGURE 12.13 The phasor diagram of a synchronous generator at unity power factor.

Phasor diagram

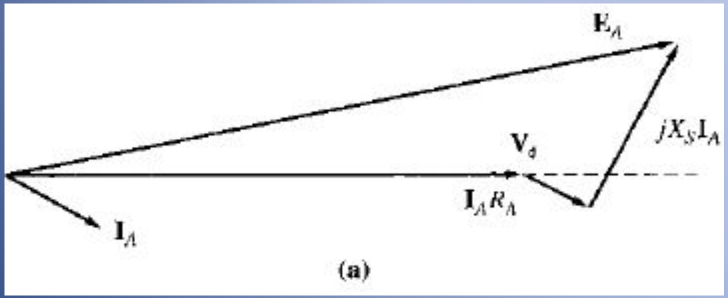
- At unity PF



- At leading PF



- At lagging PF



Alternator on LOAD

- Whenever the load on the alternator is varied, the terminal voltage will also vary.
- This variation in terminal voltage is mainly due to three reasons:
- Voltage drop due to armature resistance IR_a,
- Voltage drop due to armature leakage reactance IX_L
- Voltage drop due to armature reaction.

Voltage drop due to armature resistance

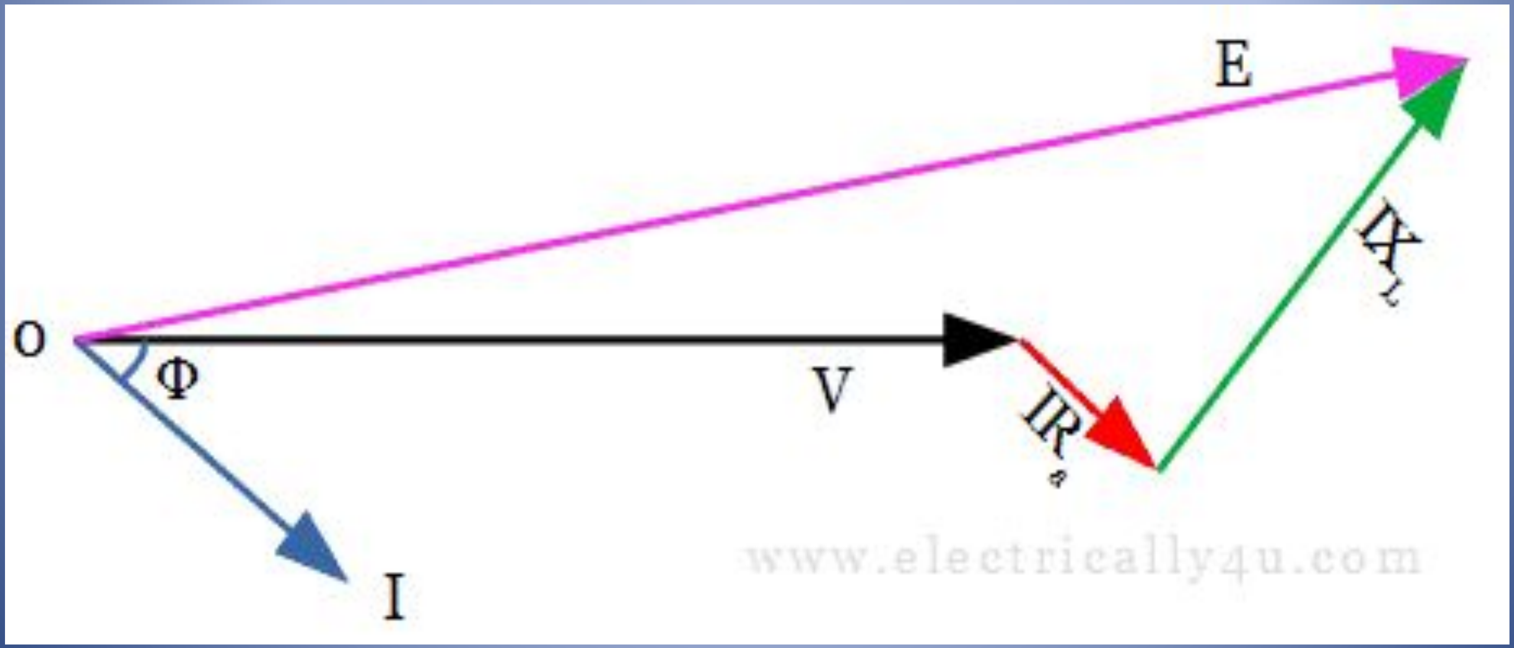
- The armature winding resistance per phase will cause a IR_a voltage drop per phase.
- The voltage drop due to armature resistance is in phase with the armature current I. Practically, this voltage drop is negligible.

Voltage drop due to armature leakage reactance

- When current flows through armature conductors, the flux will start to flow through the armature core.
- Some flux will take different paths and do not cross the air gap and are called leakage flux.
- Thus, the armature winding is said to possess a leakage reactance X_L.
- The voltage drop due to this reactance is IX_L. The generated emf has to overcome the voltage drop due to leakage reactance to give its output.

Leakage reactance drop

- $E = V + I\,(R_a + jX_L)$
- This is illustrated in the below phasor diagram.



Voltage drop due to armature reaction

- Armature reaction is the effect of armature flux on the main field flux.
- Armature reaction is an important aspect in AC synchronous Generator or Alternator.
- Armature reaction is defined as the effect of armature flux on the main flux produced by the field poles.

ARMATURE REACTION

- When the load is applied to the alternator, current starts flowing through the armature conductors.
- Since the current is alternating in nature, it induces a flux in the conductor, called as armature flux.
- The armature flux thus produced will react with the main field flux and distort the effect of main flux.
- Due to this distortion, the main flux will either strengthen or weaken.

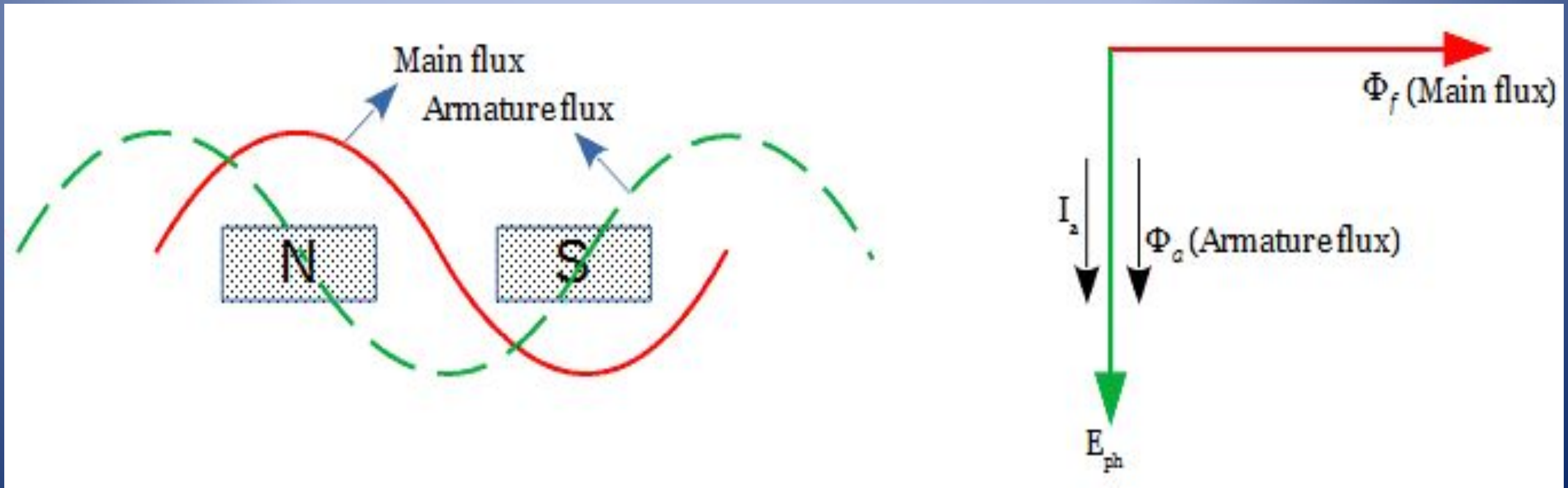
- The distortion may depend on the type of load applied to the alternator.
- There are three types of distorting effects.
- Cross magnetizing effect
- Demagnetizing effect
- Magnetizing effect.

EFFECT OF LOAD ON ARMATURE REACTION

- When an alternator supplies a load at unity power factor, the effect of armature reaction is partly cross magnetizing and partly distorting.
- The effect of armature reaction is demagnetizing, when an alternator supplies a load at lagging power factor.
- When an alternator supplies a load at leading power factor, the effect of armature reaction is magnetizing.

Armature reaction at unity power factor load

- When a resistive load with unity power factor is connected to the alternator, the load current will starts to flow through the armature conductors. As the load is resistive, the armature current will be in phase with the induced voltage.

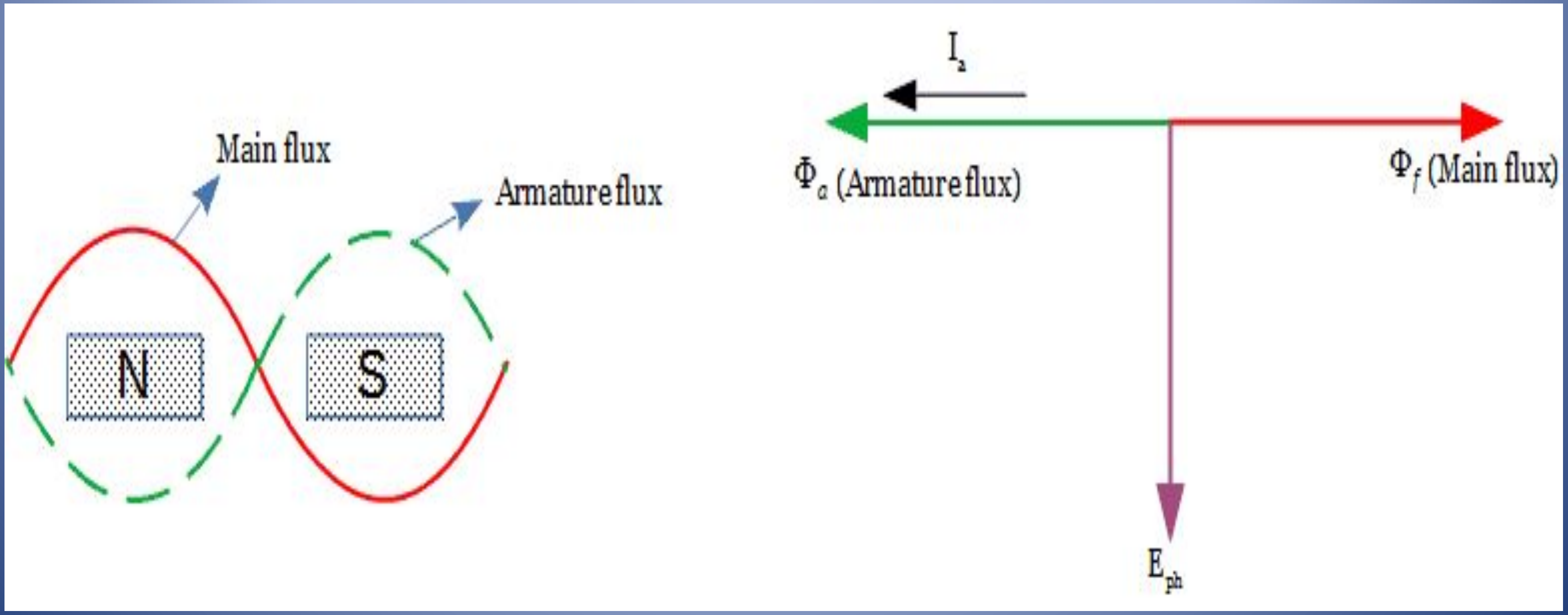


- The armature current will produce its own flux in the conductor, which will also be in phase with the induced voltage. Since the induced emf lags behind the main flux by 90^0, the armature flux produced will also be delayed by 90^0 with respect to the main flux. It is shown in the above phasor diagram.

Armature reaction at zero power factor lagging load

- When an inductive load with zero lagging power factor is connected to alternator, the load current starts to flow through the armature conductors.
- The load current will be delayed by 90^0 and so the armature flux produced will also be shifted by 90^0 with respect to the poles.

- There will be a phase difference of 90^0 between the armature flux and main field flux. It can be seen that, the armature flux will be in direct opposition to the main flux.

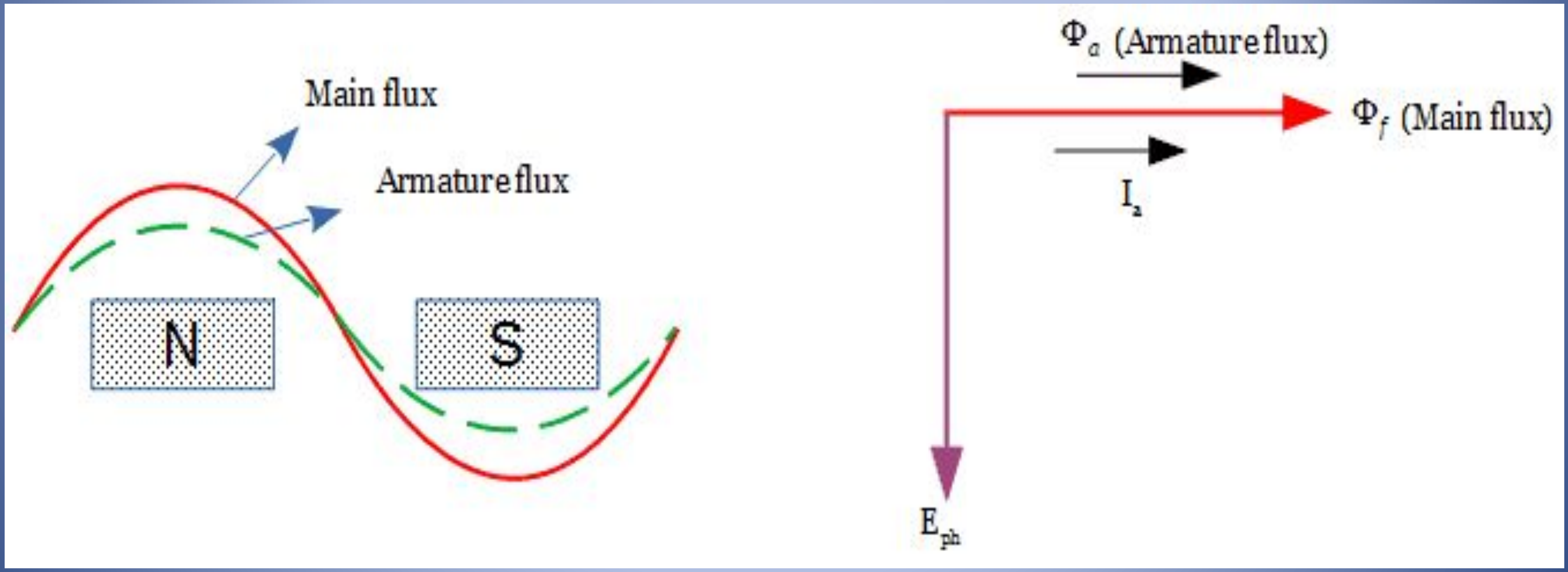


- Thus the main flux gets decreased in this loading condition. This effect of armature reaction on this load is said to be demagnetizing effect.
- Due to this, the main flux gets weaken and so the emf induced will be reduced.

