



**R. C. Patel College of Engineering and Polytechnic,
Shirpur**

Class: TYEE (EE5K)

Course:

A.C. MACHINES PERFORMANCE (ACM)

(Course Code: 315333)

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Unit - IV

**Three Phase Synchronous
Machines**

(16 Marks)

Course Outcome:

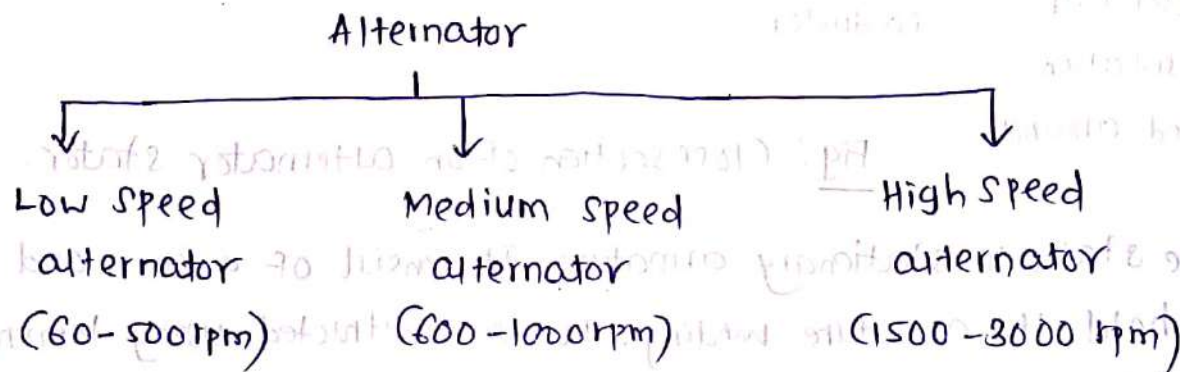
**CO4 - Test the performance of
three phase alternator.**

* Alternator:

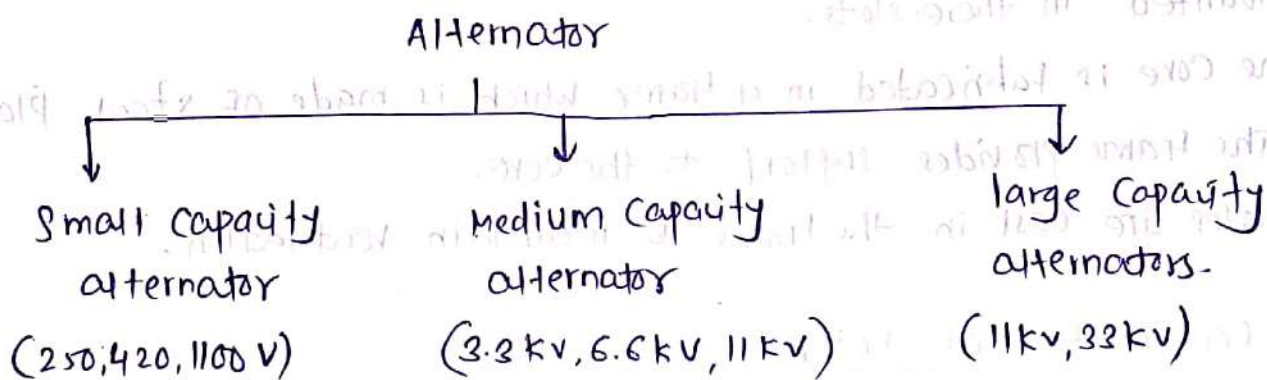
The machine that generates an alternating emf is called as synchronous generator or A.C. Generator. It is also called as alternator.

* Classification of Alternators:

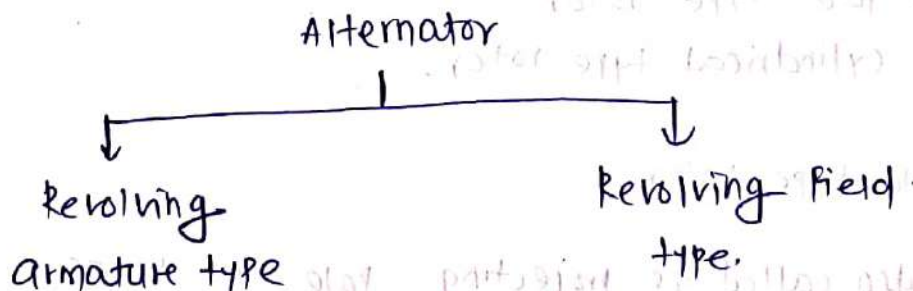
1. classification based on speed:



2. classification based on capacity and generated voltage:



3. classification based on construction:



* stator construction of 3 ϕ Alternator:

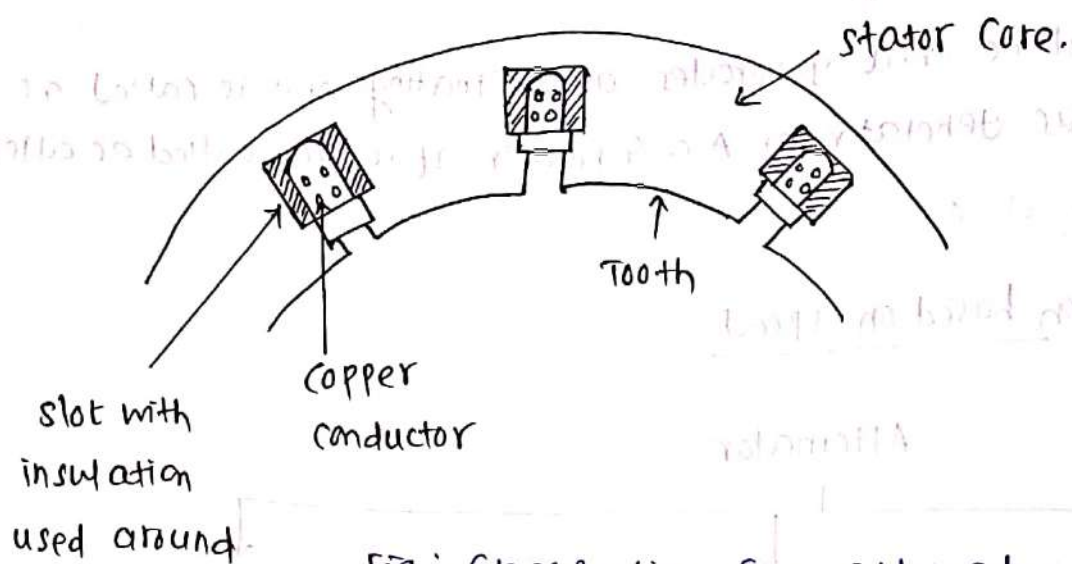


Fig: Cross section of an alternator stator.

- The stator is stationary armature. It consists of a core and slots to hold the armature winding. It is constructed using laminations in order to keep the eddy current losses small.
- The core has slots on its periphery. The armature conductors are mounted in these slots.
- The core is fabricated in a frame which is made of steel plates.
- The frame provides support to the core.
- Holes are cast in the frame to maintain ventilation.

* Construction of Rotor:

There are two types of rotors:

1. Salient pole type rotor
2. Smooth cylindrical type rotor.

1. Salient pole type rotor:

- These are also called as projecting pole type rotor.
- Projecting poles are attached to the cylindrical rotor.
- As the poles are projecting (i.e. raise from the surface of rotor) the air gap between stator and rotor is non uniform.

The poles are made up of thick steel laminations and they are attached to the rotor by means of bolting as shown in Fig.

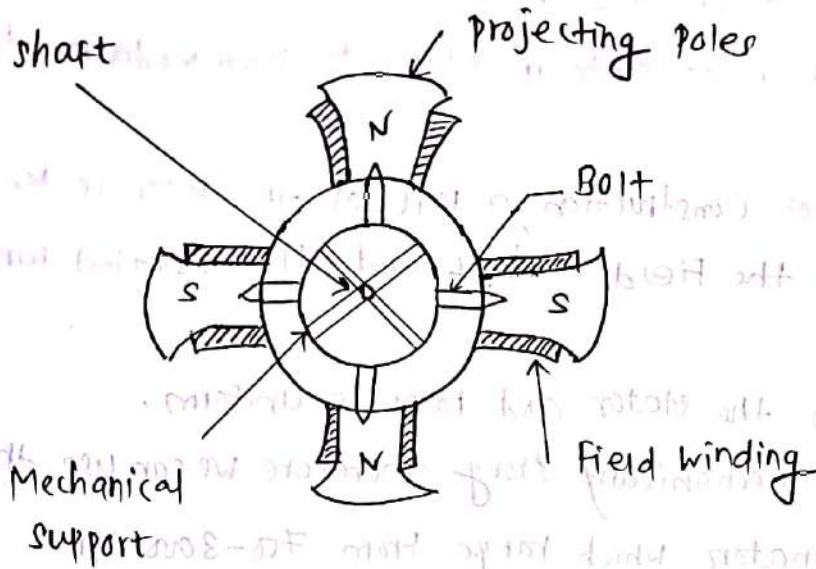


Fig: Salient pole rotor.

- Field winding is provided on the pole shoe. These construction have a large no. of poles (16, 32 etc) because the pole shoes have large diameter and small axial length. The overall size of rotor is large.
- The mechanical strength of salient pole rotor is less because the poles are externally joined to rotor. Hence it is preferred for low speed alternators which range from 125 to 500 rpm.

