MODULE 1

SYNCHRONOUS GENERATOR

There are two types of synchronous machine.

1. Synchronous generator or Alternator

2. Synchronous motor

Synchronous machine is an AC machine whose operation maintains the relation

$$N_s = \frac{120f}{P} \dots\dots\dots (1) \quad \text{or}$$

$$f = \frac{PN_s}{120}$$

Synchronous generator:

- It is a synchronous machine which convert mechanical input power given by the prime mover in to AC electrical power.
- These are mainly used for large AC power generation.
- The speed of the synchronous machine is constant and it is independent of the amount of load on the synchronous generator.

Types of Synchronous Machine

Based on armature winding and field winding

Rotating-Armature Type: The armature winding is on the rotor and the field system is on the stator.

Rotating-Field Type: The armature winding is on the stator and the field system is on the rotor. For large power applications, we prefer rotating field type alternator instead of rotating armature type alternator.

Advantages of Stationery armature type alternator

1. The insulation of stationary armature winding is easier instead of giving insulation on rotary side

2. The rotor weight is less compared to stator weight due to due to heavy armature winding is placed on stator

3. Output current can be easily collected from the fixed terminals on the armature

4. Only two slip rings are required to give DC supply to the field system

5. It is easy to insulate slip ring, because they are placed on low voltage (DC) side.

6. Commutator is not present

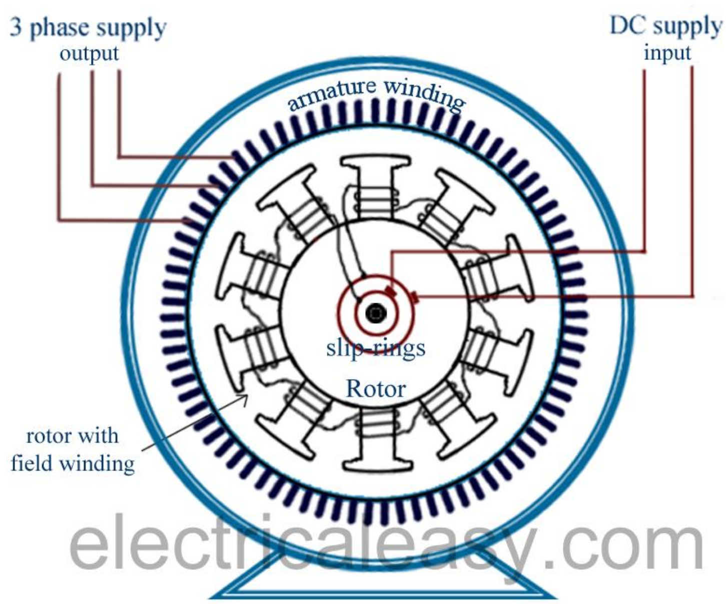
7. No Sparking at the brushes

8. Voltage rating of alternator can be easily increased

9. Cooling of the armature winding is easy

10. Higher peripheral speed can be achieved in the rotor.

Construction of Alternator



The main parts of an alternator are

1. **Stator frame**
   • It is the most outermost part of the machine
   • Made up of cast iron or cast steel
   • Main function is to give the mechanical protection and hold the armature core
2. **Stator core**
   • Stator core is laminated to reduce eddy current loss.
   • It is made up of silicon steel
   • Inner periphery of stator core contains slots. Within this slot, armature windings are placed

• There are three types of slots

1. Open type 2. Semi-closed type 3. Totally closed type

3. Stator winding or Armature winding

• Armature windings are placed in the armature slots.
• It is usually made up of copper or aluminium

4. Rotor

• It is the rotating part of the alternator. Mainly used to carry magnetic poles and field windings
• The supply to the field windings (Excitation) are usually provided from dc shunt or compound generator known as exciter.

- The excitation is given to rotor through two slip ring and brush arrangement.