Armature reaction at zero power factor leading load

- When a capacitive load with zero leading power factor is connected, the load current starts to flow through the armature conductors.
- In this load condition, the load current will be advanced by 90^0 and so the flux produced will also be advanced by 90^0 with respect to emf induced. So the armature flux will be in phase with the main field flux, resulting in strengthening of the field flux. Thus the main flux gets increased in this loading condition.

- The armature reaction in this load is said to be magnetizing effect.



- The voltage drop due to armature reaction may be assumed as there is a presence of fictitious reactance Xa called armature reactance reaction.

- The voltage drop due to armature reactance reaction is represented as IXa.

- **The leakage reactance X_L and armature reaction reactance Xa together called as synchronous reactance X_s.**

-

- Thus the voltage drop in an alternator under loaded conditions is the total sum of voltage drop due to armature resistance, armature leakage reactance, and armature reaction reactance.
- $V = I R_a + j I X_L + j I X_a = I (R_a + j X_L + j X_a)$
  $= I (R_a + j (X_L + X_a))$
- $V = I (R_a + j X_S) = I Z_S$
- Where Z_S is known as **synchronous impedance** of an alternator.

- it is clear that the variation in load causes the terminal voltage of the alternator to change. It is due to the synchronous impedance of the alternator.
- The impedances are given by

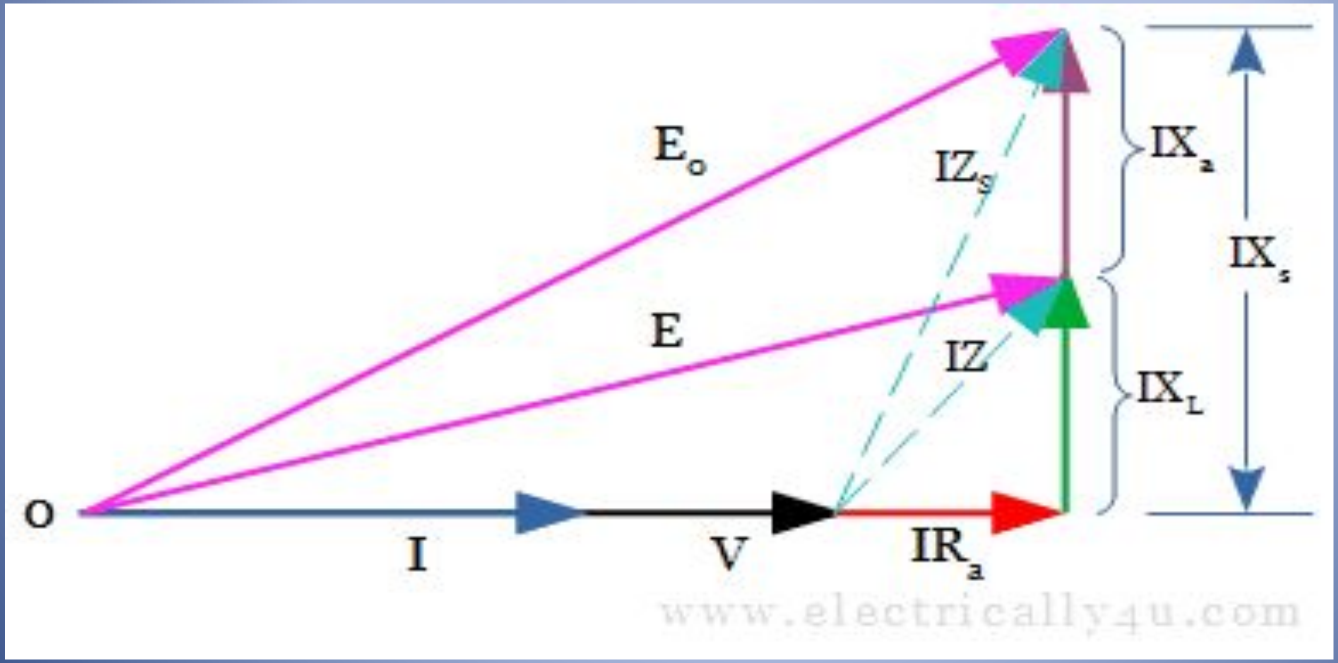
$$Z = R_a + jX_L = \sqrt{(R_a^2 + X_L^2)}$$

$$Z_S = R_a + jX_S = \sqrt{(R_a^2 + X_S^2)}$$

- where X_L is the leakage reactance, X_a is the armature reaction reactance and X_s is the synchronous reactance and Z_s is the synchronous impedance.

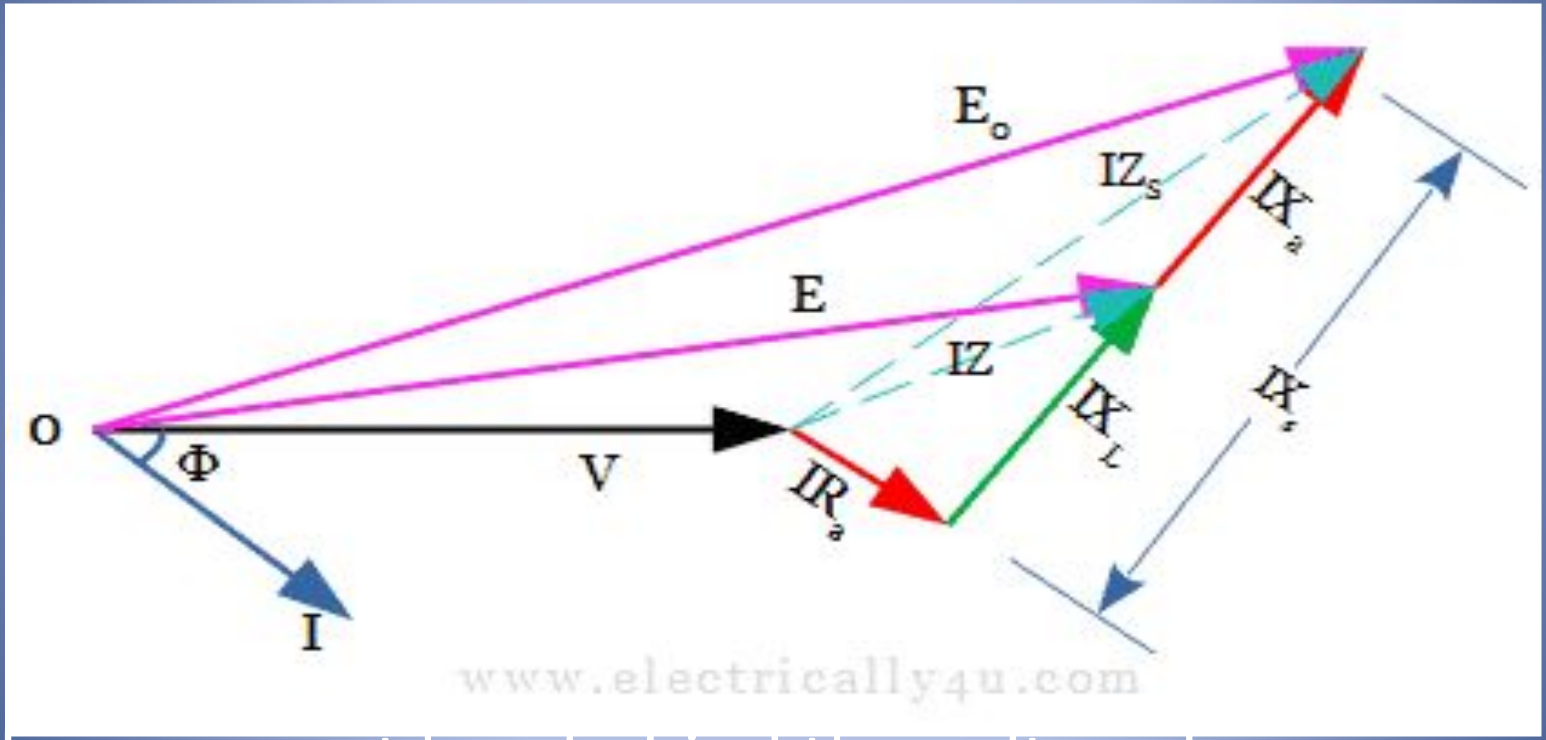
Unity power factor load

- The phasor diagram of an alternator for unity power factor load is shown below.



Lagging power factor load

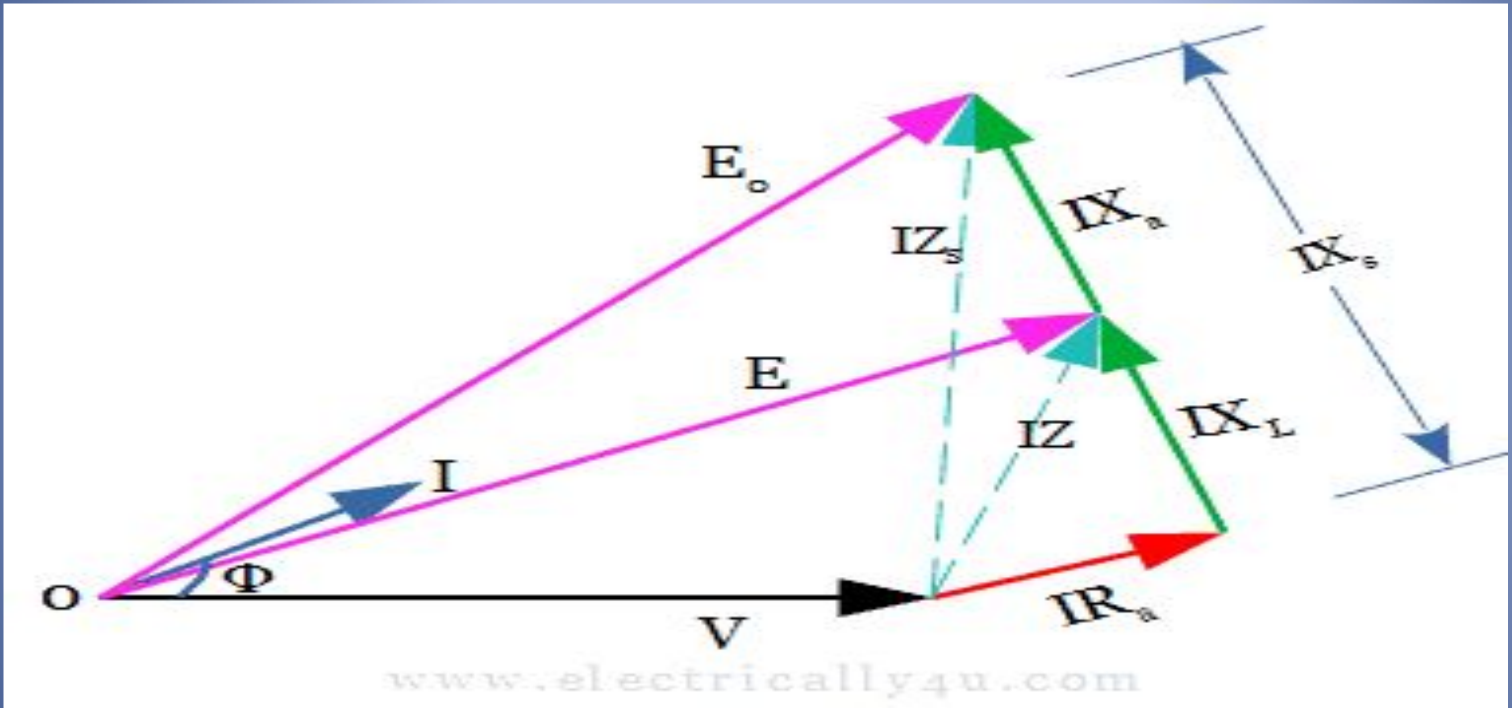
- The phasor diagram of an alternator for lagging power factor load is shown below.



- here current lags behind the voltage by an angle *Φ*. So draw the current phasor at an angle *Φ* with respect to voltage phasor V.

Leading power factor load

- The phasor diagram of an alternator for leading power factor load is shown below.



- here current leads the voltage by an angle Φ. So the current phasor is drawn at an angle *Φ* with respect to voltage phasor V.

O.C. and S.C. Test on alternator

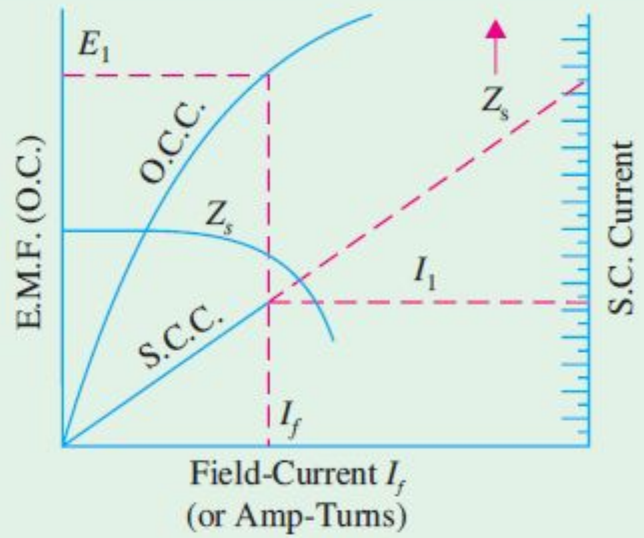


Fig. 37.33 (a)