2. Smooth cylindrical rotor (non salient pole type rotor):

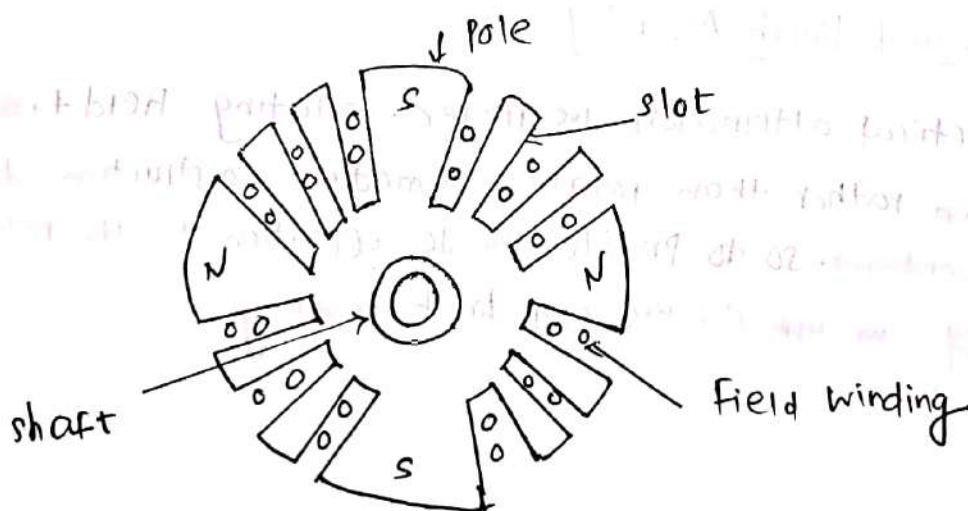


Fig: Smooth cylindrical rotor (non salient pole)

- These rotors are also called as non salient pole rotor or non projecting pole type rotor.
- The rotor consist of a smooth solid steel cylindrical rotor which has large no. of slots in order to accommodate the field winding.
- In such a type of construction, a part of the rotor is kept unslotted. The slots carry the field winding and the unslotted part would act as poles.
- The air gap betn the stator and rotor is uniform.
- These rotors are mechanically strong therefore we can use them for high speed alternators which range from 750-3000 rpm.

* Excitation system:

- The Synchronous machine i.e. alternator and synchronous motors are seperately excited machines.
- They require an external dc excitation for their operation. The field winding needs to be connected to a dc supply of the order of 110V or 220V to produce the required air gap flux.
- This supply is obtained from a small dc shunt generator called as exciter.

* slip ring and brush Assembly:

For all practical alternators we prefer rotating field type of construction rather than rotating armature construction due to certain advantages. So to provide the dc excitation to the rotating field winding, we use slip ring and brush assembly.

* Armature windings:

Two types of windings mostly used:

1. Single layer winding
2. Double layer winding.

The armature windings are also classified as:

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

① Single layer winding:

- If each slot consist of one coil side, it is said to be a single layer winding.
- If there are S number of slots, then for each phase there will be $(\frac{S}{3})$ slots are available.

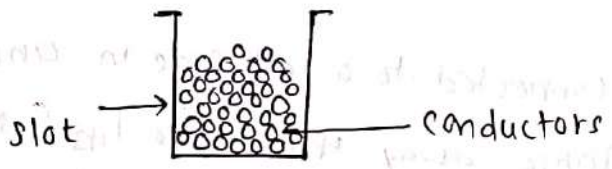


Fig. Single layer winding

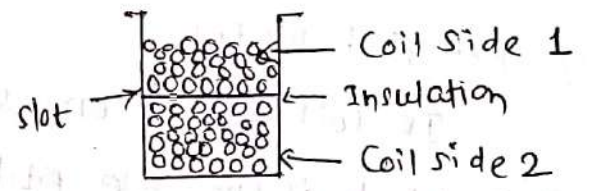


Fig. Double layer winding

② Double layer winding:

- If each slot contains two coil sides of two different coils one above the other then it is called as double layer winding.
- In this way for a total of S slots, there will be $(\frac{S}{3})$ slots per phase and there must be $(\frac{S}{3})$ coils for each phase.

Thus, No. of Coils = No. of slots for a double layer winding.

③ Concentric or Distributed windings:

i) Concentric winding:

In this type of winding, the number of slots is equal to twice the number of coils. In other words, the number of slot is equal to the number of coil sides.

In Concentrated winding the conductors belonging to a phase are placed in one slot under every pole.

ii) Distributed winding:

If the 'x' conductors per phase are distributed amongst the 'm' slots per phase available under every pole then the winding is called as a distributed winding.

④ Full pitch and short pitch windings:

i) Full pitch winding:

If coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot then the winding is said to be a full pitch winding and the coil is called as a full pitch coil.

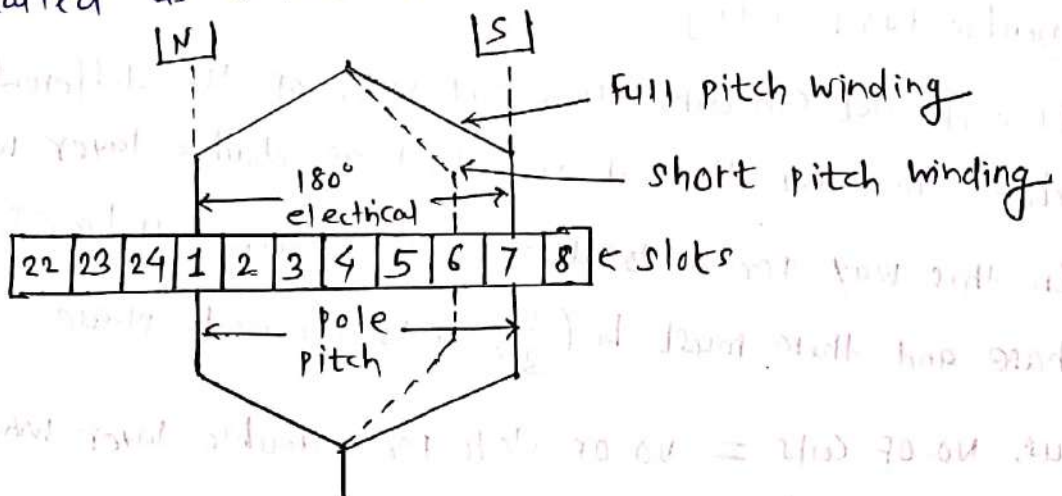


Fig: Full pitch and short pitch windings.

ii) Short pitch winding: $\text{S.P.S.} = \frac{2\pi F}{\pi} = 4\pi$ (mod) (mod 20.00)

If the coil span of a winding is less than 180° , then the winding is called as a short pitch winding.

* problems:

- ① A 3 phase, 16 pole alternator has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole 0.03 Wb, sinusoidally distributed and the speed is 375 rpm, Find the frequency, speed and phase and line emf. Assume full pitch coils.

Soln:

Given: $p = 16$

No. of slots = 144

No. of conductors/slot = 10

$\phi = 0.03 \text{ Wb/pole}$

$N = 375 \text{ rpm}$

Assume Full Pitch coil.

Find: 1. Frequency 2. Phase voltage 3. Line Voltage.

1. Frequency: = ?

$$f = \frac{PN}{120} = \frac{16 \times 375}{120} = 50 \text{ Hz}$$

2. $E_{ph} = ?$

$Z = \text{conductors/slot} \times \text{No. of slots}$

$$= 144 \times 10$$

$$= 1440$$

$$\text{No. of turns} = \frac{1440}{2} = 720$$

$$\text{No. of turns/phase } T_{ph} = \frac{720}{3} = 240$$

$$m = \frac{\text{No. of slots}}{p \times \text{No. of phase}}$$

$$= \frac{144}{16 \times 3} = 3$$

$$\beta = \frac{180^\circ}{\text{No. of slots}} = \frac{180 \times 16}{144}$$

$$\boxed{\beta = 20^\circ}$$

$$\begin{aligned} \therefore k_d &= \frac{\sin(m\beta/2)}{m \sin(\beta/2)} \\ &= \frac{\sin(3 \times \frac{20}{2})}{3 \sin(20/2)} \end{aligned}$$

$$\boxed{k_d = 0.9598}$$

$$k_c = 1 \text{ for full pitch winding}$$

$$\text{Step 3: } E_{ph} = ?$$

$$\begin{aligned} E_{ph} &= 4.44 k_c k_d \phi F T_{ph} \\ &= 4.44 \times 0.9598 \times 1 \times 0.03 \times 50 \times 240 \\ &= 1534.14 \text{ V} \end{aligned}$$

$$\begin{aligned} E_{line} &= \sqrt{3} \times E_{ph} \\ &= \sqrt{3} \times 1534.14 \end{aligned}$$

$$\boxed{E_L = 2657.2 \text{ V}}$$

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A 16 pole, 3 phase star connected alternator armature has 12 slots with 24 conductors per slot and the flux per pole is 0.1 Wb. sinusoidally distributed. Calculate the line emf generated at 50 Hz.