Based on Rotor construction, the rotor in alternator is classified as

a. Salient pole type or Projected pole type rotor

b. Non-Salient type or Cylindrical type rotor

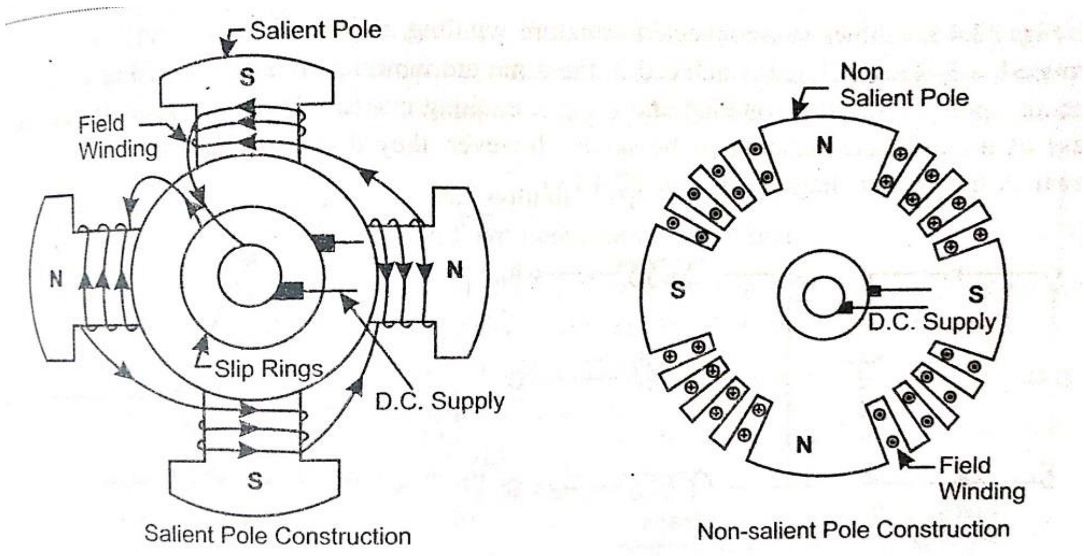
<u>**Salient pole type or Projected pole type rotor**</u>

• These types of rotor are used in the low and medium speed (125-500 rpm) alternators.
• The poles in this rotor is projected type and they are made up of steel. The pole faces of the poles carry slots and within this slots, damper windings are provided.

Damper windings are provided to prevent hunting and to provide starting torque in synchronous motor

The field windings placed on the rotor poles are connected in series and both ends of this connection is given to DC exciter

• These types of rotors are normally designed for large number of rotor poles (Since speed is low)
• These types of rotor have Large diameter and small axial length
• These are normally used with hydraulic turbines



Non-Salient type or Cylindrical type rotor

• These types of rotor are used in high speed (125-500 rpm) alternators. Hence cylindrical type alternators are also called turbo alternators

• The poles used in this rotor is not projected type. Hence the rotor shape is like a smooth cylinder. This smooth cylinder type rotor carries slots. Within these slots, the field windings are placed. The supply to the field windings is given from DC exciter

• These types of rotor have small diameter and large axial length

• These are normally used with steam turbines

• These types of rotors are normally designed for small number of rotor poles. Ie, P=2 or 4 (Since speed is high)

Damper winding - The damper winding is a squirrel-cage-like winding on the rotor of a typical synchronous electric machine. It is used to dampen the transient oscillations and facilitate the start-up operation.

5. Slip rings

• It helps to give DC current to field winding on the rotating rotor from exciter

• It is made up of hard drawn copper

6. Brush and Brush holder

• It is placed over the sliprings

• Made up of carbon

7. Shaft and Bearing

• Shaft is provided to hold the rotor and slip ring.

• Bearing allows the smooth rotation of shaft with minimal friction loss.

Comparison between salient pole type rotor and non-salient pole type rotor

Salient pole type rotor	Non-salient pole type rotor
Rotor poles are projected	Rotor poles are not projected
More number of poles are present	2 or 4 poles are present
Have large diameter and small axial length	Have small diameter and large axial length
Used for low and medium speed applications	Used for large speed applications
Used with hydraulic turbines	Used with steam turbines
Construction is difficult	Construction is easy
Windage loss is more	Windage loss is less
Air gap is present between poles	No airgap is present between poles
Flux is not uniform	Flux is uniform

Working Principle of Alternator

- Alternator consists of armature winding on stator and field winding on rotor.

• The filed winding is energized from the DC exciter and alternate N and S poles are developed on the rotor.

• When the rotor is rotated with the help of prime-mover, the stator armature conductors are cut by the magnetic flux.

• Hence an emf will be induced in the stator conductors according to faradays law of electromagnetic induction.