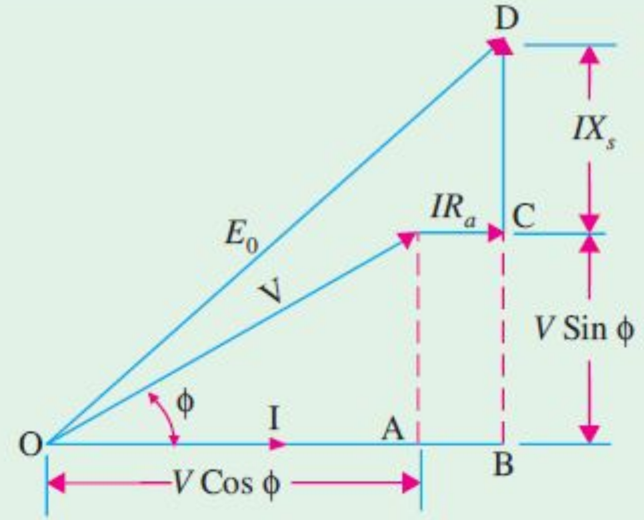
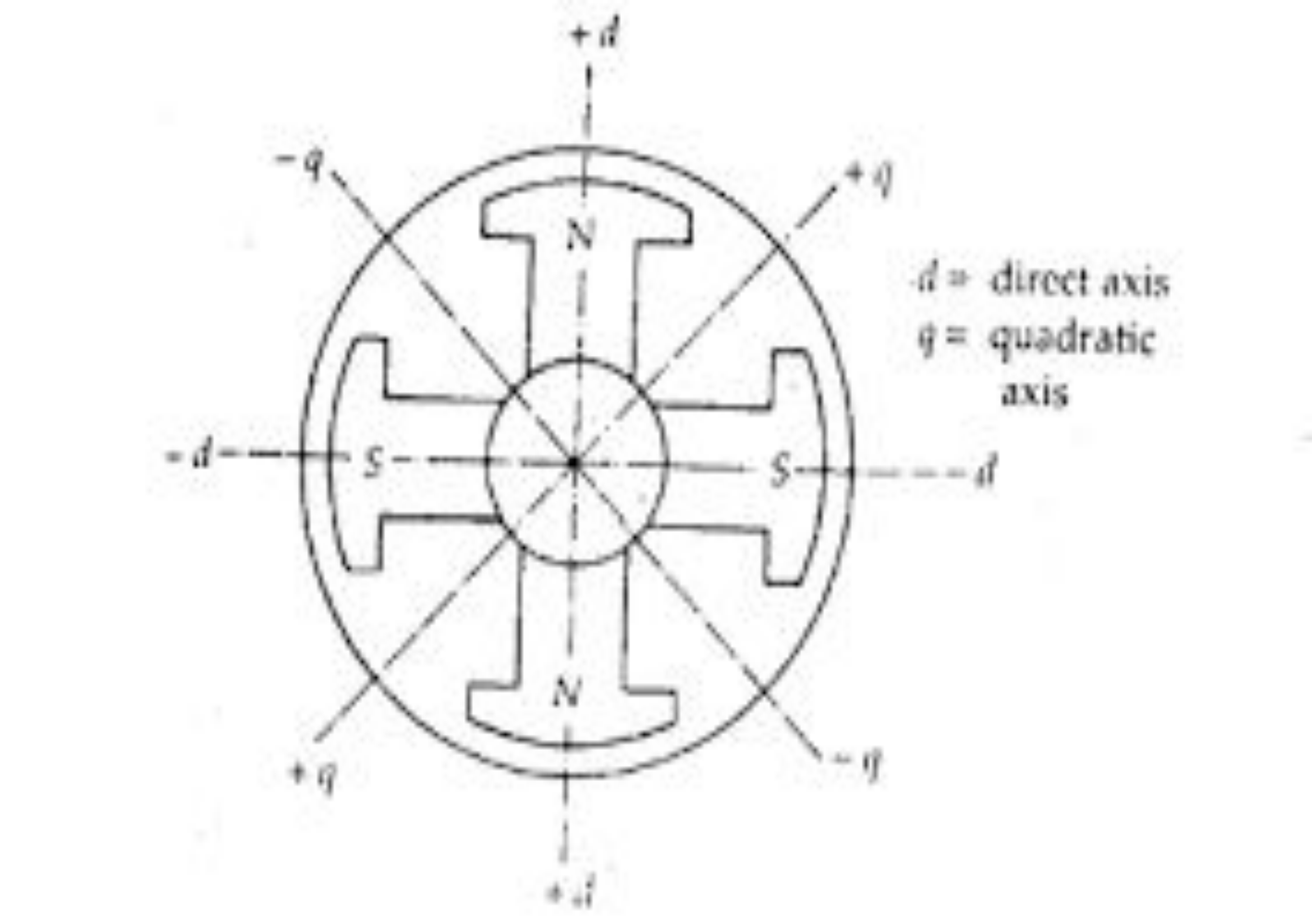


Fig. 37.33 (b)

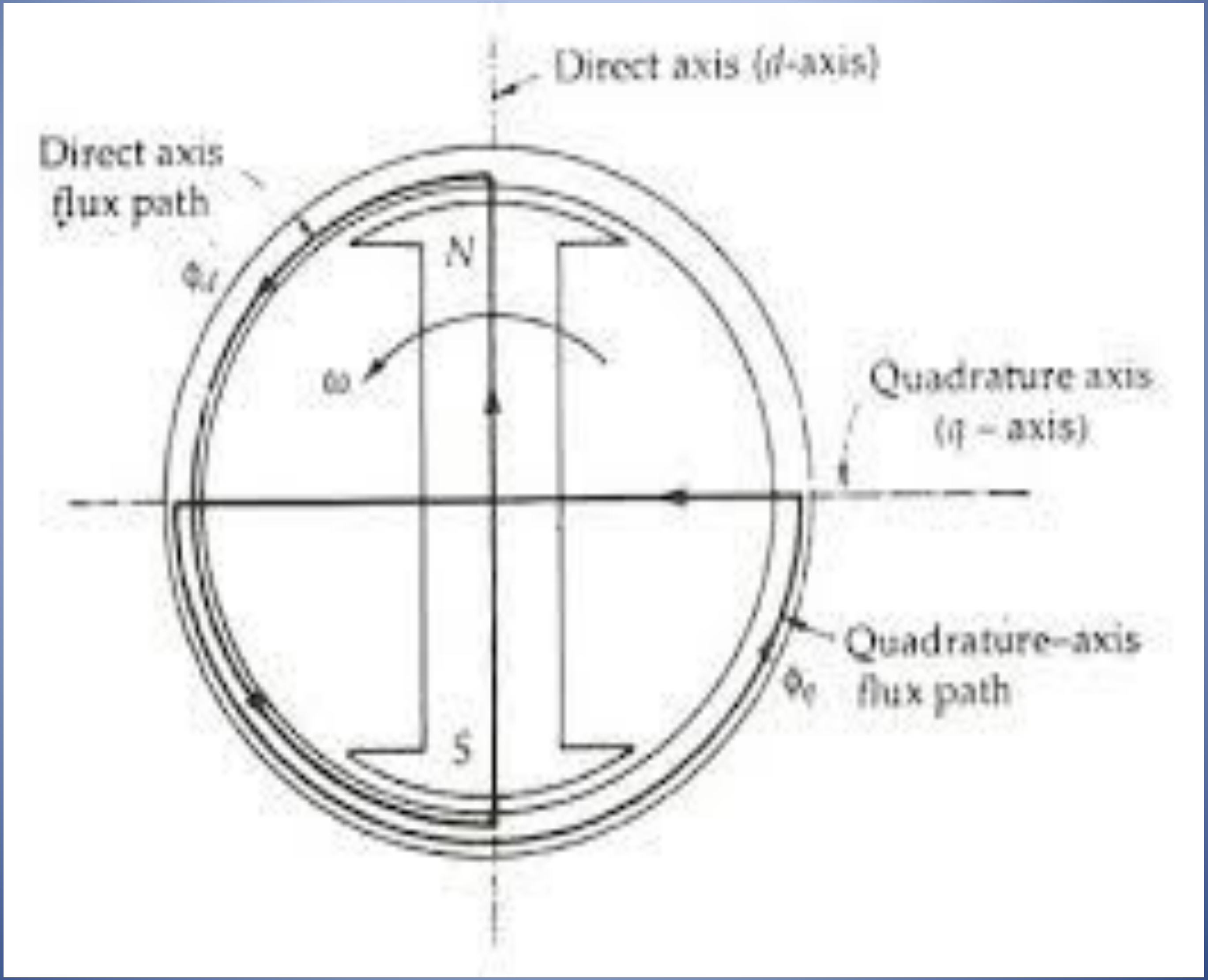
Here $\quad OD = E_0 \quad \therefore E_0 = \sqrt{(OB^2 + BD^2)}$

or $\quad E_0 = \sqrt{[(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]}$

Salient pole synchronous machines



Two reaction theory for Salient pole rotor



Two Reaction Theory was proposed by Andre Blondel.

- The theory proposes to resolve the given armature MMFs into two mutually perpendicular components, with one located along the axis of the rotor of the salient pole. It is known as the direct axis or d axis component. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature axis or q axis component.

- Armature MMF resolve into two components
  - Fd and Fq
  - Fd –magnetizing
  - Fq- cross magnetizing

Due to mmf , flux start circulating in the airgap

Two component of flux - Φ d and Φ q

Φ d-involve two small air gaps & hence path of minimum reluctance

Φ q- involve two large air gaps & hence path of maximum reluctance

Emf equation for salient pole sync m/c

- Rotor flux induces voltage Ef in stator
- If lagging load connected to generator armature current Ia will flow
- Ia lags Ef by angle ψ
- Ia produces Fs MMF
- Fs having Two component Fd and Fq
- Φ_d, Φ_q are the two components of flux
- These fluxes induces two voltages in the stator
- i.e. Ead and Eaq

EMF EQUATION CONTINUE ….

$E_{ad} = -Jx_{ad} * I_d$

$E_{aq} = -Jx_{aq} * I_q$

Total voltage induced in the stator is

$E' = E_f + E_{ad} + E_{aq}$

$E' = E_f - Jx_{ad} * I_d - Jx_{aq} * I_q$ ……….(1)

$E_f = E' + Jx_{ad} * I_d + Jx_{aq} * I_q$

$E' = V_t + I_a R_a + jX_l * I_a$ ……………..(2)

EMF EQUATION CONTINUE ....

Adding eq 1 and 2

Ef = V + IaRa + jXl Ia + jXad *Id + jXaq *Iq

by solving this equation

We get

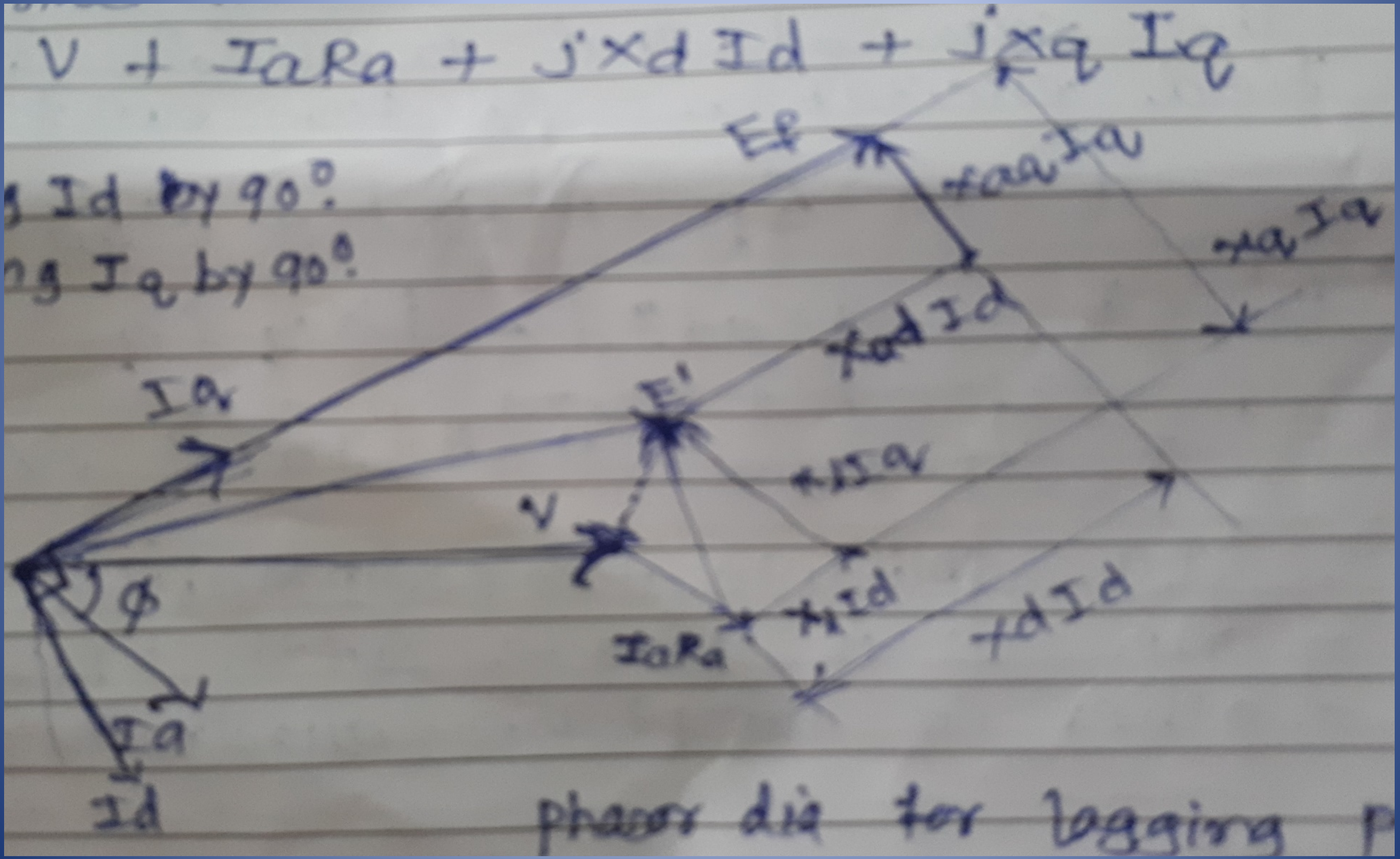
Ef = V + IaRa + jXd *Id + Xq*Iq .....(3)

where Xd= Xl+ Xad

Xq = Xl+Xaq

Eq no 3 is final EMF eqution for Salient pole Synchronous M/C .