Ans: Given:

Alternator $P = 16$
 $F = 50 \text{ Hz}$

No. of slots = 12

No. of conductors = 24

$\phi = 0.1 \text{ Wb}$

Find: Line emf generated.

$$Z = \text{Conductor / slot} \times \text{No. of slots}$$

$$= 24 \times 12$$

$$= 288$$

$$\text{No. of turns} = \frac{Z}{2} = \frac{288}{2} = 144$$

$$\text{No. of turns / phase } T_{ph} = \frac{144}{3} = 48$$

$$m = \frac{\text{No. of slots}}{P \times \text{No. of phases}}$$

$$= \frac{12}{16 \times 3}$$

$$m = 0.25$$

$$\beta = \frac{180 P}{\text{No. of slots}} = \frac{180 \times 16}{12} = 240^\circ$$

$$\beta = 240^\circ$$

$$k_d = \frac{\sin(m\beta/2)}{m \sin(\frac{\beta}{2})}$$

$$= \frac{\sin\left(0.25 \times \frac{240}{2}\right)}{0.25 \sin\left(\frac{240}{2}\right)}$$

$$\boxed{k_d = 2.309}$$

$$k_c = 1 \text{ For full pitch winding}$$

$$E_{ph} = 4.44 k_c k_d \phi F T_{ph}$$

$$= 4.44 \times 2.309 \times 1 \times 0.1 \times 50 \times 48$$

$$= 2460.8 \text{ V}$$

$$E_{line} = \sqrt{3} E_{ph}$$

$$= \sqrt{3} \times 2460.8$$

$$\boxed{E_L = 4262.4 \text{ V}}$$

Q. Define : i) Pitch Factor ii) Distribution Factor

Ans: i) Pitch Factor: (K_p or K_c) (or coil span factor)

Pitch Factor is also known as Coil span Factor.

It is defined as ratio of vector sum of induced emfs per coil to the Arithmetic sum of induced emfs per coil.

$$K_p \text{ or } K_c = \frac{\text{vector sum of induced emfs per coil}}{\text{Arithmetic sum of induced emfs per coil.}}$$

OR Pitch Factor is also defined as:

$$K_p \text{ or } K_c = \frac{\text{EMF induced in short pitch winding}}{\text{EMF induced in full pitch winding}}$$

ii) Distribution Factor: (K_d) (or Breadth Factor or Winding Factor or spread Factor)

Distribution Factor is defined as,

$$K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$$

It is given by formula,

$$K_d = \frac{\sin(m\beta/2)}{m \sin(\frac{\beta}{2})}$$

Q. State any two parts of alternator with material used for them.

Ans: Following are the ~~types~~ ~~of~~ parts of alternator:

i) Stator ii) Rotor.

Stator is the stationary armature. It consists of a core and slots to hold the armature winding.

It can be made of cast aluminium, cast iron or fabricated steel plates.

Rotor is the rotating part of alternator.

The rotor poles are made up of steel laminations.

Q. Give any three advantages of short pitch winding.

Ans: Advantages of short pitch winding:

- 1) It gives a waveform which is closer to a sinusoidal waveform by reducing the harmonic component.
- 2) It saves copper, because the length of conductor required for the connections is less.
- 3) High frequency harmonics will get eliminated. This increases the efficiency.

Q. List out the advantages of having a stationary armature and rotating field of 3 ϕ alternator.

Ans: Advantages of having a stationary armature and rotating field of 3 ϕ alternator:

- 1) Voltage developed by the alternator is in range of 11 kV, 33 kV etc. If this high voltage winding is kept rotating then providing an insulation to the slip rings is difficult. But if the armature winding is kept stationary the connections can be made easily from the terminals to the windings.
- 2) Field winding needs a low voltage dc supply of 110V or 220V just to produce the magnetic flux. Hence even if the field winding is rotating it can be easily insulated.
- 3) Higher voltages produces certain mechanical stresses. But with stationary armature these stresses are not dangerous. With rotating armature, the rotating stresses developed due to high voltage may reduce the life of armature.

Q. Derive the EMF equation of 3 ϕ alternator. (2)

Ans: let ϕ = Flux per pole

F = Frequency of induced EMF in Hz.

T_{ph} = No. of turns of armature conductor per phase.

We know that, average EMF induced into the single conductor after cutting flux

$$e_{avg} = \frac{\text{Flux cut}}{\text{Time taken}}$$

$$e_{avg} = \frac{d\phi}{dt}$$

This is the induced EMF in one conductor cutting flux of one pole.

If N rpm is the speed of rotation then time required for 1 complete revolution = $\left(\frac{60}{N}\right)$ seconds

Total flux cut by a single conductor = $d\phi = \phi \times p$.

$$\therefore e_{avg} = \frac{\phi p}{60/N} \text{ volts}$$

$$e_{avg} = \frac{\phi p N}{60} \text{ volts} \quad \text{--- (1)}$$

$$\text{but } F = \frac{PN}{120} = \frac{PN}{2 \times 60} \therefore \frac{PN}{60} = \underline{\underline{2F}}$$

$\therefore$ substituting this in eqn (1)

$$\therefore e_{avg} = \phi \times 2F \text{ volts}$$

Two conductors are placed in series so as to make one turn.

$$\therefore e_{avg}/\text{turn} = 2 \times 2\phi F = 4\phi F$$

Q. Give the relationship between N_s & F for alternator.
 Ans: Frequency of induced emf is given by

$$F = \frac{PN}{120} \text{ (Hz)}$$

where Speed N is called as synchronous speed.

$\therefore$ synchronous speed is given by

$$N_s = \frac{120F}{P}$$

Thus synchronous speed is directly proportional to frequency and inversely proportional to the no. of poles.

Q. Compare cylindrical (smooth) and salient pole rotor used in large alternator.

Ans:	sr.no.	Salient pole rotor	cylindrical rotor
	1.	Salient pole rotor has poles which are projecting out from the surface.	-cylindrical rotor does not have poles that are projecting out.
	2.	The air gap beth stator and rotor is non-uniform.	-The air gap beth the stator and rotor is uniform.
	3.	The salient pole rotor has large no. of poles.	-The smooth cylindrical rotor has small no. of poles.
	4.	Salient pole rotors are mechanically weak.	-cylindrical pole rotors are mechanically strong.
	5.	They are have large diameter and small axial length.	- they have small diameter and large axial length.
	6.	The prime movers used are water turbines, IC engines.	-The prime movers used are steam turbines and electric motors.
	7.	They are preferred for low speed alternators which range from 120-500 rpm.	-They are preferred for high speed alternators which range from 750-3000 rpm.

5) As there are T_{ph} turn per phase, the average emf per phase is

$$e_{avg}/\text{phase} = 4 \phi F T_{ph} \text{ volts}$$

We know that rms value is normally used. we

$$\text{Form Factor} = \frac{e_{rms}}{e_{avg}} = k_f = 1.11.$$

$$\therefore e_{rms} = 1.11 e_{avg}$$

$\therefore$ The rms value of emf per phase is,

$$E_{ph} = 1.11 \times 4 \times \phi \times F \times T_{ph}$$

$$E_{ph} = 4.44 \phi F T_{ph} \text{ volts}$$

This is emf equation of 3ϕ alternator with full pitched and concentrated type winding.

But in practice, the winding is short pitched and distributed.

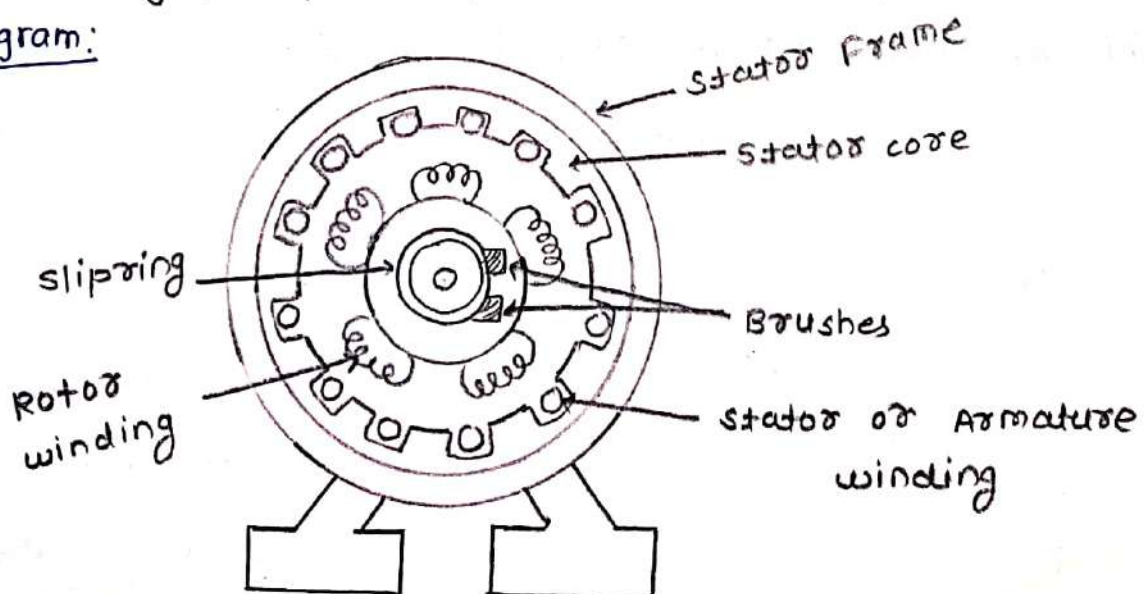
Hence the actual induced emf is given by

$$E_{ph}(\text{actual}) = 4.44 \phi F T_{ph} \times k_c k_d.$$

Where k_c and k_d are generally less than 1.