- The induced e.m.f is alternating since N and S poles of rotor alternately cuts the stator conductors. The direction of induced e.m.f. can be found by Fleming right-hand rule and frequency of induced emf is given by;
  $f = PN / 1\ 20$
  where N = speed of the rotor in r.p.m. P = number of rotor pole

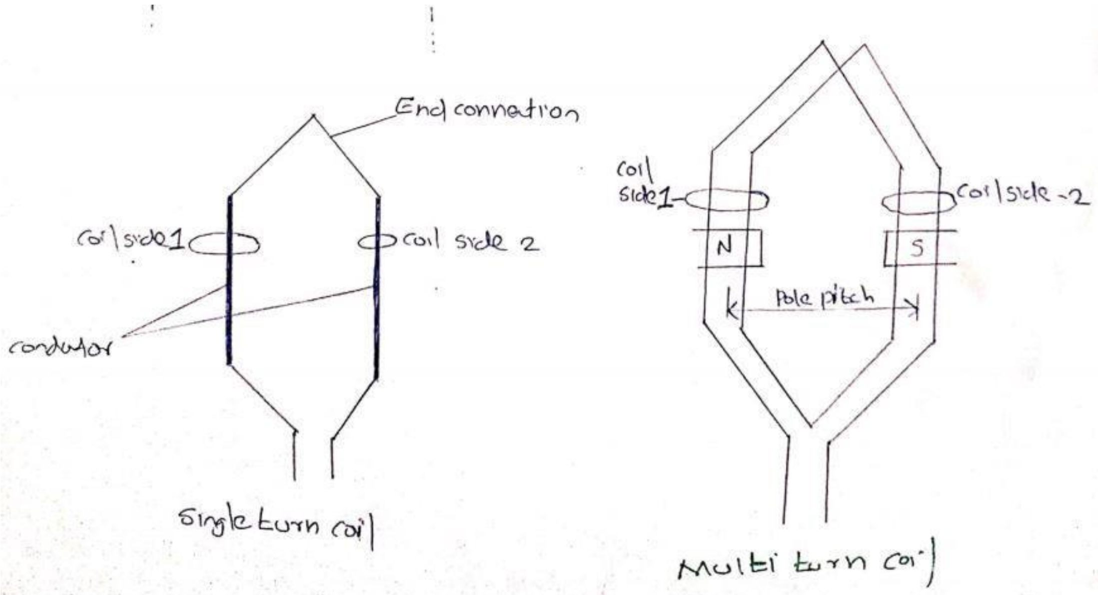
Basic terms

• **Conductor**: it is part of the coil where emf is induced

• Turn: 2 conductors joined by end connection forms one turn. If there are Z conductors, then number of turns= Z / 2

• **Coil**: A coil is formed by connecting several turns in the series

- **Pole pitch:** - Distance between two adjacent opposite main poles. It is measured in terms of number of slots or in electrical degree. One pole pitch is 180 degree electrical



- **Coil span:** - Distance b/w two coil sides of a coil. It is measured in terms of number of slots
- **Slot angle**: Angle between adjacent slots. It is measured in electrical degree

  Slot angle (β) = $\frac{180}{n}$, n = slots/Pole

CLASSIFICATION OF ARMATURE WINDING IN ALTERNATOR

1. Single phase winding and Polyphase winding

Single phase winding is seen in single phase alternator and poly phase winding is seen in alternator which are not single phase.

2. Concentrated and Distributed winding

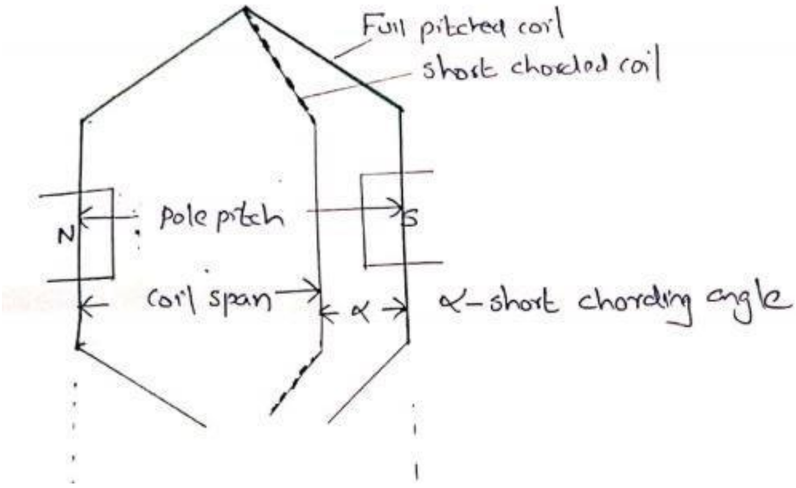
In concentrated winding, all the conductors of a coil side is placed in the same slot. This winding is used in the field winding of alternator. In distributed winding all conductors of the same coil side is not placed in the same slot. It is distributed in adjacent slots