Phasor diagram for Salient pole Synchronous M/C



Phasor diagram for Salient pole Synchronous M/C

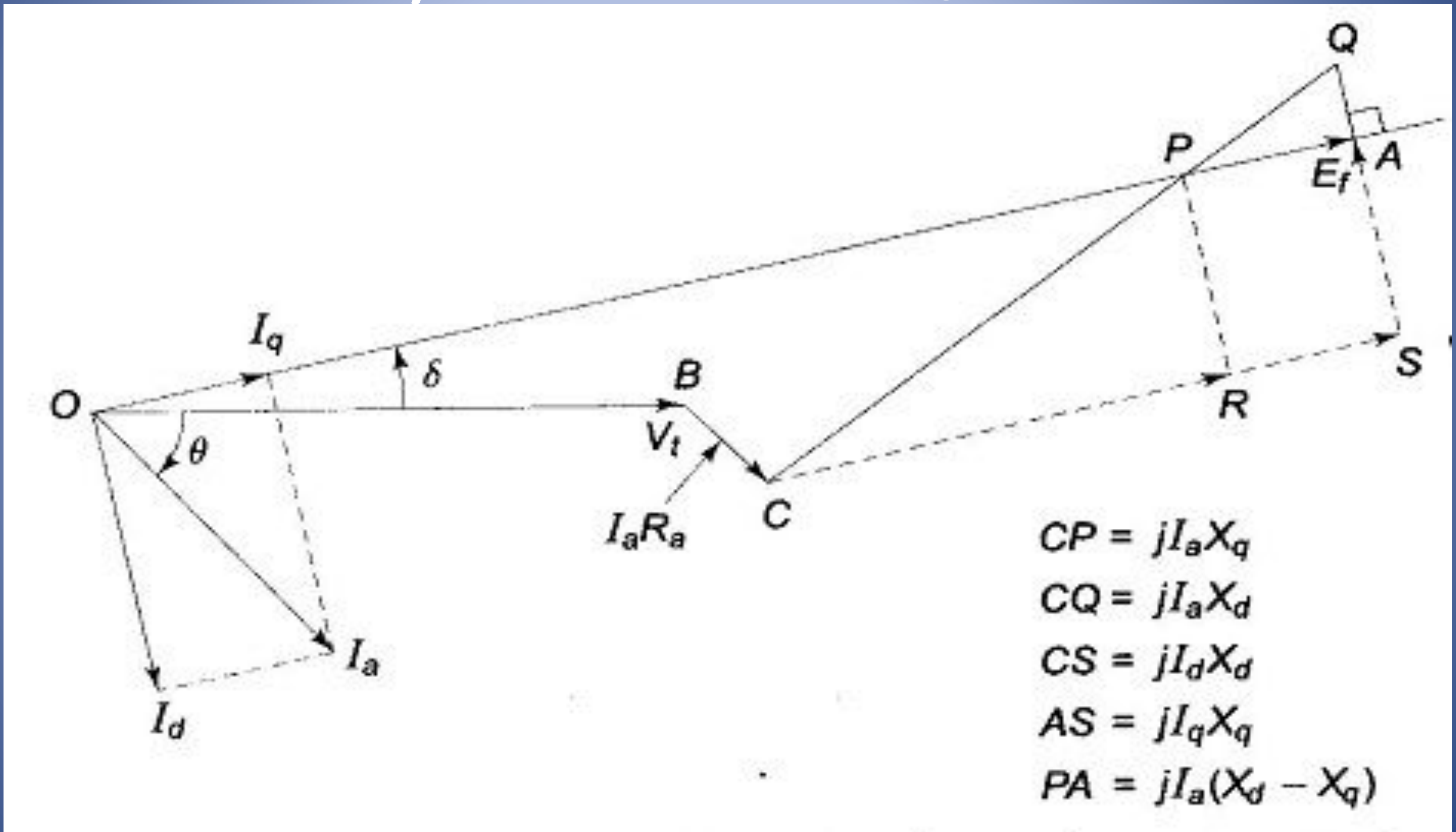
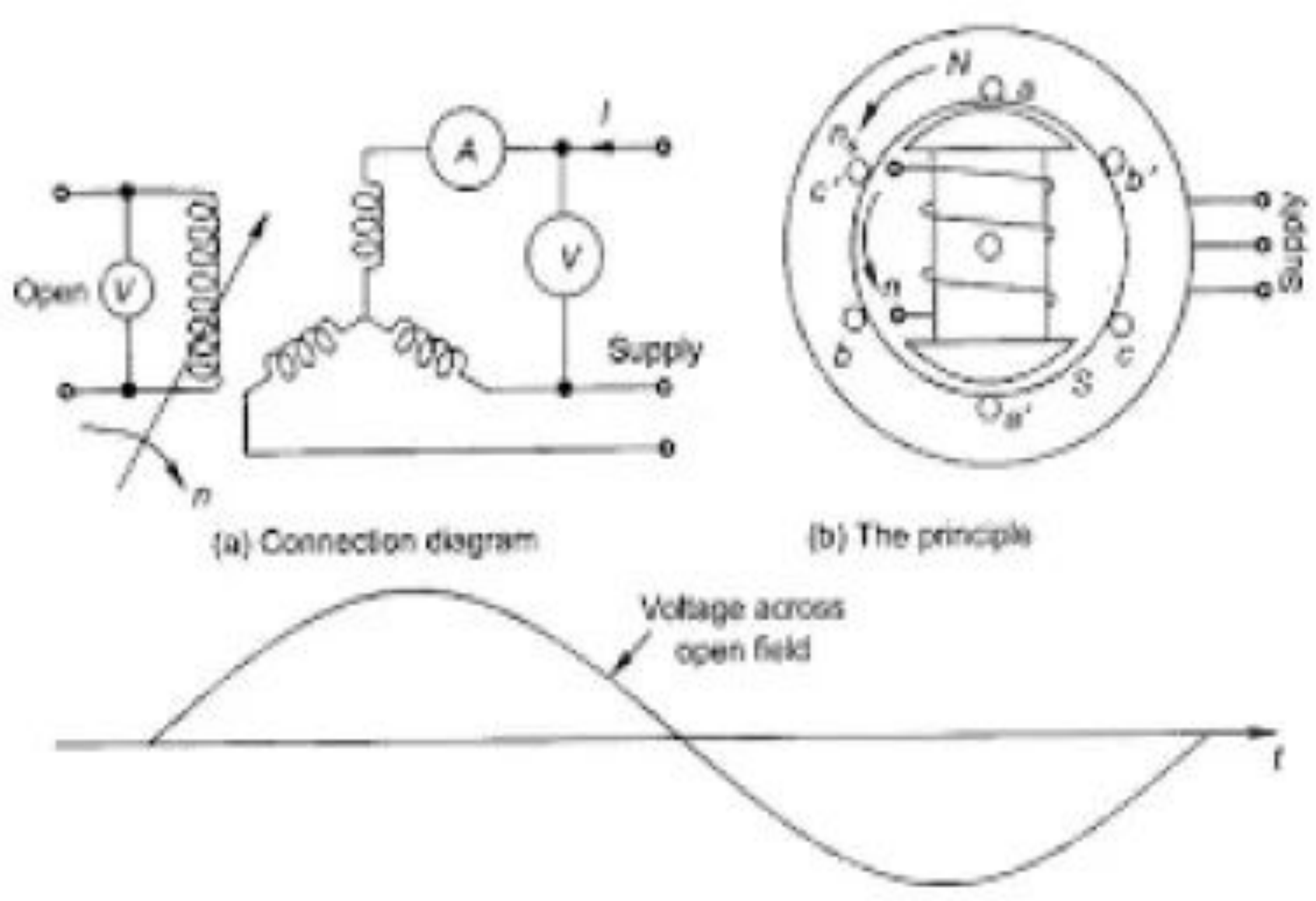


Fig. 4.30 Phasor diagram of salient pole synchronous generator

Slip test on Alternator

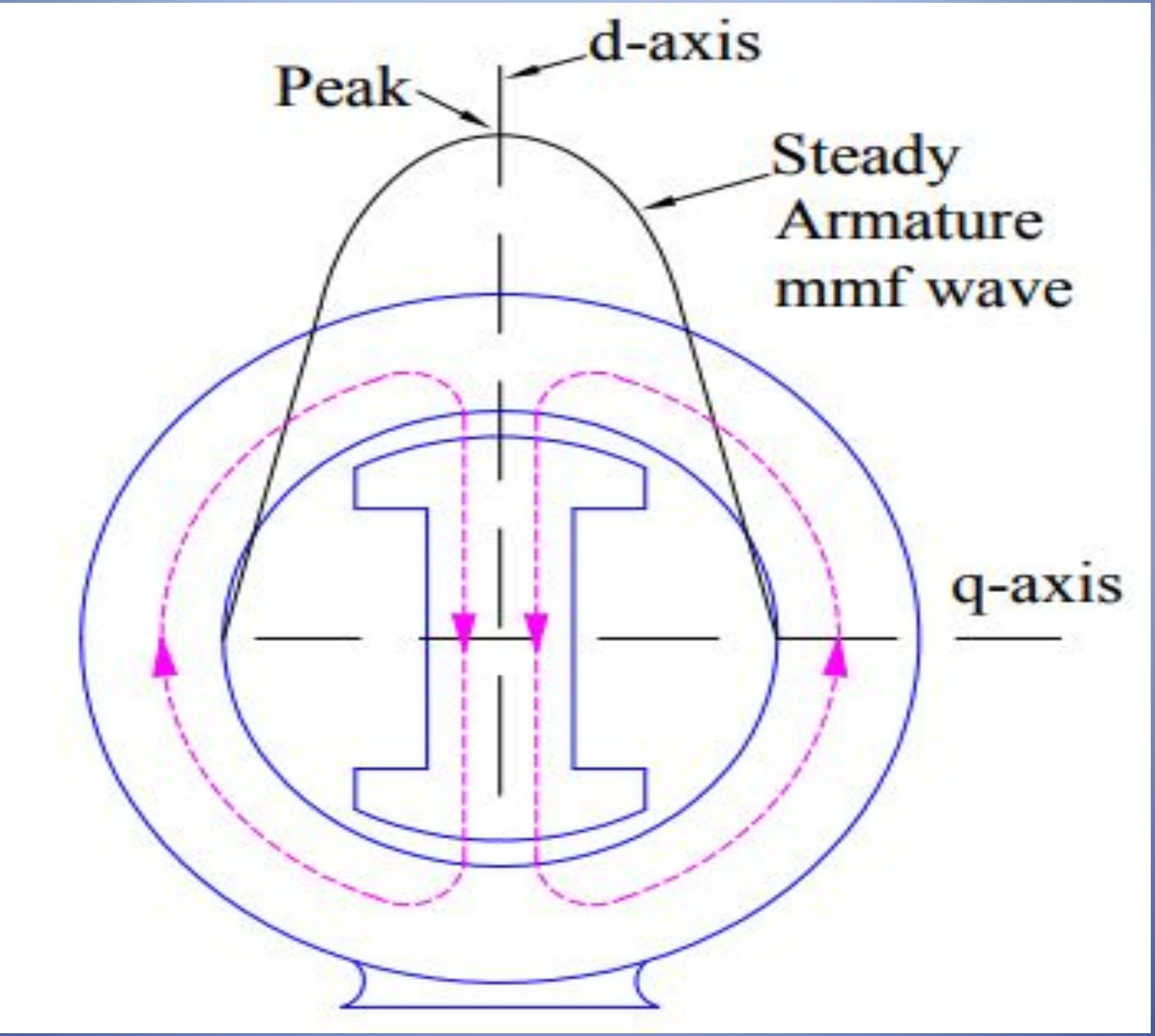


(a) Connection diagram
(b) The principle

Determination of Xd and Xq by slip test

- Simple no load test for finding out Xd and Xq and there by regulation of Salient pole Alternator
- Small voltage at rated frequency is applied to 3 phase stator
- Field winding is kept open
- Rotor is driven by Auxiliary motor normally Dc motor
- Motor runs at speed of ‘nr’ less than synchronous speed and stator RMF runs at ‘ns’

- Due to these two different speeds there exists slip between two i.e (ns-nr)
- Due to slip ,at certain instant peak of Armature mmf in line with axis of actual salient pole
- At this instant
  - Reluctance offered by small airgap is minimum
  - Minimum magnetizing current indicated by line ammeter
  - Flux linkage is max but rate of change of flux linkage is zero
  - Induced voltage across field winding is zero


d-axis
Peak
Steady
Armature
mmf wave
q-axis

Xd calculation

- At this point direct axis in line with RMF axis
  - Armature current is minimum
  - Hence drop in armature is minimum
  - Armature terminal voltage is maximum

$$Xd = \frac{maximum\ terminal\ voltage}{minimum\ armature\ current}$$

Xq calculation

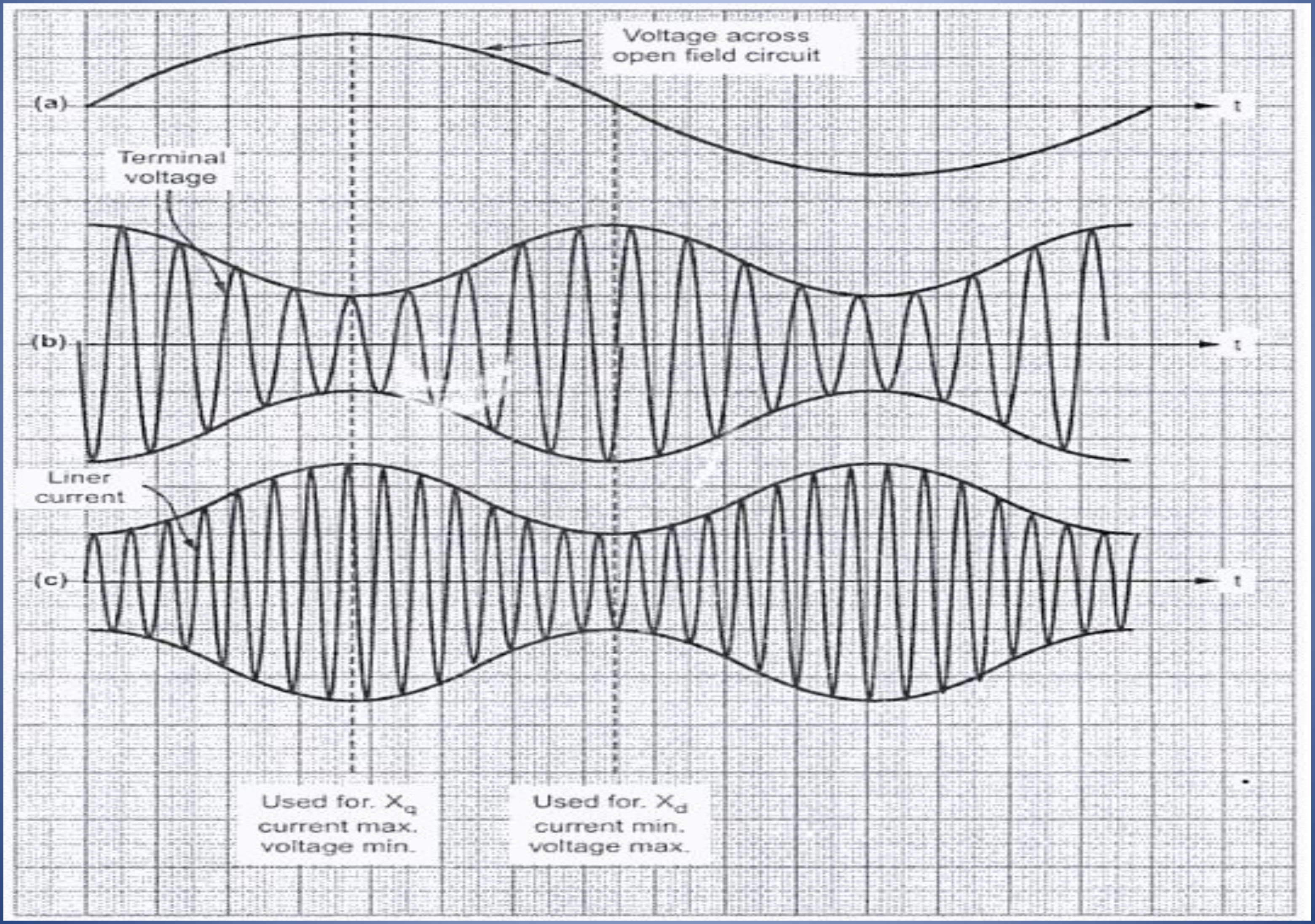
- After one quadrature peak of armature mmf coincides with q axis
  - Reluctance offered by air gap is maximum
  - Large magnetizing current is needed to establish airgap flux
  - Ia is maximum measured from line ammeter
  - Rate of change of flux linkage is maximum
  - Hence induced voltage in the field winding is maximum.

Calculation of Xq continue….

- Xq can be find out at this point where
  - Open circuit field voltage Maximum
  - Armature current is Maximum
  - Terminal voltage is minimum

$$Xq = \frac{minimum\ terminal\ voltage}{maximum\ armature\ current}$$

calculation of Xd and Xq by slip test



Power angle curve in synchronous machines

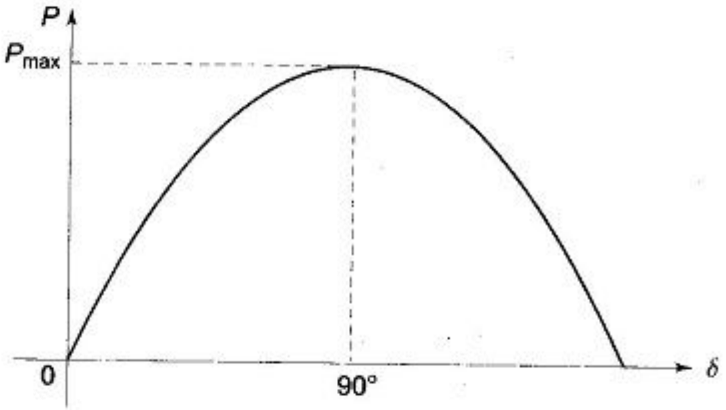


Fig. 4.25 Power angle curve of a synchronous generator

$$P_e = P_{emax} sin\delta$$

$$P_{e,\,max} = \frac{V_t E_f}{X_s} \tag{8.43}$$

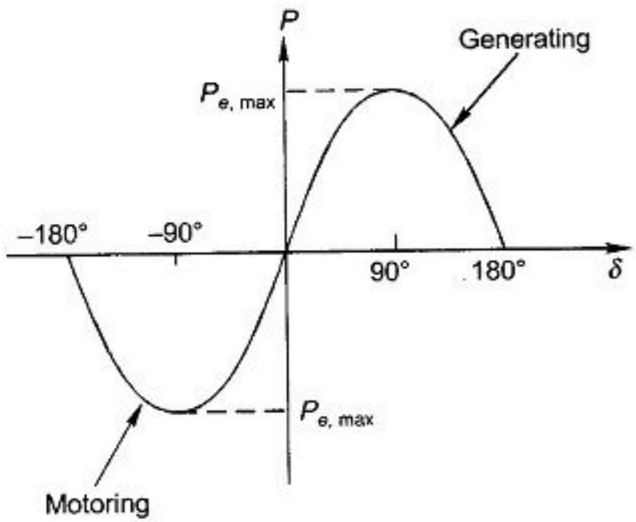


Fig. 8.30 *Power-angle characteristic*

$$P_e = \frac{EV}{X} sin\delta$$

Power angle curve in synchronous machines

- Power Angle Curve of Synchronous Machine is the graphical representation of electrical output with respect to the power angle.