Q. With the help of neat labeled diagram, explain the construction and working principle of 3ϕ Alternator.

Ans: Diagram:



As shown in Fig. Field windings are placed on the rotor and the armature winding is wound and placed in the stator slots of suitable shape.

The Field windings (rotor) is connected to an external dc source called exciter through a pair of sliprings.

The armature winding is a 3ϕ winding placed on the stator and the induced voltage in this winding is applied to the load.

This is a 3ϕ Ac voltage.

The stator frame is made of cast iron to support the stator core.

The stator core has slots on its inner periphery in order to hold the stator conductor.

The rotor has alternate N and S poles fixed on its outer periphery.

These magnetic poles of the rotor are excited from an external dc source.

Working principle:

When the rotor of alternator is rotated through prime mover the stationary armature conductor cuts the magnetic field produced by rotor poles. According to Faraday's law of electromagnetic induction an emf get induced in armature conductors.

As the armature winding on stator, is 3ϕ winding, emf induced is 3ϕ emf.

This 3ϕ induced emf is supplied to load.

—————x—————

* Parameters of Armature winding:

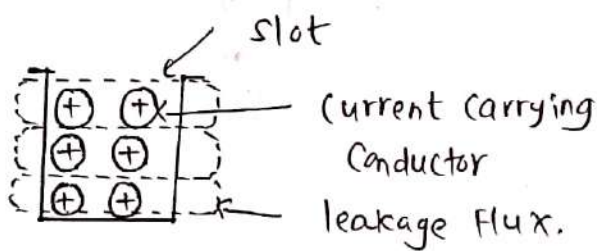
- ① Armature resistance (R_a)
- ② Armature leakage reactance
- ③ Reactance corresponding to armature reaction.

① Armature resistance : (R_a)

Armature has its own resistance. The effective resistance of an armature winding per phase is denoted by ' R_{aph} ' or ' R_a ' / phase.

The armature resistance can be obtained by applying d.c voltage & measuring d.c current flowing through it.

② Armature leakage reactance X_L :



The flux which does not link with armature conductor is called leakage flux. It is no useful.

The inductance of the armature winding is called as leakage inductance and its reactance is known as leakage reactance (X_L).

Defn: A part of flux produced by the field winding, that does not cross the air gap and reach armature conductors but completes its path through the surrounding iron part is called as leakage flux and the corresponding inductive reactance is known as leakage reactance.

* Armature Reaction :

The effect of armature flux on the pole flux is called as armature reaction.

$\phi_a \propto I_a \propto \text{load}$ Hence load p.f.

* Armature Reaction at various power Factor:

① Effect of unity P.F load : (i.e. Resistive load)

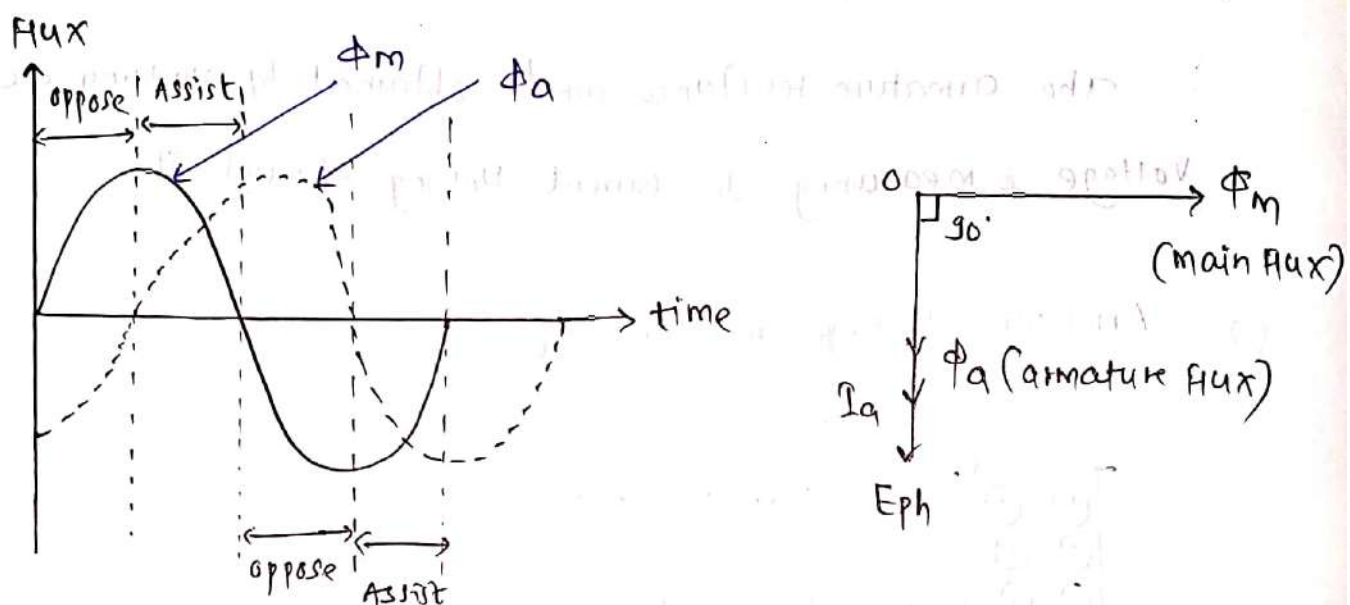


Fig. Armature reaction For unity P.F.

- Consider that a purely resistive load is connected to the alternator having unity p.f. This indicates that the induced emf E_{ph} will be in phase with the current I_{aph} . As power factor is unity, the directions of E_{ph} and I_{aph} are the same.
- The emf E_{ph} lags behind the main flux by 90° . The direction of ϕ_a and I_a is same.
- From the waveforms of the two fluxes the pole or main flux ϕ_m and the armature flux ϕ_a , we can see that the two fluxes oppose each other on the left of each pole and they help each other

on right half of each other pole.

- Therefore the average flux in the air gap will remain constant. But the distortion of flux gets distorted i.e. armature flux, distorts the pole flux.

- Such effect of armature reaction is called as cross magnetizing effect of the armature reaction.
- This causes the terminal voltage available on load to decrease by a small amount.

② Effect of lagging p.f. (purely inductive)

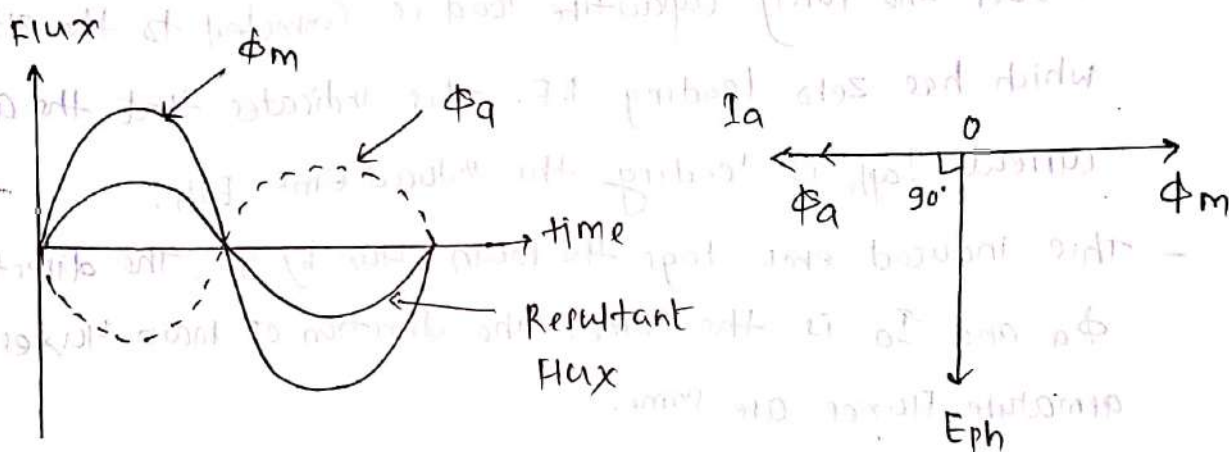


Fig. Armature reaction for zero lagging p.f.

- Consider purely inductive load is connected to the alternator which has zero lagging p.f.
- This indicates that the armature current I_a is lagging behind the induced emf E_{ph} by 90° . This emf lags the main flux by 90° . The direction of Φ_a and I_a is same.
- The directions of the pole flux i.e. Φ_m and the armature flux Φ_a are exactly opposite.
- So the armature flux tries to cancel the pole flux. The net result is decrease in the flux. This effect is called as demagnetizing effect. This causes the terminal voltage on load to decrease.