3. Single layer and Double layer winding

In a single layer winding, one coil side is placed in one slot. It I used in small rated alternators. In double layer winding, 2 coil sides is placed in one slot as 2 layer. It is used in large power rated alternators

4. Full pitched coil winding and short chorded (or fractional pitched or short pitched) winding

If in a winding, coil span=pole pitch, such a winding is called full pitched winding.
If in a winding, coil span is not equal to pole pitch, such a winding is called short chorded winding.



Advantages of short chorded winding

1. Copper can be saved because end connection length is reduced
2. The generated emf waveform shape will be improved. Ie, emf waveform become sinusoidal shape
3. Due to short coding, high frequency harmonics can be eliminated. It helps to reduce eddy current loss and hysteresis loss in alternator

Disadvantages of short chorded winding

1. Net emf induced in the coil reduces

WINDING FACTORS

There are 2 kinds of winding factors
1. Pitch factor or Chording factor or coil span factor
2. Distribution or breadth factor

Pitch factor (Kp or Kc)

- It is also known as chording factor.
- It is the ratio of resultant emf of a short pitched coil to the resultant emf of the full pitched coil. It is always less than 1

- $Kp = \frac{\text{resultant emf of a short pitched coil}}{\text{resultant emf of the full pitched coil}}$
- $Kp = \cos\left(\frac{\alpha}{2}\right)$

α =Short chorded angle

Distribution factor (Kd or Kb)

- It is the ratio of resultant emf induced in a coil if it is distributed winded to the resultant emf induced in a coil if it is concentrated winded. It is always less than 1
- $Kb = \frac{\text{resultant emf induced in distributed winding}}{\text{resultant emf induced in concentrated winding}}$
- $Kb = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{\beta}{2}\right)}$

  Where m= (slots/pole) / phase

  β = slot angle

Frequency of induced EMF

Let,

P- no. of poles

f - frequency of the generated voltage

N – speed of the rotor in rpm

No. of cycles per revolutions= $\frac{P}{2}$

no. of revolutions\sec= $\frac{N}{60}$

Frequency of induced EMF, f = No. of cycles per revolutions × no. of revolutions\sec

$$= \frac{P}{2} \times \frac{N}{60}$$

$$\boxed{f = \frac{PN}{120}}$$

EMF EQUATION OF ATERNATOR

Let,

Z_{ph} = Number of conductor / phase

= 2T

T = Turns /Phase

Φ = flux per pole

N= speed in rpm

Kp or Kc =Pitch factor or chording factor

Kb or Kd = breadth factor or distribution factor

Kf = form factor

Total flux cut in one revolution = PΦ webber

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

According to faradays law of electromagnetic induction,

Average emf induced / conductor = $\frac{\text{Total flux cut}}{\text{Time taken}}$

$$= \frac{P\Phi}{\frac{60}{N}}$$

$$= \frac{P\Phi N}{60} \text{ volt}$$

Put N = 120f /P in above equation

$$= \frac{P\Phi}{60} \times \frac{120f}{P} = 2f\phi$$

Average emf induced / phase = $2f\phi \times Z_{ph}$

$= 2f\phi \times 2T$

$= 4f\phi\ T$

Form factor ,Kf = $\frac{\text{RMS Value}}{\text{Average value}}$ =1.11 for sinusoidal emf

RMS value of induced emf /phase = Average value of induced emf x Form factor

$= 4f\phi\ T \times 1.11$

$=4.44\ f\phi\ T$ volt

If Kc and Kd are also considered, then

Actual emf induced /phase = 4.44 fϕ T Kc Kd volt

ALTERNATOR ON LOAD OR VOLTAGE VARIATION ON LOAD

- When alternator is on no-load, the induced emf is equal to terminal voltage.
- When load is connected across the alternator, then the induced emf is not equal to terminal voltage. It is due to following reasons

1. Voltage drop due to armature resistance,Ra
2. Voltage drop due to armature leakage reactance,XL
3. Voltage drop due to armature reaction reactance,Xa

1. Voltage drop due to armature resistance

- Armature resistance per phase Ra causes voltage drop= IRa.
- This voltage drop will be in phase with armature current. (I= Load current)

2. Voltage drop due to armature leakage reactance,XL

- When current flows through armature conductors, small part of the flux does not cross the air gap and can't link the rotor.
- Such a flux is called leakage flux.
- Leakage flux setup a voltage drop and armature winding possess a leakage reactance XL
- The voltage drop due to this leakage reactance is IXL.
- This voltage drop will be 90 degree leading the armature current .