- As we know, power angle is also known as load angle, therefore it can be said that this curve is graphical representation of electrical output of generator with respect to load angle.

- The electrical output of synchronous generator is given as below.

- $P_e = (E_f V_t / X_s)\mathrm{Sin}\delta$

- Where E_f, V_t, X_s and δ are no load excitation voltage, generator terminal voltage, generator synchronous reactance and load angle respectively.

Importance of Power Angle Curve

- Power Angle Curve tells us about the electrical power output of synchronous machine when power angle δ is varied.
- It can be seen from this curve that as we increase δ from 0 to 90°, the output increases sinusoidally.
- But a further increase in power angle δ beyond 90°, the generator electrical output decreases.

- the generator electrical output is less than the mechanical input.
- Therefore, the poles of the machine will start to slip and eventually it will lose synchronism.
- Thus the machine i.e. generator becomes unstable.
- Steady state stability limit is the maximum power flows possible through a specific point without lose of synchronism, when the power is increased gradually.
- steady state stability limit of synchronous machine corresponds to power for load angle $\delta = 90°$.

- transient stability limit is also affected by the load angle at which machine is operating.
- Transient state stability limit is basically the maximum amount of power flow possible without loss of synchronism when a sudden disturbance occurs.
- The transient stability limit is determined by Equal Area Criteria which uses power angle curve.
- Thus power angle curve is very important for study of stability limit of synchronous machine.
-

Power and power angle curve

- Maximum power is transferred when $\delta = 90^o$. As the value of load angle δ is above 90, P_e decrease and becomes zero at $\delta = 180^o$. Above 180^o, Pe becomes negative, which show that the direction of power flow is reversed, and the power is supplied from infinite bus to the generator. The value of P_e is often called pull out power. It is also called the steady-state limit.

Parallel operation of ac generators

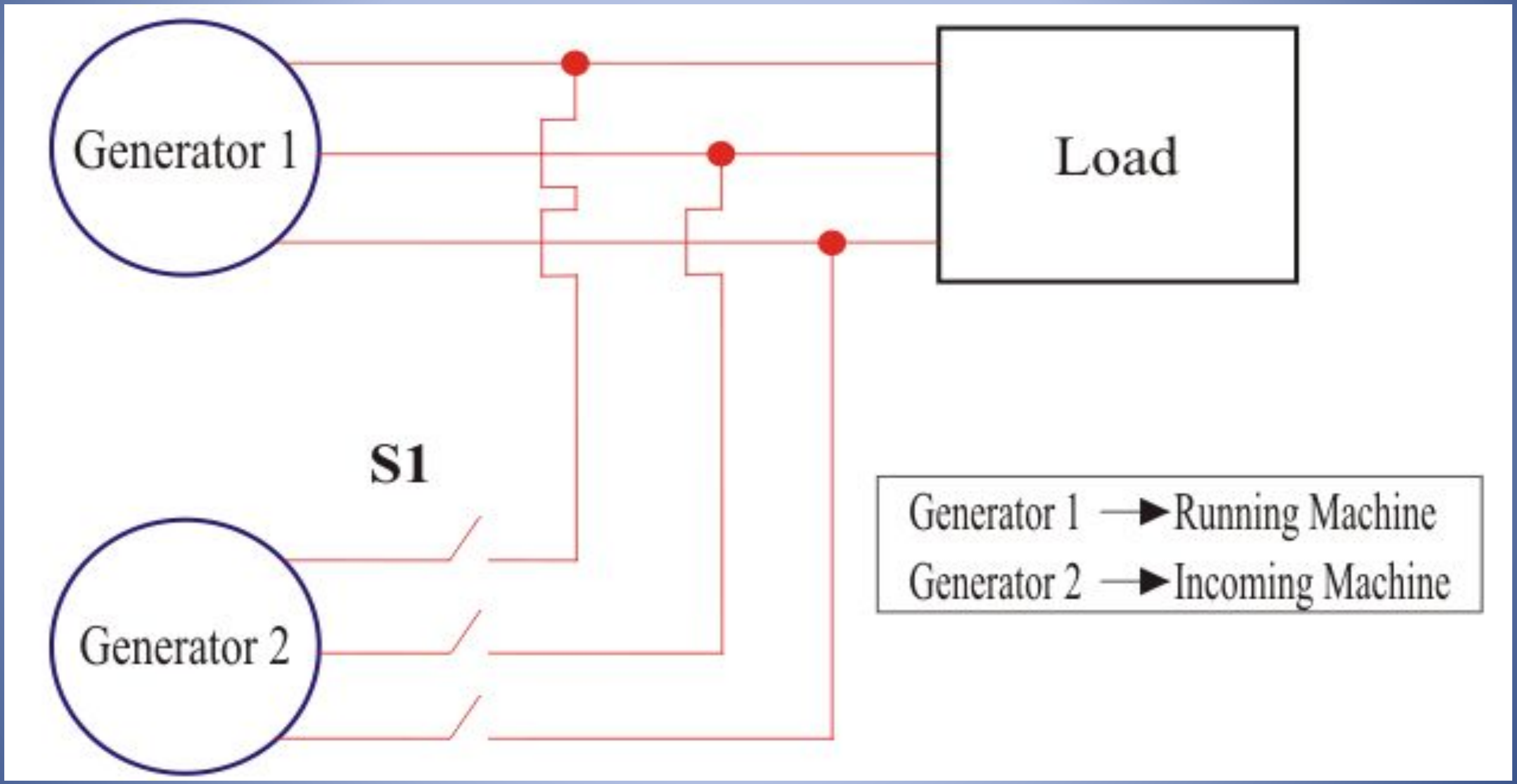
- Why parallel operation is needed?
  - Several AC generators can supply a bigger load than one machine by itself.
  - Having many synchronous generators increases the reliability of the power system
  - Having many synchronous generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.

Continue……

- In order to meet increasing future demand of load more machines can be added without disturbing original installation
- Operating cost and cost of energy generated are reduced

The Conditions Required for Paralleling

1. The rms line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of the two a phases must be equal.
4. The frequency of the new generator, called the incoming generator, must be slightly higher than that of the frequency of the running system.

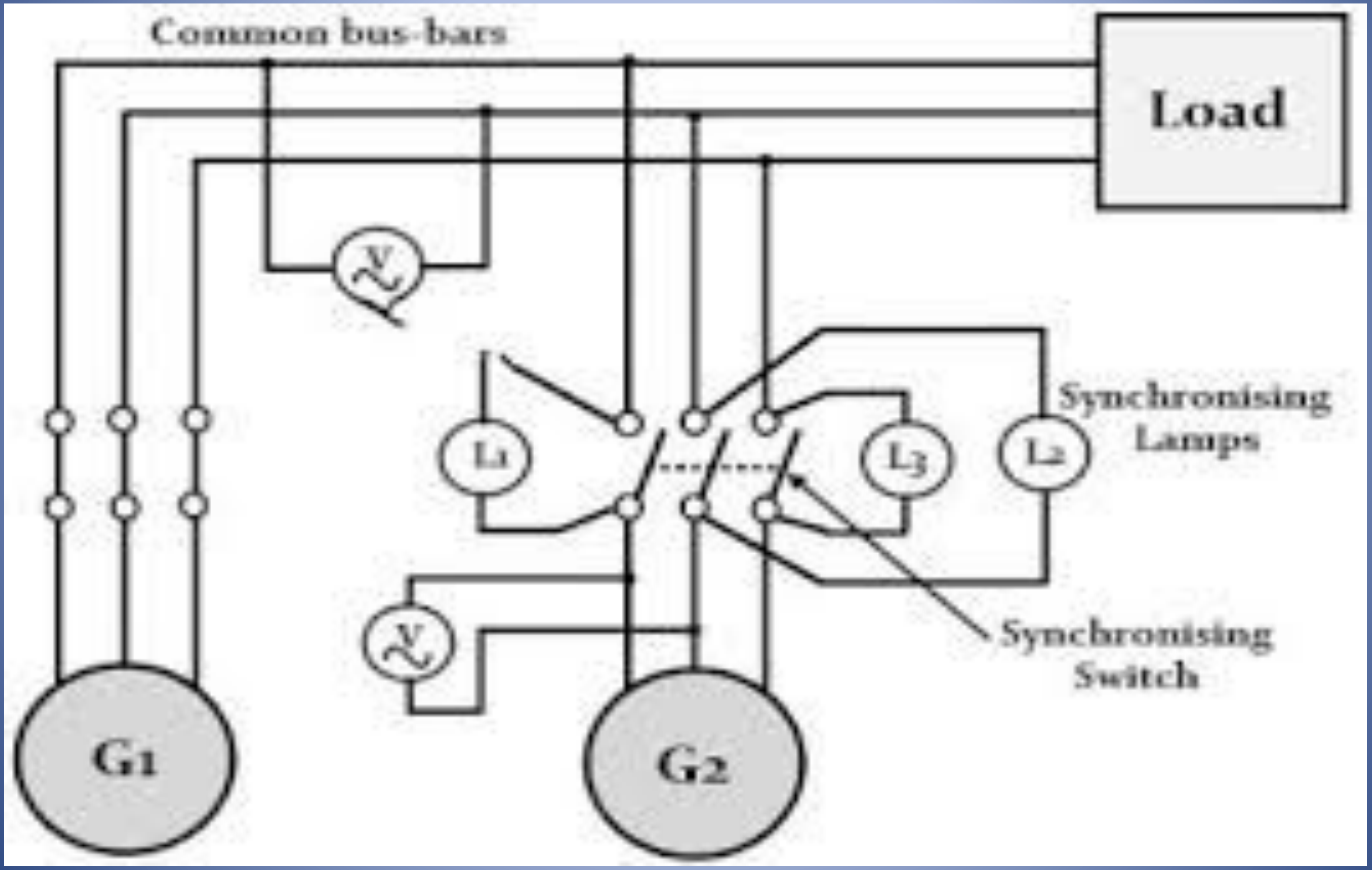


Generator 1
Load
S1
Generator 2
Generator 1 → Running Machine
Generator 2 → Incoming Machine

Methods of synchronization of Alternator

- Three dark lamp method
- Two bright one dark lamp method
- Synchronoscope method
  - Important conditions
    - Terminal voltage must be same
    - Phase sequence must be same
    - Frequency must be same

Three dark lamp method



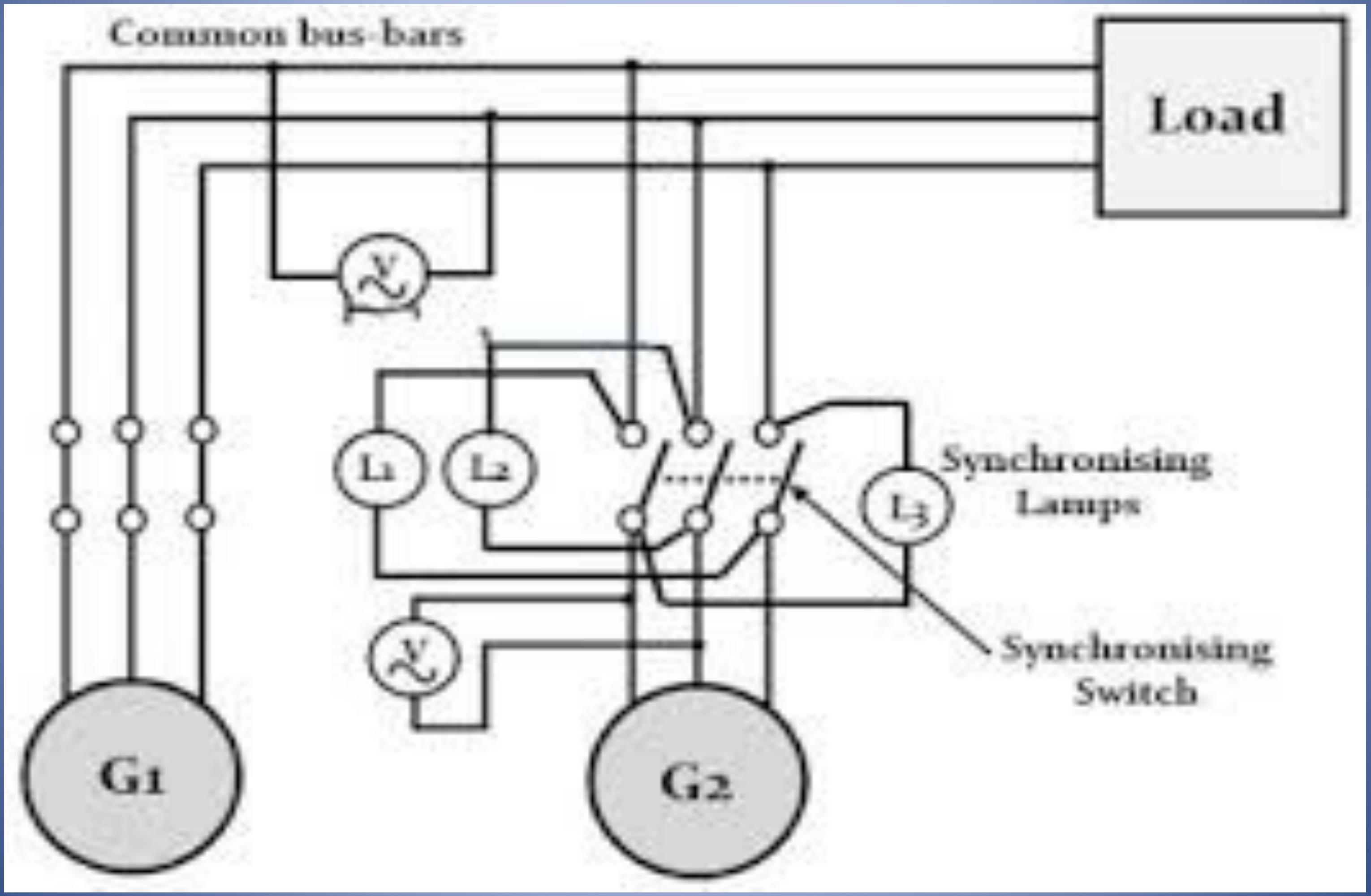
Procedure to synchronize …

- Across the 3 switches of alternator-2, three lamps are connected
- To match the terminal voltage of alternator-2 with bus-bar voltage we need to adjust the field current of alternator-2
- To know whether the phase sequence of alternator -2 matches with the bus-bar phase sequence, when all the three bulbs ON and OFF concurrently