③ Effect of leading p.f: (purely capacitive load):

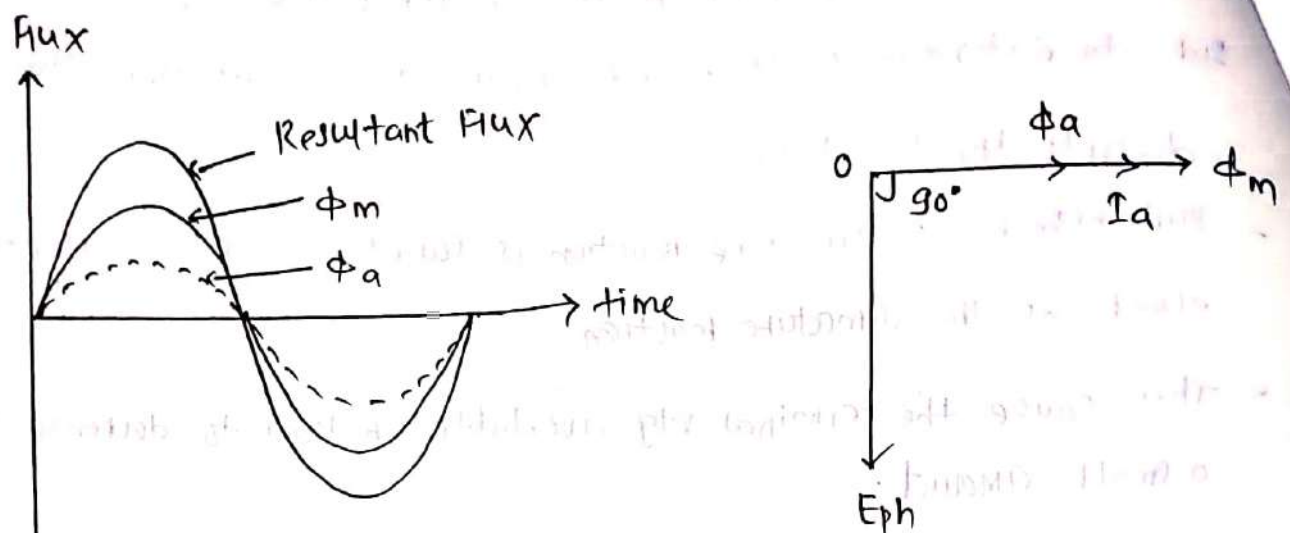


Fig. Armature reaction for leading P.F.

- Consider the purely capacitive load is connected to the alternator which has zero leading P.F. This indicates that the armature current I_a is leading the induced emf E_{ph} .
- This induced emf lags the main flux by 90° . The direction of Φ_a and I_a is the same. The direction of main fluxes and armature fluxes are same.
- Therefore now the armature flux will help the main flux Φ_m . Therefore the total flux will increase on load. Such effect of armature reaction is called as magnetizing effect of the armature reaction.
- Due to this effect the terminal vty becomes higher than the no load emf.

(15)

* Synchronous reactance (X_s) and synchronous impedance (Z_s):

① Synchronous Reactance (X_s):

Both the armature reaction effect and leakage flux effect are represented by imaginary coils X_a and X_L respectively & they are considered to be in series with the armature.

- The vty drops across them are $I_a X_a$ and $I_a X_L$.
- Hence it is possible to combine these reactances in series & the net effect is called synchronous reactance. X_s ohm.

$$X_s = X_a + X_L$$

Defn: The synchronous reactance (X_s) is the imaginary reactance used to represent the vty effects in the armature circuit produced by the actual leakage reactance & by the armature reaction.

→ Unit is ohm.

$$\therefore X_s = (X_a + X_L) \text{ } \Omega/\text{ph}$$

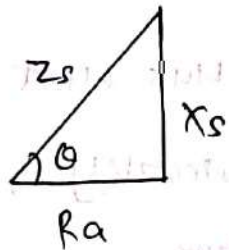
② Synchronous Impedance (Z_s):

Synchronous impedance Z_s is a fictitious impedance used to represent the voltage effects in the armature circuit, produced by the actual armature resistance, actual armature leakage reactance & armature reaction. Its unit - ohm.

$$Z_s = R_a + jX_s \text{ } \Omega/\text{ph}$$

$$|Z_s| = \sqrt{(R_a)^2 + (X_s)^2} \text{ } \Omega/\text{ph}$$

* Relation beth R_a , X_s & Z_s :



$$Z_s = [R_a^2 + X_s^2]^{1/2}$$

$$\theta = \tan^{-1} \left(\frac{X_s}{R_a} \right)$$

* Equivalent circuit of an Alternator:

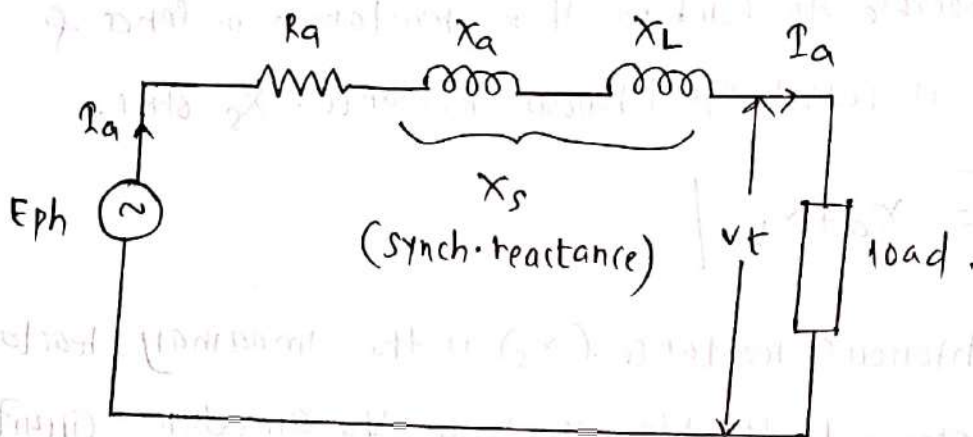


Fig. Equivalent Circuit of an alternator.

Fig. Shows equivalent circuit of an 3ϕ alternator. All the quantities in the equivalent ckt are per phase quantities.

E_{ph} = Induced emf per phase

V_t = Terminal vty per phase on load

I_a = Armature current per phase.

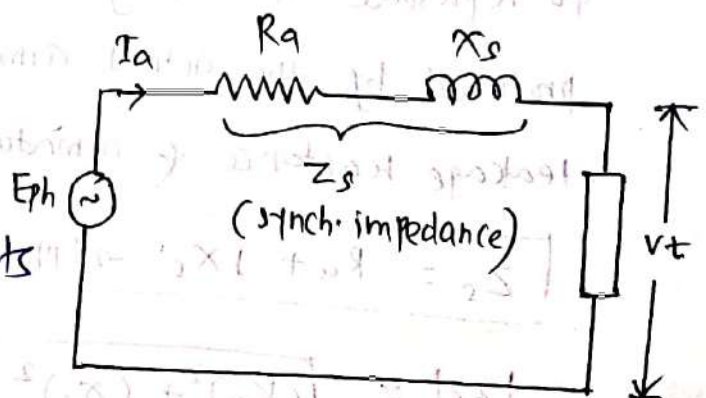
X_a = Reactance due to armature reaction

X_L = leakage reactance.

we know that

$$X_s = X_a + X_L$$

Therefore, the equivalent ckt gets modified as shown in fig.



* Terminal voltage:

The vty that is available at the load terminals is called as the terminal vty V_t or V_{ph} .

* Factor affecting the terminal vty:

The factor affecting the terminal vty are:

1. Armature resistive drop ($I_a R_a$)
2. leakage reactance drop ($I_a X_L$)
3. Drop due to armature reaction ($I_a X_a$)

* voltage equation:

$$\bar{E}_{ph} = \bar{V}_{ph} + \bar{I}_a R_a + \bar{I}_a X_s.$$

* vector (phasor) diagrams of a loaded alternator:

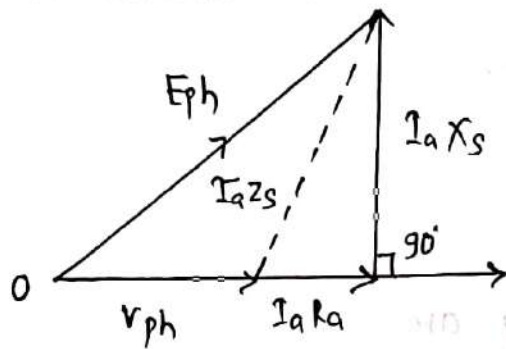
In order to draw the phasor diagram, we need to refer the following expression:

$$\bar{E}_{ph} = \bar{V}_{ph} + \bar{I}_a R_a + \bar{I}_a X_s$$

procedure:

1. choose the phasor current (I_a) as reference phasor
2. Draw the phasor V_{ph} at an angle ϕ with respect to I_a .
3. Draw the ' $I_a R_a$ ' drop in phase with I_a .
4. Drop ' $I_a X_s$ ' is as purely inductive vty drop, so draw it 90° leading to I_a .
5. join the starting points to the terminating points, draw the phasor ' E_{ph} '.

1. phasor diagram for unity P.F. load:

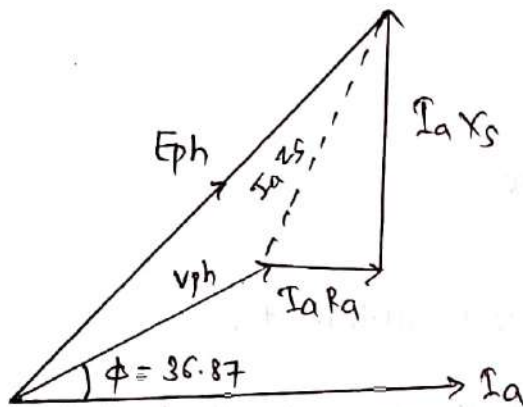


$$\cos \phi = 1$$

$$\text{Hence } \phi = 0.$$

Fig. phasor diagram for unity P.F.