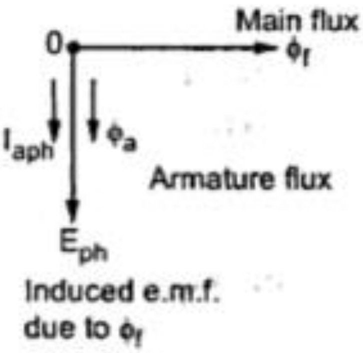
3. Voltage drop due to Armature reaction reactance,Xa

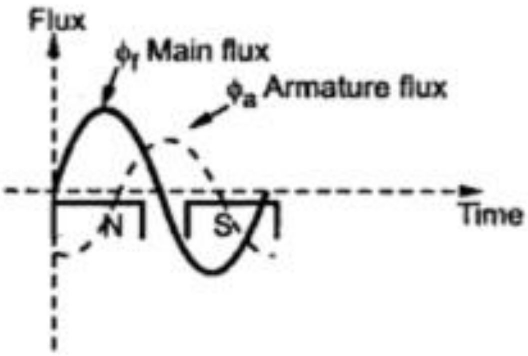
- When current flows, main field flux Φf is setup by the rotor poles.
- When rotor is rotated, induced e.m.f, Eph produced.
- This emf Eph causes a current (Iaph)flow when load is connected across the armature.
- This armature current Iaph produces a flux, Φa.
- Φa will be always in phase with Iaph.
- **The effect of armature flux on the main flux is called armature reaction.**
- **Effect of armature reaction depends on the power factor of the load.**

Effect of power factor on armature reaction

a. At UPF or Purely Resistive Load

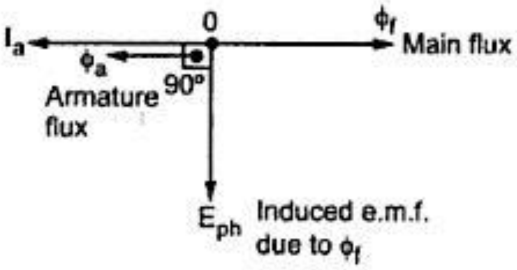
- At UPF load, Eph ,Iaph will be in phase.
- armature flux will be lagging main flux by 90 degree.
- Here the effect of armature reaction is cross magnetising effect.
- It distorts the main flux.

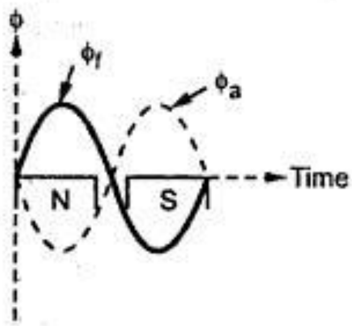




b. At Zero power factor lagging or Purely Inductive Load

- Here, Iaph **lag behind** Eph by 90 degree
- The effect of armature reaction is demagnetising effect.
- It weakens the main flux.
- Hence emf generated by the alternator reduces.
- To keep the same emf, excitation has to be increased

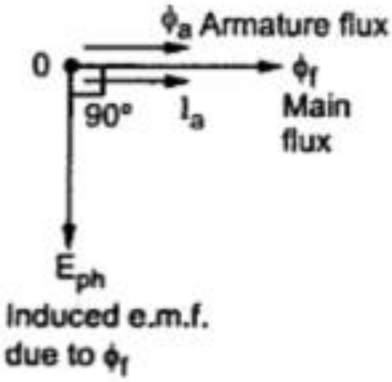


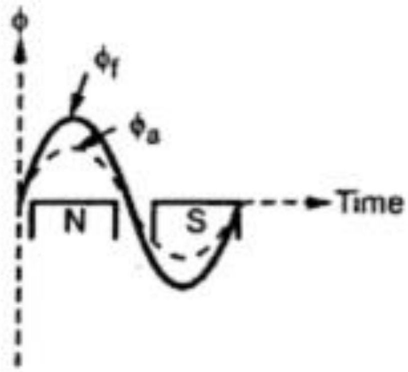


c. At Zero power factor leading or Purely capacitive Load

- At zero power factor leading, Iaph lead Eph by 90 degree .
- Armature flux will be in phase with main flux.
- It strengthens the main flux.
- So emf generated by the alternator increases.