- To match the frequency of alternator-2 with the bus-bar frequency we need to run the prime mover of alternator-2 at nearly synchronous speed
- ON and OFF rate of bulbs depends upon frequency difference of alternator-2 voltage and bus-bar voltage. Rate of flickering of bulbs is reduced when we match the frequency of alternator-2 with bus-bar voltage

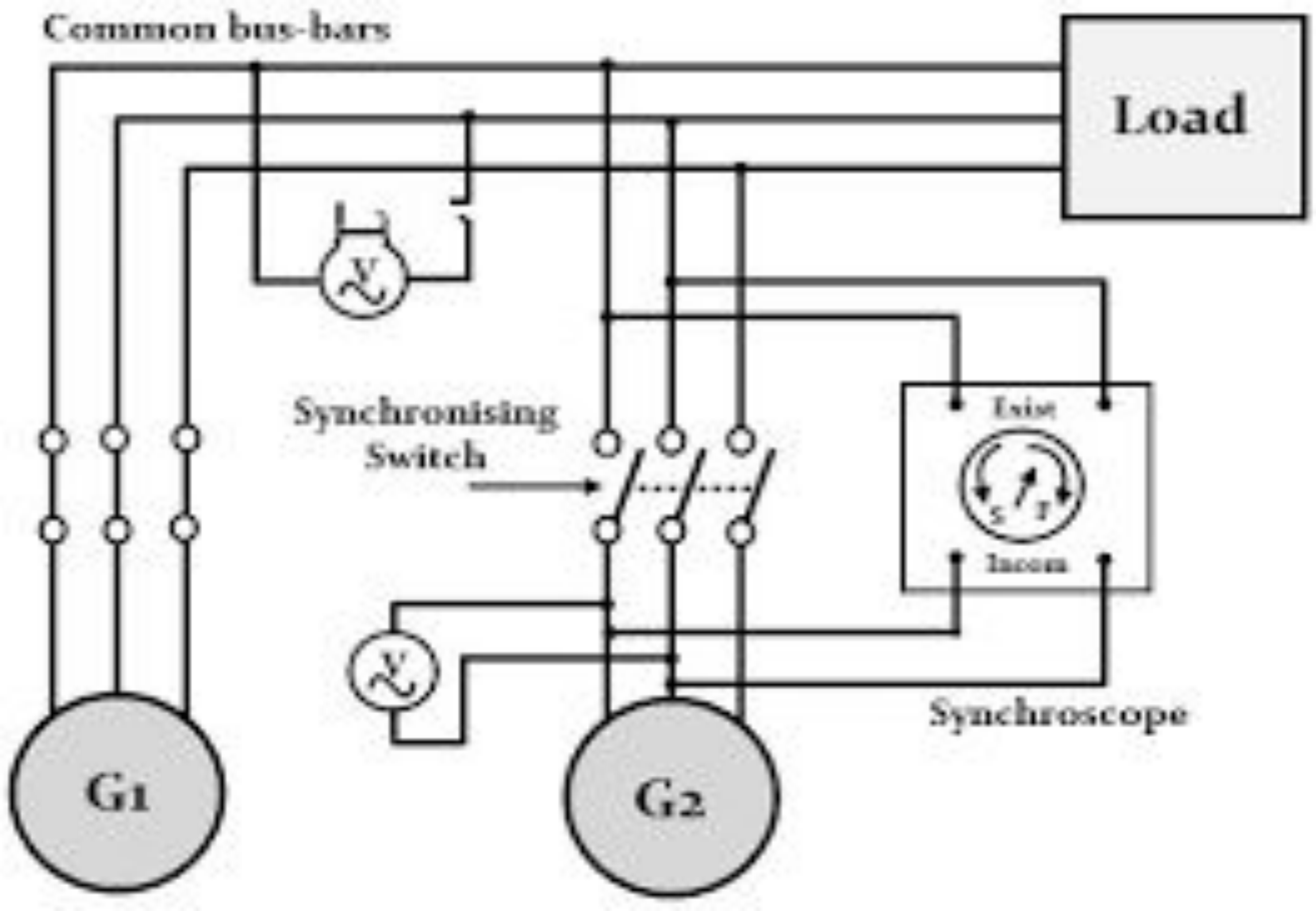
- If all the conditions required for synchronization are satisfied then the lamps will become dark.
- Now close the switches of alternator -2 to synchronize with alternator-1.
- Now the alternators are in synchronism.

Two bright one dark lamp method



- Here lamp L-2 is connected similar to the **three dark lamp method.**
- Lamps L-1 and and L-3 are connected in different manner. lamp L-1 is connected phase 1 and 3 and lamp L-3 is connected between phase 3 and 1
- When the L1 and L3 are equally bright and lamp L2 is dark then close the switches.

Synchroscope method



- A synchroscop is used to achieve synchronization accurately.
- This contains two terminals they are a) existing terminal b) incoming terminal.
- Synchroscop has a circular dial inside which a pointer is present and it can move both in clockwise and anti clockwise direction
- Depending upon the rate at which the pointer is rotating the difference of frequency of voltage between incoming alternator and bus-bar can be known.
-

- And also if the pointer moves anti clockwise then the incoming alternator is running slower and has frequency less than the bus bar or existing alternator frequency
- if the pointer moves clock-wise then the incoming alternator is running faster and has frequency greater than bus-bar or existing alternator frequency.
- So by adjusting the speed of prime mover of incoming alternator we can match the frequency with bus bar or existing alternator frequency.
- Frequency matches when the pointer is straight up-wards. At this point close the switch.

Parallel generator theorem

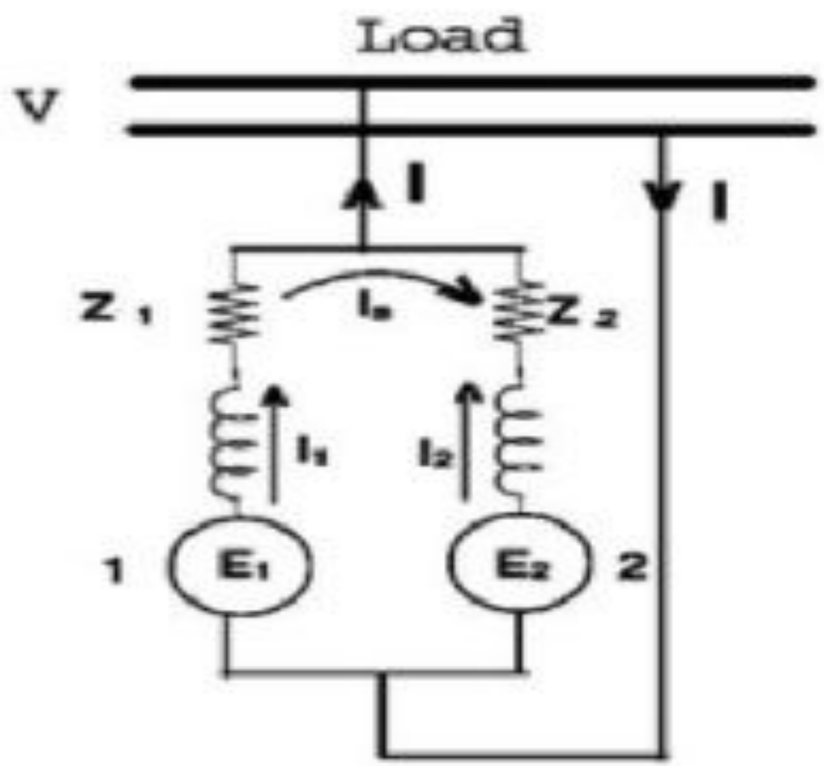


Fig:

- Let the load be I amps at V volts such that V / I = Z.
- Then , $V = (I_1+I_2)Z$

$$= [(E_1-V)/Zs_1 + (E_2-V)/Zs_2]$$

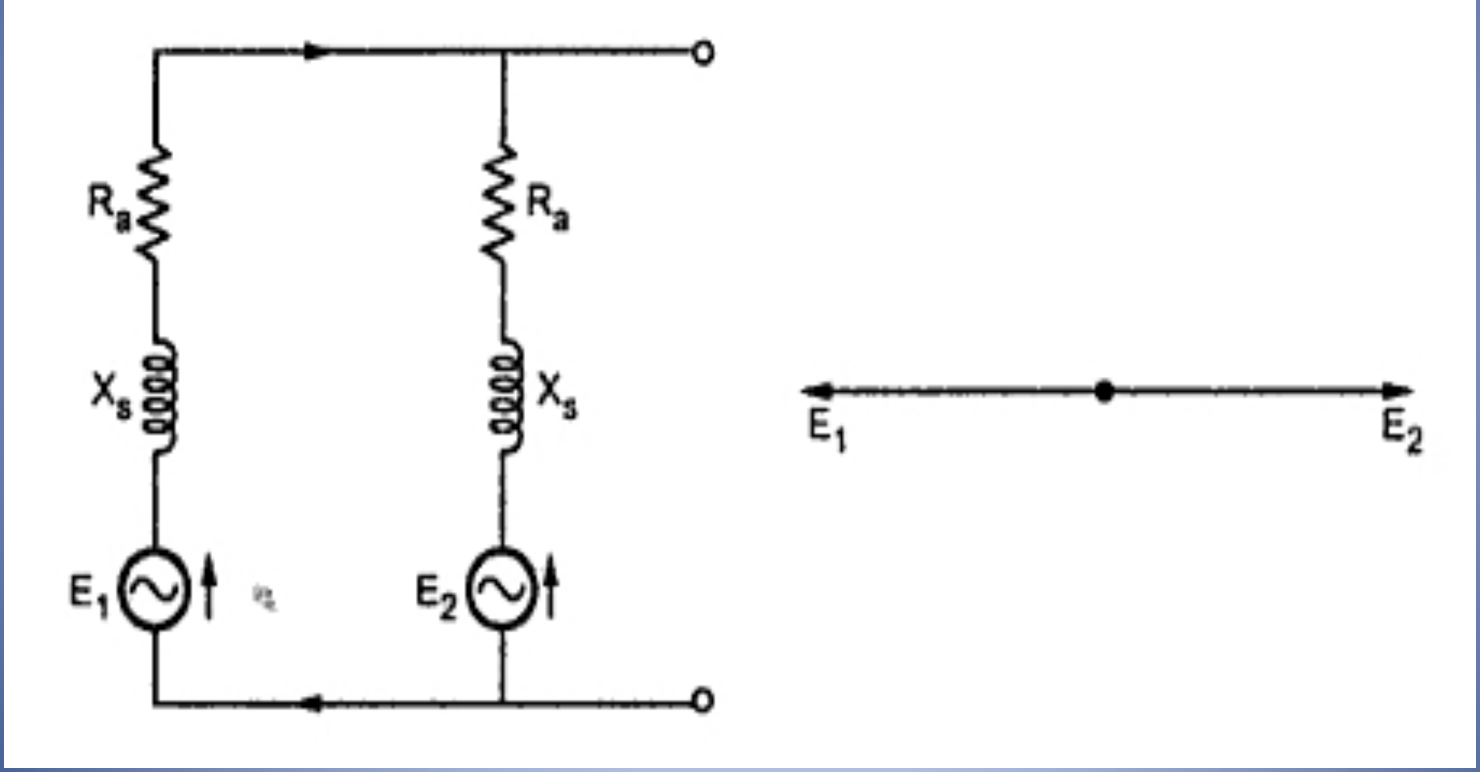
$$= [E_1/Zs_1 + E_2/Zs_2]Z - V[1/Zs_1 + 1/Zs_2]Z$$

- i.e. $V[1/Z + 1/Zs_1 + 1/Zs_2] = \quad E_1/Zs_1 + E_2/Zs_2 = Isc$
- **i.e.** $V[1/Z_0] = I_{sc}$

- where I_{sc} is the total short circuit current obtained by summing the terms E_1/Zs_1 and E_2/Zs_2 where
- $1/Z_0 = 1/Z + 1/Zs_1 + 1/Zs_2$

- This theorem holds true for any number of generator.

Equivalent circuit for parallel connected Alternators



Synchronizing current

- Now assume that speed of alternator 2 is changed such that its e.m.f. E_2 falls by an angle α
- The resultant voltage in this case will cause a current in the local circuit which is called synchronizing current.

$$\mathbf{I_{SY} = E_r / Z_s}$$

The phase angle of I_{SY} is given by an angle θ which can be computed as $\tan\theta = X_s/R_a$ where X_s is synchronous reactance and R_a is armature resistance. This angle is almost 90°.

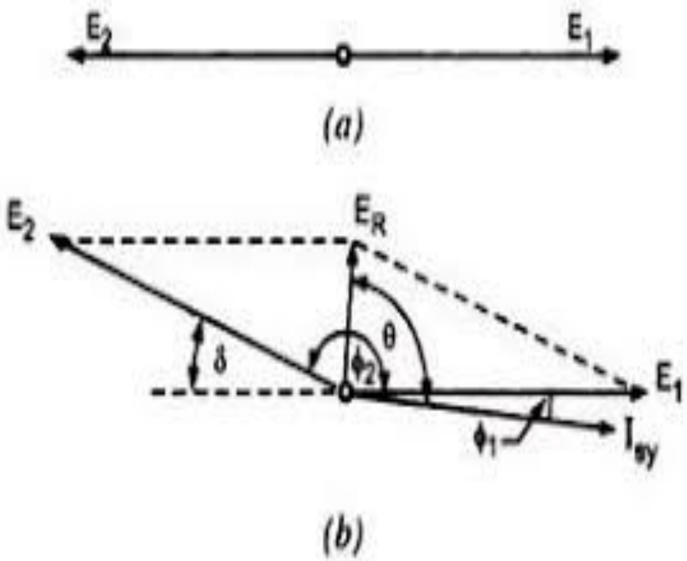


Fig. 13.1

Now, $$I_{SY} = \frac{E_r}{\text{Synchronous impedance}} = \frac{E_r}{2X_s} = \frac{\alpha E}{2X_s}$$

... Assuming R_a of both machines to be negligible.

- Thus I_{SY} lags E_r by almost 90° and approximately in phase with E_1. This current is generating current with respect to alternator 1 since it is in the same direction as that of e.m.f. of alternator 1 while it will be motoring current for alternator 2 as it is in the opposite direction as that of e.m.f. of alternator 2. This current I_{SY} will produce a synchronizing torque which will try to retard alternator 1 whereas accelerate the alternator 2

- The power output of alternator 1 supplies power input to alternator 2 and copper losses in the local path formed by armatures of two alternators.
- Power output of alternator 1 = $E_1 I_{SY} \cos\Phi_1$
- $P_{sy} = E_1 I_{SY}$ as Φ is very small
- $E_1 = E_2 = E_r$
- Er =resultant voltage

Synchronizing power

- Synchronizing power per phase = Isy .Er
- Isy = $\frac{Er}{2Xs}$
- Er = ἀE
- Psy = $\frac{\text{ἀ}\,E^2}{2Xs}$ per phase
- For 3 phase
- Psy = $3\,\frac{\text{ἀ}\,E^2}{2Xs}$

Synchronizing Torque

- Tsy = $\frac{Psy}{2\pi N}$ per phase
- For 3 phase
- Tsy = $\frac{3Psy60}{2\pi Ns}$ as Ns = N/60
- This torque will tend to accelerate the lagging machine while will try to retard the leading machine.