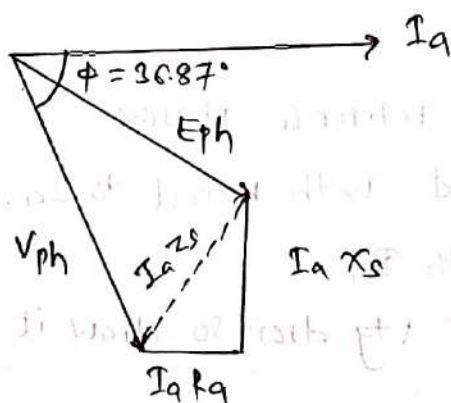
2. phasor diagram with $\cos \phi = 0.8$ lagging:



$$\cos \phi = 0.8 \text{ lagging}$$

$$\therefore \phi = 36.87^\circ$$

3. phasor diagram for $\cos \phi = 0.8$ leading:



$$\cos \phi = 0.8 \text{ (leading)}$$

$$\therefore \phi = 36.87^\circ$$

voltage regulation of an alternator:

(19)

Defn: It is defined as the change in its terminal V_{tg} when full load is removed, keeping field excitation and speed constant, divided by the rated terminal V_{tg} .

$$\% \text{ Regulation} = \frac{V_{tg} \text{ at no load} - V_{tg} \text{ at full load}}{V_{tg} \text{ at full load}} \times 100$$

No load $V_{tg} = E_{ph}$ (induced emf)

V_{tg} at full load = V_{ph} i.e. terminal V_{tg} (V_t)

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

* Factor affecting V_{tg} regulation:

1. Value of load current
2. Value of P.F.
3. Types of load.

* Regulation by direct loading method:

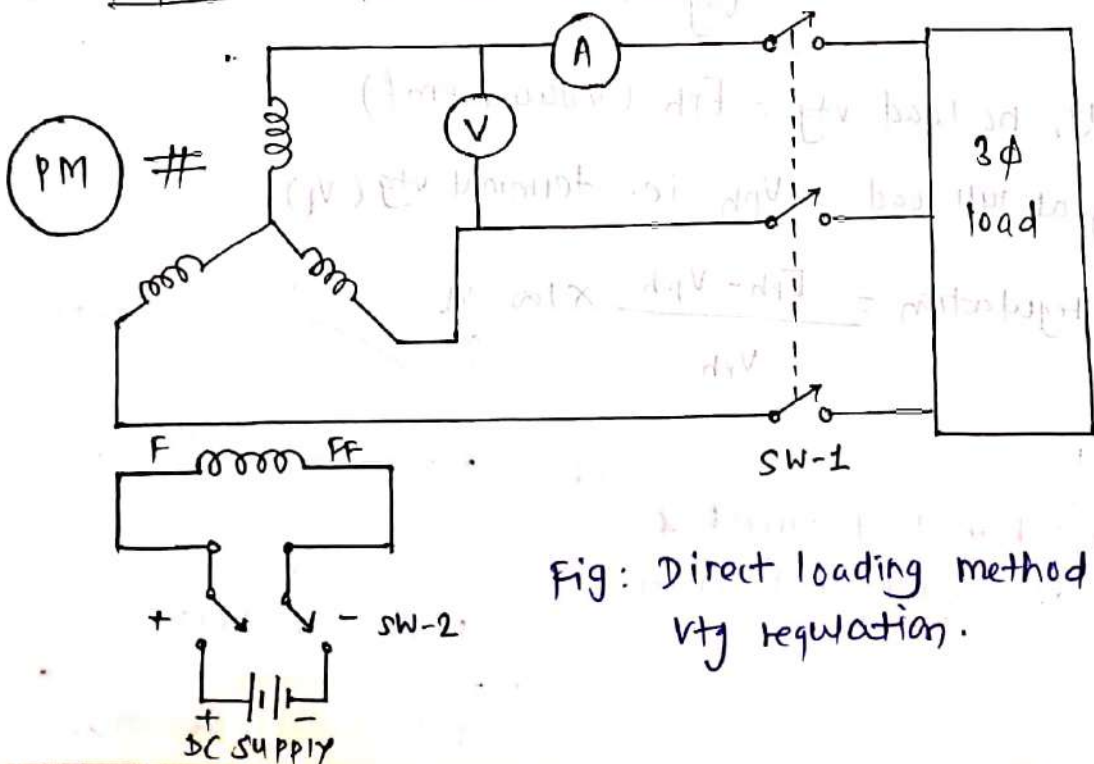


Fig: Direct loading method for V_{tg} regulation.

fig. shows the set up for direct loading method to

measure the V_{tg} regulation.

procedure:

- Turn on the prime mover and adjust its speed to the synchronous speed.
- switch on DC excitation and adjust it in such a way that V_{tg} developed gives a rated full value across the load terminals.
- Keep DC excitation constant.
- Keep three switches closed and vary the load until the wattmeter and ammeter indicate the rated values at desired p.f.
- Now measure the F.L. terminal V_{tg} using ac voltmeter.
- Now keeping the speed and the field excitation constant.
- Disconnect the load from the alternator output by open circuiting the switches and measure the no load terminal V_{tg} .
- From these V_{tg} readings, calculate the V_{tg} regulation of the alternator, using the following expression.

$$\% \text{ regulation} = \frac{V_{tg} \text{ at no load} - V_{tg} \text{ at full load}}{V_{tg} \text{ at full load}} \times 100$$

Normally, no load $V_{tg} = E_{ph}$ (induced emf)

V_{tg} at full load = V_{ph} i.e. terminal V_{tg} (V_t).

$$\% \text{ regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

* load characteristics:

The relationship between load current & terminal V_{tg} is called load chs of an alternator.

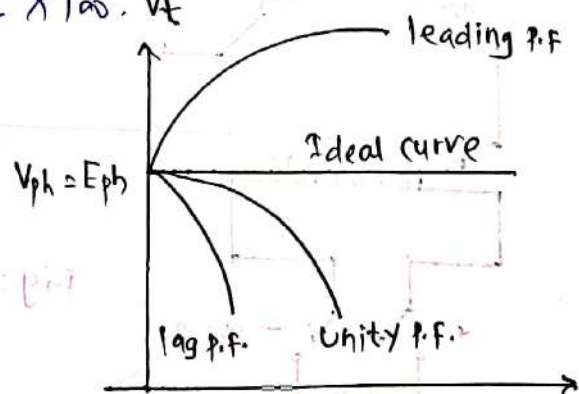


Fig. load characteristics.

* Drawback of direct loading method:

- Direct loading method is useful only for small capacity alternator.
- In case of large machines, the cost of finding the regulation by direct loading becomes prohibited.
- Hence other indirect methods are used.

* Indirect methods to find Regulation:

For large alternator, indirect method is used. Following are the indirect methods used to find the regulation:

1. Synchronous impedance or emf method.
 2. The ampere-turn or mmf method.
 3. Zero power factor or potier method.
- All these methods require the following:
1. Armature resistance R_a
 2. open circuit / no load characteristics
 3. short circuit characteristics.

In this chapter we will learn about synchronous impedance method or emf method.

* Regulation of An alternator by synchronous impedance

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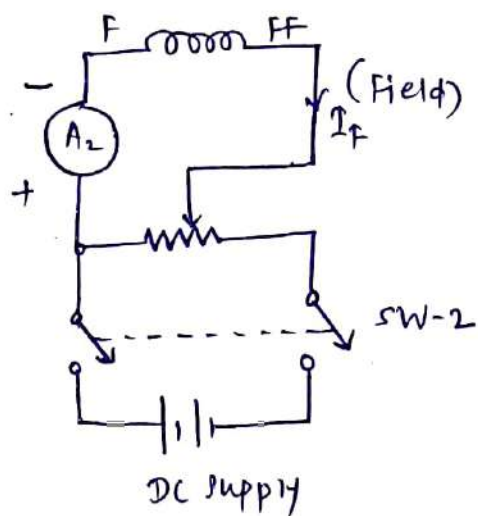
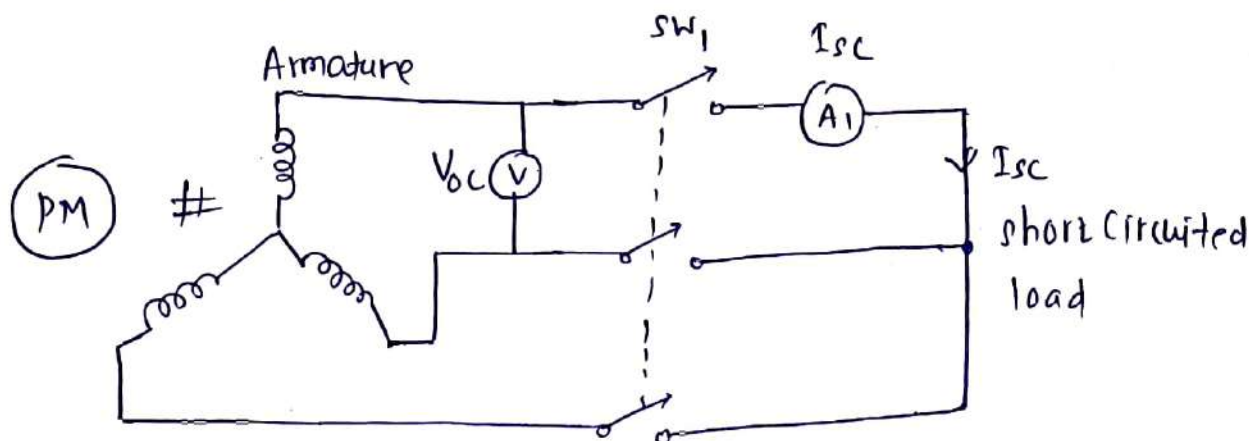
Method:

→ It is also called as EMF method: of determining voltage regulation of an alternator.