- To keep the same emf, excitation has to be reduced





SYNCHRONOUS IMPEDENCE (Z_s)

• Vector sum of armature resistance(Ra) and synchronous reactance ($\mathbf{X_s}$) is called synchronous impedance

• $\mathbf{Z_s = Ra + jXs}$

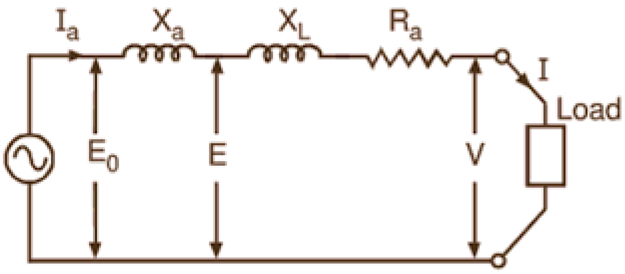
SYNCHRONOUS REACTANCE (X_s)

• It is the sum of leakage reactance, $\mathbf{X_L}$ and armature reaction reaction reactance, Xa

That is $\mathbf{X_s} = \mathbf{X_L} + \mathbf{X_a}$

PHASOR DIAGRAM OF ALTERNATOR

Consider the equivalent circuit of alternator shown below.



(a)

$E_0 = V + IRa + j\,IXs$.

Using this equation, we can plot phasor diagram of alternator at UPF, lagging P.F and leading P.F.

Steps:

1. Take V as reference

2. Plot load current, I corresponding to different power factor I is in phase with V at UPF , I lags by an angle Φ with V at lagging P.F and I leads by an angle Φ with V at leading P.F

3.Plot Voltage drop due to armature resistance= IRa, in the same direction of I

4. Plot Voltage drop due to armature leakage reactance = IXL, in the direction perpendicular to direction of I

5. Plot Voltage drop due to armature reaction = IXa, in the direction perpendicular to direction of I

6. Now join point O and D, It gives E_0

At UPF

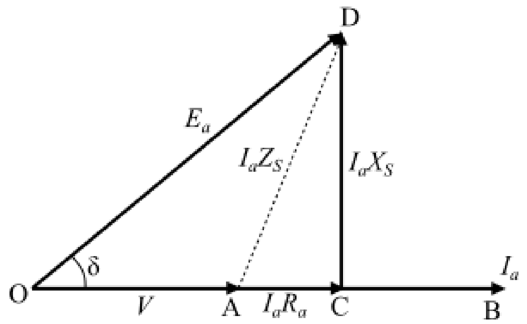


Figure-4

Eo = $\sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$

At Lagging Power factor

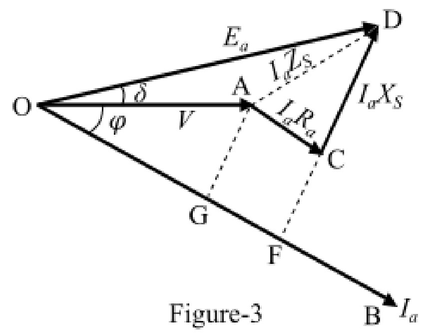


Figure-3

Eo = $\sqrt{(V\cos\emptyset + I_a R_a)^2 + (V \operatorname{Sin}\emptyset + I_a X_s)^2}$

At Leading Power factor

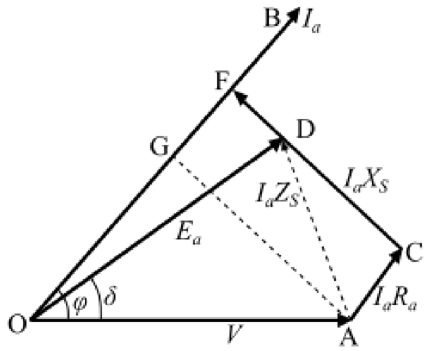


Figure-5

Eo = $\sqrt{(V\cos\emptyset + I_a R_a)^2 + (V\sin\emptyset - I_a X_s)^2}$