Numerical 1

A 3000 KVA, 6 pole alternator runs at 1000 rpm in parallel with other m/cs on 3,300 V bus-bars. The synchronous reactance is 25%. Calculate the synchronising power for one mechanical degree of displacement & the corresponding synchronising ~~power~~ torque.

Given :—

Power rating 3000 KVA

$P = 6$ poles

$N = 1000$ rpm.

$V = 3300$ V

$IX_s = 25\%$ of Volt/phase

α for 1 mech. degree of displacement

Soln :—

$$\text{Volt/phase} = \frac{3300}{\sqrt{3}} = 1905 \text{ V.}$$

$$\text{F.L. current } I = \frac{3 \times 10^6}{\sqrt{3} \times 3300} = 525 \text{ Amp.}$$

$$IX_s = 25\% \text{ of } 1905 \quad \therefore X_s = \frac{0.25 \times 1905}{525}$$

$$\boxed{X_s = 0.9075\ \Omega}$$

$$P_{sy} = \frac{3 \times \alpha E^2}{X_s}$$

where

$\alpha = 1^\circ$ mech $\quad \therefore \alpha$ electrical $= 1 \times \left(\frac{P}{2}\right)$

$= 1 \times 6/2 = 3^\circ$

$$\alpha = 3 \times \frac{\pi}{180^\circ} = \frac{\pi}{60} \text{ elect. radian.}$$

$$P_{sy} = \frac{3 \times \pi \times (1905)^2}{60 \times 0.9075 \times 1000} = \underline{628.4 \text{ kW}}$$

$$T_{sy} = \frac{60 \cdot P_{sy}}{2\pi N_s} = 9.55 \times \frac{628.4 \times 10^3}{1000}$$

$$\boxed{T_{sy} = 6000 \text{ N.m}}$$

Example 37.44. *A 3,000-kVA, 6-pole alternator runs at 1000 r.p.m. in parallel with other machines on 3,300-V bus-bars. The synchronous reactance is 25%. Calculate the synchronizing power for one mechanical degree of displacement and the corresponding synchronizing torque.*

(Elect. Machines-I, Gwalior Univ. 1984)

Solution. It may please be noted that here the alternator is working in parallel with many alternators. Hence, it may be considered to be connected to infinite bus-bars.

$$\text{Voltage/phase} = 3{,}300/\sqrt{3} = 1905 \text{ V}$$

F.L. current $\quad I = 3 \times 10^6/\sqrt{3} \times 3300 = 525 \text{ A}$

Now, $\quad IX_S = 25\% \text{ of } 1905 \quad \therefore X_S = 0.25 \times 1905/525 = 0.9075\ \Omega$

Also, $\quad P_{SY} = 3 \times \alpha E^2/X_S$

Here $\quad \alpha = 1° \text{ (mech.)}; \alpha \text{ (elect.)} = 1 \times (6/2) = 3°$

$\therefore \quad \alpha = 3 \times \pi/180 = \pi/60 \text{ elect. radian.}$

$$\therefore \quad P_{SY} = \frac{3 \times \pi \times 1905^2}{60 \times 0.9075 \times 1000} = 628.4 \text{ kW}$$

$$T_{SY} = \frac{60.P_{SY}}{2\pi N_S} = 9.55\,\frac{P_{SY}}{N_S} = 9.55\,\frac{628.4 \times 10^3}{1000} = \mathbf{6{,}000\ N\text{-}m}$$

Example 37.45. *A 3-MVA, 6-pole alternator runs at 1000 r.p.m on 3.3-kV bus-bars. The synchronous reactance is 25 percent. Calculate the synchronising power and torque per mechanical degree of displacement when the alternator is supplying full-load at 0.8 lag.*

(Electrical Machines-1, Bombay Univ. 1987)

Solution. $V = 3{,}300/\sqrt{3} = 1905$ V/phase, F.L. $I = 3 \times 10^6/\sqrt{3} \times 3{,}300 = 525$ A

$IX_S = 25\%$ of $1905 = 476$ V; $X_S = 476/525 = 0.9075\ \Omega$

Let, $\mathbf{I} = 525 \angle 0°$, then, $\mathbf{V} = 1905\,(0.8 + j0.6) = 1524 + j1143$

$\mathbf{E_0} = \mathbf{V} + \mathbf{IX_S} = (1524 + j1143) + (0 + j476) = (1524 + j1619) = 2220 \angle 46°44'$

Obviously, E_0 leads I by $46°44'$. However, V leads I by $\cos^{-1}(0.8) = 36°50'$.

Hence, $\alpha = 46°44' - 36°50' = 9°54'$

$\alpha = 1°$ (mech.), No. of pair of poles $= 6/2 = 3$ $\therefore\ \alpha = 1 \times 3 = 3°$ (elect.)

$$P_{SY} \text{ per phase} = \frac{EV}{X_S} \cos\alpha \sin\delta = \frac{2220 \times 1905}{0.9075} \times \cos 9°54' \sin 3° = 218 \text{ kW}$$

P_{SY} for three phases $= 3 \times 218 =$ **654 kW**

$T_{SY} = 9.55 \times P_{SY}/N_S = 9.55 \times 654 \times 10^2/1000 = 6245$ N-m

Example 37.46. *A 750-kVA, 11-kV, 4-pole, 3-ϕ, star-connected alternator has percentage resistance and reactance of 1 and 15 respectively. Calculate the synchronising power per mechanical degree of displacement at (a) no-load (b) at full-load 0.8 p.f. lag. The terminal voltage in each case is 11 kV.* **(Electrical Machines-II, Indore Univ. 1985)**

Solution. F.L. Current $\quad I = 75 \times 10^3/\sqrt{3} \times 11 \times 10^3 = 40 \text{ A}$

$$V_{ph} = 11{,}000/\sqrt{3} = 6{,}350 \text{ V}, IR_a = 1\% \text{ of } 6{,}350 = 63.5$$

or $$40\, R_a = 63.5, R_a = 1.6\ \Omega;\ 40 \times X_S = 15\% \text{ of } 6{,}350 = 952.5 \text{ V}$$

$\therefore$ $$X_S = 23.8\ \Omega;\ Z_S = \sqrt{1.6^2 + 23.8^2} \cong 23.8\ \Omega$$

(*a*) No-load

$\alpha\,(\text{mech}) = 1° : \alpha\,(\text{elect}) = 1 \times (4/2) = 2°$

$= 2 \times \pi/180 = \pi/90$ elect. radian.

$$P_{SY} = \frac{\alpha E^2}{Z_S} \cong \frac{\alpha E^2}{X_S} = \frac{(\pi/90) \times 6350^2}{23.8}$$

$= 59{,}140 \text{ W} =$ **59.14 kW/phase.**

On no-load, V has been taken to be equal to E.

(*b*) F.L. 0.8 p.f.

As indicated in Art. 37.35, $P_{SY} = \alpha EV/X_S$. The value of E (or E_0) can be found from Fig. 37.87.

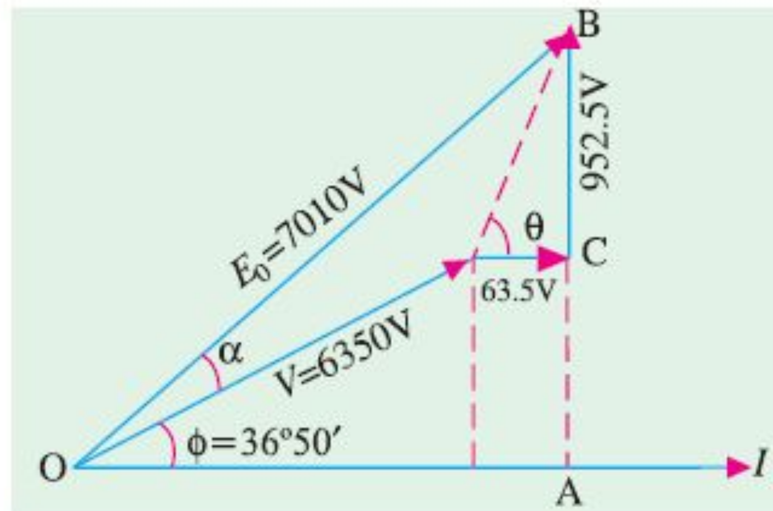


Fig. 37.87

$$E = [(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]^{1/2}$$

$$= [(6350 \times 0.8 + 63.5)^2 + (6350 \times 0.6 + 952.5)^2]^{1/2} = 7010 \text{ V}$$

$$P_{SY} = \frac{\alpha EV}{X_S} = \frac{(\pi/90) \times 7010 \times 6350}{23.8} = 65{,}290 \text{ W}$$

$=$ **65.29 kW/phase**

More Accurate Method [Art. 37.35]

$$P_{SY} = \frac{EV}{X_S} \cos \alpha \sin \delta$$

Now, $E = 7010$ V, V = 6350 V, $\delta = 1° \times (4/2) = 2°$ (elect)

As seen from Fig. 37.87, $\sin (\phi + \alpha) = AB/OB = (6350 \times 0.6 + 952.5)/7010 = 0.6794$

$\therefore \quad (\phi + \alpha) = 42°30'; \alpha = 42°30' - 36°50' = 5°40'$

$$\therefore \quad P_{SY} = \frac{7010 - 6350}{23.8} \times \cos 5°40' \times \sin 2°$$

$= 7010 \times 6350 \times 0.9953 \times 0.0349/23.8 = 64{,}970$ W = **64.97 kW/phase**

Example 37.49. *Two 3-phase, 6.6-kW, star-connected alternators supply a load of 3000 kW at 0.8 p.f. lagging. The synchronous impedance per phase of machine A is (0.5 + j10) Ω and of machine B is (0.4 + j 12) Ω. The excitation of machine A is adjusted so that it delivers 150 A at a lagging power factor and the governors are so set that load is shared equally between the machines.*

Determine the current, power factor, induced e.m.f. and load angle of each machine.

(Electrical Machines-II, South Gujarat Univ. 1985)

Solution. It is given that each machine carries a load of 1500 kW. Also, $V = 6600/\sqrt{3} = 3810$ V. Let $V = 3810 \angle 0° = (3810 + j\,0)$.

For machine No. 1

$$\sqrt{3} \,/\, 6600 \times 150 \times \cos\phi_1 \;=\; 1500 \times 10^3;$$

$$\cos\phi_1 = 0.874,\ \phi_1 = 29°;\ \sin\phi_1 = 0.485$$

Total current $I = 3000/\sqrt{3} \times 6.6 \times 0.8 = 328$ A

or $\quad I = 828\,(0.8 - j\,0.6) = 262 - j\,195$

Now, $\quad \mathbf{I_1} = 150\,(0.874 - j\,0.485) = 131 - j\,72.6$

$\therefore \quad \mathbf{I_2} = (262 - j\,195) - (131 - j\,72.6)$

$\quad = (131 - j\,124.4)$

or $\quad I_2 =$ **181 A,** $\cos\phi_2 = 131/181 =$ **0.723 (lag).**

$\mathbf{E_A} = \mathbf{V} + \mathbf{I_1 Z_1} = 3810 + (131 - j\,72.6)\,(0.5 + j10)$

$\quad = 4600 + j1270$

Line value of e.m.f. $\quad = \sqrt{3}\,\sqrt{(4600^2 + 1270^2)} =$ **8,260 V**

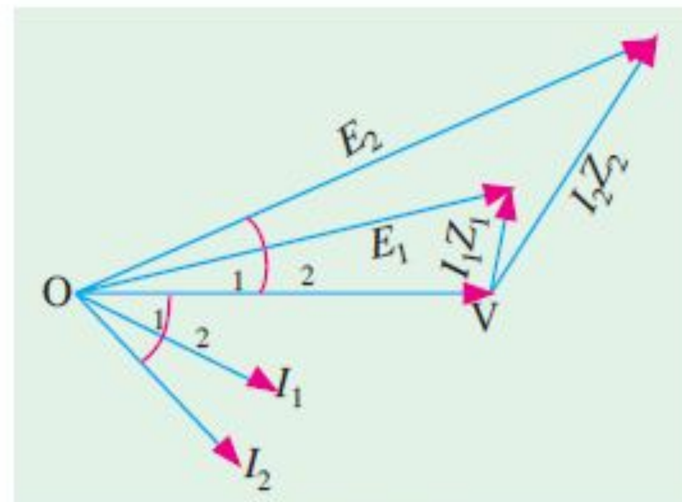


Fig. 37.90

Load angle $\alpha_1 = (1270/4600) = 15.4°$

$$E_B = V + I_2Z_2 = 3810 + (131 - j124.4)(0.4 + j12)$$
$$= 5350 + j1520$$

Line value of e.m.f $= \sqrt{3}\sqrt{5350^2 + 1520^2} = 9600\ V$

Load angle $\alpha_2 = \tan^{-1}(1520/5350) = 15.9°$

Numerical on load sharing Between parallel Alternator

Example 37.50. *Two single-phase alternator operating in parallel have induced e.m.fs on open circuit of 230 ∠ 0° and 230 ∠ 10° volts and respective reactances of j2 Ω and j3 Ω. Calculate **(i)** terminal voltage **(ii)** currents and **(iii)** power delivered by each of the alternators to a load of impedance 6 Ω (resistive).* **(Electrical Machines-II, Indore Univ. 1987)**

Solution. Here, $\mathbf{Z_1} = j2$, $\mathbf{Z_2} = j.3$, $\mathbf{Z} = 6$; $\mathbf{E_1} = 230\angle 0°$ and

$$\mathbf{E_2} = 230\angle 10° = 230\,(0.985 + j\,0.174) = (226.5 + j\,39.9)\text{, as in Fig. 37.90}$$

(ii) $$\mathbf{I_1} = \frac{(E_1 - E_2)\,Z + E_1 Z_2}{Z\,(Z_1 + Z_2) + Z_1 Z_2} = \frac{[(230 + j0) - (226.5 + j39.9)] \times 6 + 230 \times j3}{6\,(j2 - j3) + j2 \times j3}$$

$$= 14.3 - j3.56 = 14.73\angle -14° \qquad \text{—Art. 37.38}$$

$$\mathbf{I_2} = \frac{(E_2 - E_1)\,Z + E_2 Z_1}{Z\,(Z_1 + Z_2) + Z_1 Z_2} = \frac{(-3.5 + j39.9) + (222.5 + j39.9) \times j2}{6\,(j2 + j3) + j2 \times j3}$$

$$= 22.6 - j\,1.15 = 22.63\angle -3.4°$$

(i) $$\mathbf{I} = \mathbf{I_1} + \mathbf{I_2} = 36.9 - j\,4.71 = 37.2\angle -7.3°$$

$$\mathbf{V} = \mathbf{IZ} = (36.9 - j4.71) \times 6 = 221.4 - j28.3 = 223.2\angle -7.3°$$

(iii) $$P_1 = VI_1\cos\phi_1 = 223.2 \times 14.73 \times \cos 14° = \mathbf{3190\ W}$$

$$P_2 = VI_2\cos\phi_1 = 223.2 \times 22.63 \times \cos 3.4° = \mathbf{5040\ W}$$

Regulation of Alternator

Example 37.18 (*a*). *In a 50-kVA, star-connected, 440-V, 3-phase, 50-Hz alternator, the effective armature resistance is 0.25 ohm per phase. The synchronous reactance is 3.2 ohm per phase and leakage reactance is 0.5 ohm per phase. Determine at rated load and unity power factor :*

(a) Internal e.m.f. E_a (b) no-load e.m.f. E_0 (c) percentage regulation on full-load (d) value of synchronous reactance which replaces armature reaction.