→ Two tests are carried out for this

1. Open circuit test

2. Short circuit test



* Open circuit test (o.c.):

① p.m. started and the alternator is driven at the rated speed. switch SW-1 is kept open.

② switch on SW-2. Using variable resistance, the field current is increased from zero to its rated value.

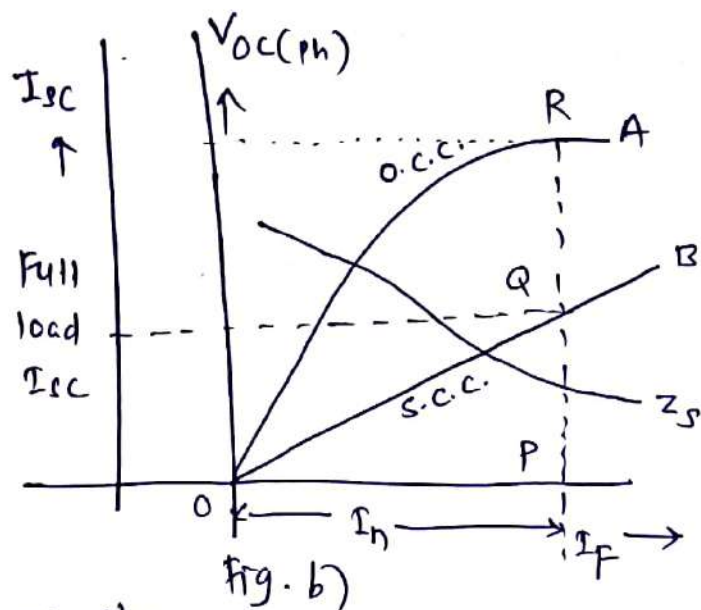
③ Measure the vtg using an ac voltmeter across an armature winding. This is value of open circuit vtg.

④ Now, vary the field current and for various values of field currents, note down the voltmeter readings.

Obs. Table

Sl. No.	$I_f (A)$	$V_{oc} (line)$	$V_{oc} (ph) = V_{oc} (line) / \sqrt{3}$
1			
2			
3			

From the observation, plot the graph of Field current I_f Vs $V_{oc(ph)}$. This is called as open circuit characteristics of an alternator.



The open circuit characteristics are indicated by the curve OA.

This char indicates how the magnetic circuit of the alternator gets saturated with the increase in field currents.

Therefore, it is also called as the saturation curve of an alternator.

* Short circuit test:

Procedure:

1. P.M. is started and the alternator is driven at rated speed. Switch sw-1 is kept open.
2. Switch on sw-2. The Field current is kept to its minimum value by the variable resistance and the armature winding terminals are short circuited through an ammeter by closing the switch sw-1.
3. The field excitation I_f is then gradually increased till the full load current is drawn from the armature winding.
4. The curve of armature current against the field current is then plotted. It is plotted as curve OB as shown in Fig. b). It represents the short circuit char of an alternator.

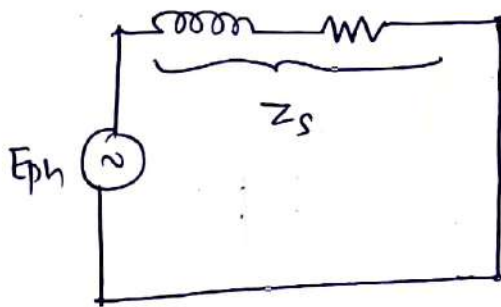
Obs. Table:

Sr. No.	$I_f (A)$	Short circuit Arm. Current $I_{sc} (A)$

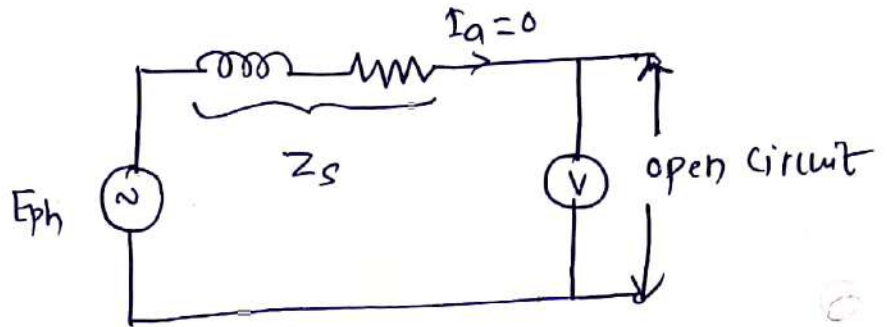
5. The S.C.C. is straight line which passes through the origin. The O.C.C. i.e. open circuit char looks similar to the B-H curve of a magnetic material.

* To obtain synchronous impedance Z_s :

- The synchronous impedance Z_s of an alternator changes with the load conditions.
- The open circuit & s.c. tests are used to determine the value of the synchronous impedance Z_s for any load and load p.f. conditions.



a) Equivalent circuit for short circuit test



b) Equivalent circuit for open circuit test.

- From the equivalent circuit we get,

$$Z_s = \frac{E_{ph}}{I_{sc}} \quad \text{For same } I_f.$$

$$E_{ph} = V_{oc} (ph)$$

$$\therefore Z_s = \frac{V_{oc} (ph)}{I_{sc}} \quad \text{For same } I_f$$

Thus,

$$Z_s = \frac{\text{phase emf on open circuit}}{\text{phase current on short circuit}} \quad \left. \vphantom{\frac{\text{phase emf on open circuit}}{\text{phase current on short circuit}}} \right\} \text{For same field current}$$

- The o.c.c and s.c.c. can be used to calculate Z_s
- The value of Z_s are different for different values of I_f .

* Calculation of Z_s From o.c.c and s.c.c

(25) 4

- The o.c.c. is non linear in nature

$$V_{oc(ph)} = \text{emf given by distance } PR$$

- From s.c.c., the field current I_f required to drive the Full load short circuit current can be found

$$I_{sc(ph)} = \text{current given by distance } PQ.$$

$$\text{Thus, } Z_s \text{ at Full load} = \frac{V_{oc(ph)}}{I_{sc(ph)}} \quad \left| \text{For same } I_f \right.$$

$$Z_s = \frac{PR}{PQ} \quad \left| \text{same } I_f = OP \right.$$

* Regulation Calculations :-

We know that

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$\left[\begin{array}{l} \because V_{ph} = E_{ph} - I_a Z_s \\ V_{ph} = \text{Rated voltage} \\ \quad \quad \quad (\text{Rated phase vltg}) \\ I_a = \text{Armature phase current} \end{array} \right.$$

$$E_{ph} = \sqrt{(V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi + I_a X_s)^2}$$

* Procedure:

- The steps to calculate the percent regulation using the synchronous impedance method are as follows:
1. Measure DC resistance of the armature circuit of the alternator. The effective AC resistance may be taken to be 1.2 times the D.C. resistance.

2. Calculate Z_s from oc and sc tests for any load conditions as follows:

$$Z_s = \frac{V_{oc(ph)}}{I_{sc}} \quad \left| \quad \text{for same } I_f \right.$$

3. Calculate the synchronous reactance X_s as follows:

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

4. Determine the no load emf per phase E_{ph} as follows:

$$E_{ph} = \sqrt{(V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi \pm I_a X_s)^2}$$

5. Where V_t is the rated phase V_{tg} and I_a is the armature phase current. (V_t means V_{ph})

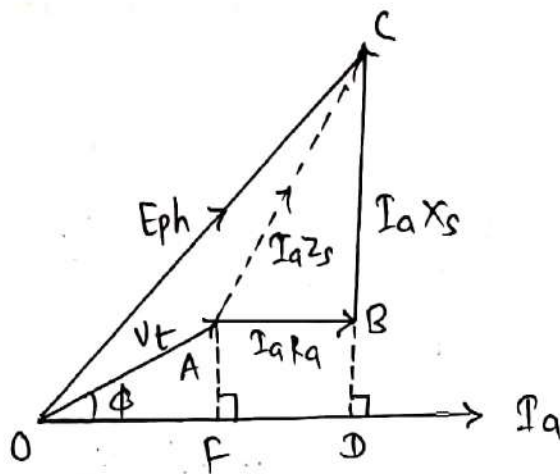
6. The positive sign in the above expression is for the ^{lagging} ~~leading~~ PF and negative sign is for the ~~lagging~~ ^{leading} PF load.