(Electrical Engg. Bombay Univ. 1987)

Solution. (*a*) The e.m.f. E_a is the vector sum of (*i*) terminal voltage V (*ii*) IR_a and (*iii*) IX_L as detailed in Art. 37.17. Here,

$$V = 440/\sqrt{3} = 254 \text{ V}$$

F.L. output current at u.p.f. is

$$= 50{,}000/\sqrt{3} \times 440 = 65.6 \text{ A}$$

Resistive drop $= 65.6 \times 0.25 = 16.4$ V

Leakage reactance drop $IX_L = 65.6 \times 0.5 = 32.8$ V

$$\therefore \quad E_a = \sqrt{(V + IR_a)^2 + (IX_L)^2}$$

$$= \sqrt{(254 + 16.4)^2 + 32.8^2} = 272 \text{ volt}$$

Line value $= \sqrt{3} \times 272 =$ **471 volt.**

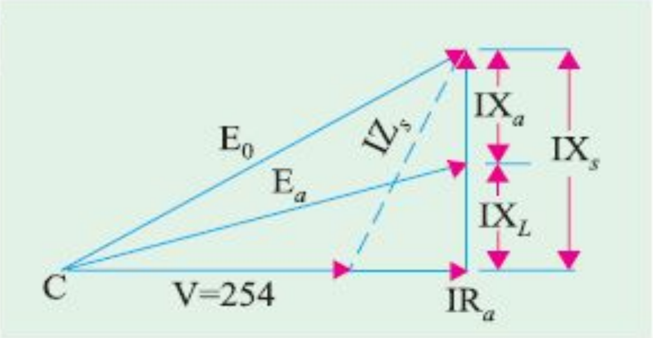


Fig. 37.31

(*b*) The no-load e.m.f. E_0 is the vector sum of (*i*) V (*ii*) IR_a and (*iii*) IX_S or is the vector sum of V and IZ_S (Fig. 37.31).

$\therefore \quad E_0 = \sqrt{(V + IR_a)^2 + (IX_S)^2} = \sqrt{(254 + 16.4)^2 + (65.6 \times 3.2)^2} = 342$ volt

Line value $= \sqrt{3} \times 342 =$ **592 volt**

(*c*) % age regulation 'up' $= \dfrac{E_0 - V}{V} \times 100 = \dfrac{342 - 254}{254} \times 100 =$ **34.65 per cent**

(*d*) $X_a = X_S - X_L = 3.2 - 0.5 =$ **2.7 Ω** ...Art. 37.17

O.C. and S.C. Test

Example 37.20. *From the following test results, determine the voltage regulation of a 2000-V, 1-phase alternator delivering a current of 100 A at (i) unity p.f. (ii) 0.8 leading p.f. and (iii) 0.71 lagging p.f.*

Test results : Full-load current of 100 A is produced on short-circuit by a field excitation of 2.5A. An e.m.f. of 500 V is produced on open-circuit by the same excitation. The armature resistance is 0.8Ω. **(Elect. Engg.-II, M.S. Univ. 1987)**

Solution. $Z_S = \dfrac{\text{O.C. volts}}{\text{S.C. current}}$ —for same excitation

for same excitation

$$= 500/100 = 5\ \Omega$$

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{5^2 - 0.8^2} = 4.936\ \Omega$$

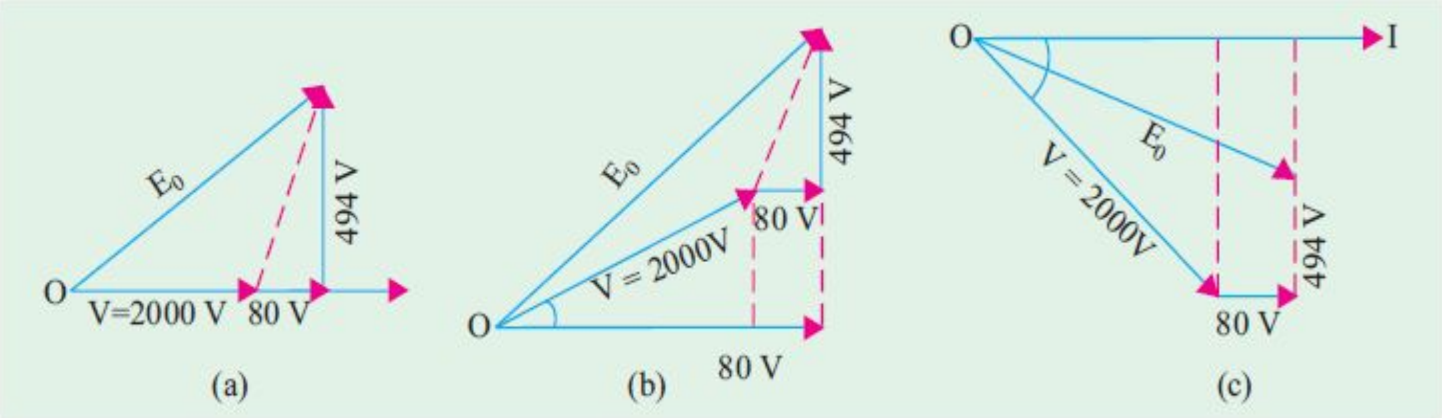


Fig. 37.35

(*i*) **Unity p.f.** (Fig. 37.35 (*a*)]

$$IR_a = 100 \times 0.8 = 80\text{ V}; \quad IX_S = 100 \times 4.936 = 494\text{ V}$$

$$\therefore \quad E_0 = \sqrt{(2000+80)^2 + 494^2} = 2140\,V$$

$$\%\text{ regn} = \frac{2140 - 2000}{2000} \times 100 = \mathbf{7\%}$$

(*ii*) **p.f. = 0.8 (lead)** [Fig. 37.35 (*c*)]

$$E_0 = [(2000 \times 0.8 + 80)^2 + (2000 \times 0.6 - 494)^2]^{1/2} = 1820\text{ V}$$

$$\%\text{ regn} = \frac{1820 - 2000}{2000} \times 100 = \mathbf{-9\%}$$

(*iii*) **p.f. = 0.71(lag)** [Fig.37.35 (*b*)]

$$E_0 = [(2000 \times 0.71 + 80)^2 + (2000 \times 0.71 + 494)^2]^{1/2} = 2432\text{ V}$$

$$\%\text{ regn} = \frac{2432 - 2000}{2000} \times 100 = \mathbf{21.6\%}$$

37.28. Calculations from Phasor Diagram

In Fig. 37.73, dotted line AC has been drawn perpendicular to I_a and CB is perpendicular to the phasor for E_0. The angle $ACB = \psi$ because angle between two lines is the same as between their perpendiculars. It is also seen that

$$I_d = I_a \sin \psi \,;\, I_q = I_a \cos \psi \,;\, \text{hence, } I_a = I_q / \cos \psi$$

In ΔABC, $$BC/AC = \cos \psi \text{ or } AC = BC/\cos \psi = I_q X_q / \cos \psi = I_a X_q$$

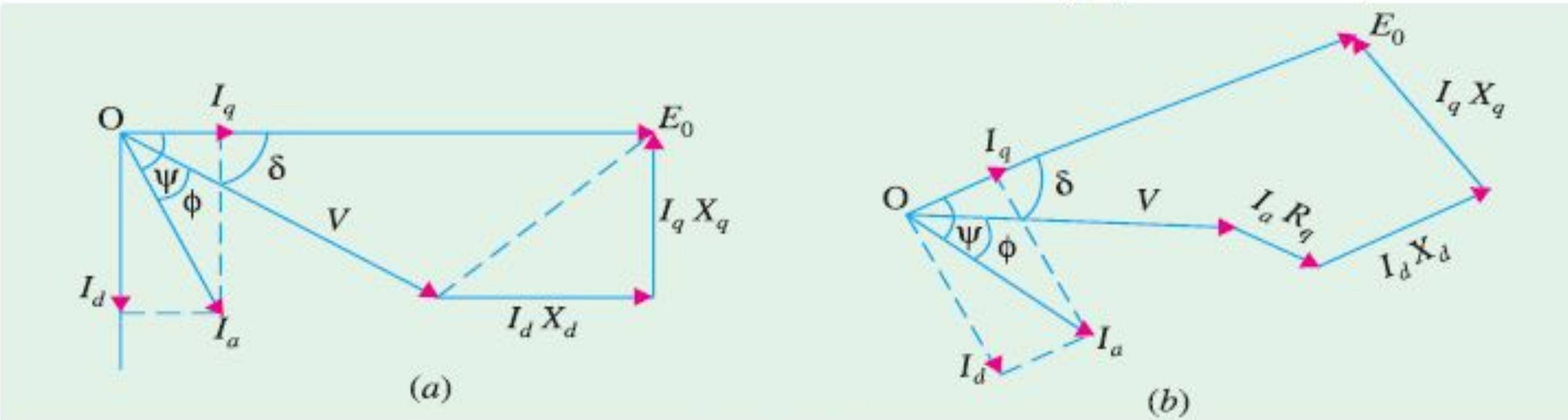


Fig. 37.72

From $\Delta\, ODC$, we get

$$\tan \psi = \frac{AD + AC}{OE + ED} = \frac{V \sin \phi + I_a X_q}{V \cos \phi + I_a R_a} \qquad \text{—generating}$$

$$= \frac{V \sin \phi - I_a X_q}{V \sin \phi - I_a R_a} \qquad \text{—motoring}$$

The angle ψ can be found from the above equation. Then, $\delta = \psi - \phi$ (generating) and $\delta = \phi - \psi$ (motoring)

Numerical on Salient pole machine regulation

Example 37.39. *A 3-phase alternator has a direct-axis synchronous reactance of 0.7 p.u. and a quadrature axis synchronous reactance of 0.4 p.u. Draw the vector diagram for full-load 0.8 p.f. lagging and obtain therefrom (i) the load angle and (ii) the no-load per unit voltage.*

(Advanced Elect. Machines, AMIE Sec. B 1991)

Solution.

$$V = 1\text{ p.u.}; X_d = 0.7\text{ p.u.}; X_q = 0.4\text{ p.u.};$$

$$\cos\phi = 0.8; \sin\phi = 0.6; \phi = \cos^{-1} 0.8 = 36.9°; I_a = 1\text{ p.u.}$$

(*i*)

$$\tan\delta = \frac{I_a X_q \cos\phi}{V + I_q \sin\phi} = \frac{1\times 0.4\times 0.8}{1 + 0.4\times 0.6} = 0.258, \delta = 16.5°$$

(*ii*)

$$I_d = I_a \sin(\phi+\delta) = 1 \sin(36.9° + 14.9°) = 0.78\text{ A}$$

$$E_0 = V\cos\delta + I_d X_d = 1\times 0.966 + 0.78\times 0.75 = \mathbf{1.553}$$

Example 37.40. *A 3-phase, star-connected, 50-Hz synchronous generator has direct-axis synchronous reactance of 0.6 p.u. and quadrature-axis synchronous reactance of 0.45 p.u. The generator delivers rated kVA at rated voltage. Draw the phasor diagram at full-load 0.8 p.f. lagging and hence calculate the open-circuit voltage and voltage regulation. Resistive drop at full-load is 0.015 p.u.*

(Elect. Machines-II, Nagpur Univ. 1993)

Solution.

$$I_a = 1 \text{ p.u.}; V = 1 \text{ p.u.}; X_d = 0.6 \text{ p.u.}; X_q = 0.45 \text{ p.u.} ; R_a = 0.015 \text{ p.u.}$$

$$\tan\psi = \frac{V\sin\phi + I_a X_q}{V\cos\phi + I_a R_a} = \frac{1\times 0.6 + 1\times 0.45}{1\times 0.8 + 1\times 0.015} = 1.288; \quad \psi = 52.2°$$

$$\delta = \psi - \phi = 52.2° - 36.9° = 15.3°$$

$$I_d = I_a \sin\psi = 1\times 0.79 = 0.79 \text{ A} ; I_q = I_a\cos\psi = 1\times 0.61 = 0.61\text{A}$$

$$E_0 = V\cos\delta + I_q R_a + I_d X_d$$

$$= 1\times 0.965 + 0.61\times 0.015 + 0.79\times 0.6 = 1.448$$

$$\therefore \quad \%\text{ regn.} = \frac{1.448 - 1}{1}\times 100 = \mathbf{44.8\%}$$

Example 37.41. *A 3-phase, Y-connected syn. generator supplies current of 10 A having phase angle of 20° lagging at 400 V. Find the load angle and the components of armature current I_d and I_q if X_d = 10 ohm and X_q = 6.5 ohm. Assume arm. resistance to be negligible.*

(Elect. Machines-I, Nagpur Univ. 1993)

Solution. $\cos\phi = \cos 20° = 0.94;\ \sin\phi = 0.342;\ I_a = 10\text{ A}$

$$\tan\delta = \frac{I_a X_q \cos\phi}{V + I_a X_q \sin\phi} = \frac{10 \times 6.5 \times 0.94}{400 + 10 \times 6.5 \times 0.342} = 0.1447$$

$$\delta = 8.23°$$

$$I_d = I_a \sin(\phi + \delta) = 10 \sin(20° + 8.23°) = 4.73\text{ A}$$

$$I_q = I_a \cos(\phi + \delta) = 10 \cos(20° + 8.23°) = 8.81\text{ A}$$

Incidentally, if required, voltage regulation of the above generator can be found as under:

$$I_d X_d = 4.73 \times 10 = 47.3\text{ V}$$

$$E_0 = V\cos\delta + I_d X_d = 400 \cos 8.23° + 47.3 = 443\text{ V}$$

$$\%\,\text{regn.} = \frac{E_0 - V}{V} \times 100$$

$$= \frac{443 - 400}{400} \times 100 = \mathbf{10.75\%}$$

EMF EQUATION

- Let,

- P be the number of poles
- φ is Flux per pole in Webers
- N is the speed in revolution per minute (r.p.m)
- f be the frequency in Hertz
- Zph is the number of conductors connected in series per phase
- Tph is the number of turns connected in series per phase
- Kc is the coil span factor
- Kd is the distribution factor
- .

- Flux cut by each conductor during one revolution is given as Pφ Weber. Time taken to complete one revolution is given by 60/N sec

- Average EMF induced per conductor will be given by the equation shown below:

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

$$\frac{P\varphi N}{60} \times Z_{ph} = \frac{P\varphi N}{60} \times 2T_{ph} \quad \text{and}$$

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\text{Average EMF} = 4 \times \varphi \times T_{ph} \times \frac{PN}{120} = 4\varphi f T_{ph}$$

- The average EMF equation is derived with the following assumptions given below.
- Coils have got the full pitch.
- All the conductors are concentrated in one stator slot.

- **Root mean square** (R.M.S) value of the EMF induced per phase is given by the equation shown below:
- **E_{ph} = Average value x form factor**
- Therefore,

$$E_{ph} = 4\varphi f T_{ph} \text{ x } 1.11 = 4.44\, \varphi\, f\, T_{ph} \text{ volts}$$

- If the coil span factor K_c and the distribution factor K_d, are taken into consideration then the Actual EMF induced per phase is given as:

$$E_{ph} = 4.44\, K_c K_d \varphi\, f\, T_{ph} \text{ volts } \ldots \ldots (1)$$

- Equation (1) shown above is the EMF equation of the Synchronous Generator.