* phasor diagrams and Regulation calculation:

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

1. Case 1: Lagging Power Factor:

The P.F of the load $\cos \phi$ is lagging, so I_a lags V_{ph} or V_t (terminal V_{tg}) by angle ϕ . The phasor diagram is shown in Fig:



$$OA = V_t$$

$$AB = I_a R_a$$

$$BC = I_a X_s$$

$$OC = E_{ph}$$

$$AC = I_a Z_s$$

Fig: phasor diagram for lagging P.F. load.

now,

Considering $\triangle OCD$,

$$(OC)^2 = (OD)^2 + (CD)^2$$

$$(E_{ph})^2 = (OF + FD)^2 + (CB + BD)^2$$

$$\therefore (E_{ph})^2 = (V_t \cos \phi + I_a R_a)^2 + (I_a X_s + V_t \sin \phi)^2$$

$$\therefore E_{ph} = \sqrt{(V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi + I_a X_s)^2}$$

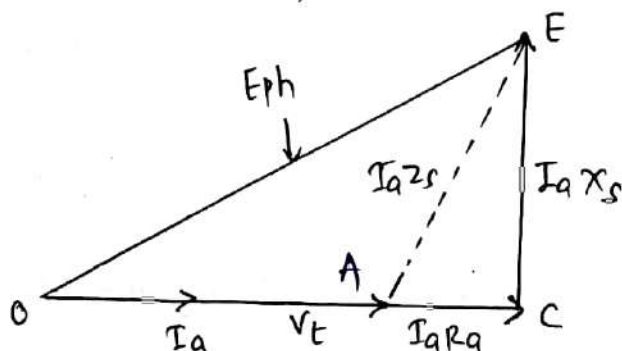
$$\% \text{ Regulation} = \frac{E_{ph} - V_t}{V_t} \times 100$$

(E_{ph} is greater than V_t and regulation is positive)

2) Case-2 Unity Power Factor:

The power of load is unity i.e. $\cos \phi = 1$ i.e. $\phi = 0$

So, V_t (or V_{ph}) is in phase with I_a .



$$OA = V_t$$

$$AE = I_a Z_s$$

$$AC = I_a R_a$$

$$CE = I_a X_s$$

$$OE = E_{ph}$$

Fig: phasor diagram for Unity P.F. load.

Consider ΔDCE then

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$$(OE)^2 = (OC)^2 + (CE)^2$$

$$(E_{ph})^2 = (OA + AC)^2 + (I_a X_s)^2$$

$$(E_{ph})^2 = (V_t + I_a R_a)^2 + (I_a X_s)^2$$

$$E_{ph} = \sqrt{(V_t + I_a R_a)^2 + (I_a X_s)^2}$$

$$\% \text{ Regulation} = \frac{E_{ph} - V_t}{V_t} \times 100$$

$E_{ph} > V_t$ always and regulation is positive.

3. Case-3 Leading Power Factor:

The P.F. of load is leading so I_a leads V_{ph} or V_t by angle ϕ .

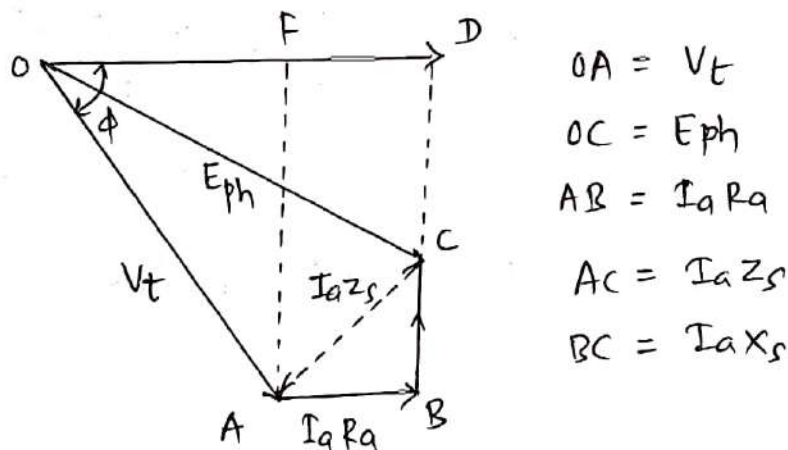


Fig: phasor diagram for leading P.F. load.

Consider ΔOCD ,

$$(OC)^2 = (OD)^2 + (CD)^2$$

$$E_{ph}^2 = (OF + FD)^2 + (BD - BC)^2$$

We know that $OF = V_t \cos \phi$

$AF = BD = V_t \sin \phi$

$$FD = I_a R_a$$

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$$\therefore E_{ph}^2 = (V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi - I_a X_s)^2$$

$$E_{ph} = \sqrt{(V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi - I_a X_s)^2}$$

$$\therefore \text{regulation} = \frac{E_{ph} - V_t}{V_t} \times 100$$

Here $V_t > E_{ph}$ and hence regulation is negative

* Relation between N_s and F for alternator:

Frequency of induced emf is given by

$$F = \frac{PN}{120} \text{ (Hz)}$$

Where speed N is called as Synchronous speed.

$\therefore$ synchronous speed is given by

$$N_s = \frac{120F}{P}$$

Thus, synchronous speed is directly proportional to Frequency and inversely proportional to the no. of Poles.

* precautions in oc and sc test:

Following precautions should be taken during short ckt test on alternator;

1. for the alternator initially DC supply provided to the field winding should be kept zero.
2. After adjusting the speed, vary the field current of alternator carefully in smaller steps, because large change in alternator field current causes large change in induced emf and due to short circuit, very large change in armature current will be observed.
3. Constant speed throughout the experiment should be maintained.
4. The alternator should not be overloaded for longer duration.

* problems:

- ① A 150 kVA, 100V, 50 Hz, 3 ϕ alternator has the following parameters.
 DC resistance / ph = 0.2Ω , ratio of effective to dc resistance = 1.25,
 synchronous reactance / ph = 3.5Ω , leakage reactance / ph = 0.5Ω .
 Determine at rated load, unity p.f. 1. internal emf, 2. regulation,
 3. value of reactance which represents armature reaction.

Soln: Given: $V_{line} = 1000V = \text{rated } v_{tg}$.

$$f = 50 \text{ Hz}$$

$$\text{Rated o/p} = 150 \text{ kVA}$$

$$\text{DC resistance / ph} = 0.2\Omega$$

$$\text{Ratio to effective dc resistance} = 1.25$$

$$X_s = 3.5\Omega$$

$$X_d = 0.5\Omega$$

$$\cos\phi = 1$$

Find:

1. Internal emf
2. Regulation
3. value of reactance that represents armature reaction.

We know that

$$I_a = \frac{\text{Rated output}}{\sqrt{3} \times \text{Rated voltage}}$$

$$= \frac{150 \times 10^3}{\sqrt{3} \times 1000}$$

$$= 86.6 \text{ A}$$

$$E_{ph} = ?$$

$$V_t \text{ or } V_{ph} = \frac{V_{\text{Line}}}{\sqrt{3}} = \frac{1000}{\sqrt{3}} = 577.35 \text{ V}$$

$$E_{ph}^2 = (V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi + I_a X_s)^2$$

$$E_{ph}^2 = (577.35 \times 1 + 86.6 \times 0.2 \times 1.25)^2 + (86.6 \times 3.5)^2$$

$$\therefore E_{ph} = 671.32 \text{ V}$$

$$\% \text{ Regulation} = ?$$

$$\% \text{ Regulation} = \frac{E_{ph} - V_t}{V_t} \times 100$$

$$\% \text{ Regulation} = \frac{671.32 - 577.35}{577.35} \times 100$$

$$\% \text{ Regulation} = 16.276\%$$

Reactance per phase representing armature reaction

$$= (3.5 - 0.5)$$

$$= 3 \Omega$$

$$\begin{cases} X_s = X_a + X_L \\ \therefore X_a = X_s - X_L \end{cases}$$

- ② O.C. and S.C. test were performed on a 3ϕ , 0.5 MVA, 3.6 kV, star connected alternator. The results are given below:

$$\text{OC: } I_F = 10 \text{ A, } V_{sc} = 3000 \text{ V}$$

$$\text{SC: } I_F = 10 \text{ A, } I_{sc} = 150 \text{ A}$$

$$R_{aph} = 1 \Omega$$

Calculate the percentage regulation for full condition at

1. 0.8 PF lagging 2. 0.8 P.F. leading.

Soln: Given: Rated output = 0.5 MVA

$$\text{Rated voltage } V_L = 3.6 \text{ kV}$$

$$\text{O.C. test: } I_F = 10 \text{ A, } V_{oc} = 3000 \text{ V}$$

$$\text{S.C. test: } I_F = 10 \text{ A, } I_{sc} = 150 \text{ A}$$

$$R_a = 1 \Omega$$

Find: 1. % Regulation for 0.8 P.F. lagging
2. % Regulation for 0.8 P.F. leading.

① $I_a = ?$

$$\text{kVA} = \sqrt{3} V_L I_a$$

$$\therefore I_a = \frac{0.5 \times 10^6}{\sqrt{3} \times 3.6 \times 10^3}$$

$$\therefore I_a = 80.189 \text{ A}$$

$$V_t = V_{ph} = \frac{V_{line}}{\sqrt{3}}$$

$$\therefore V_t = \frac{3.6 \times 10^3}{\sqrt{3}} = 2078.46 \text{ V}$$

② Find Z_{ph} and $X_s = ?$

$$V_{oc(ph)} = \frac{V_{oc(line)}}{\sqrt{3}} = \frac{3000}{\sqrt{3}} = 1732 \text{ V}$$

$$I_{sc} = 150 \text{ A}$$

$$V_{oc}(ph) = Z_{ph} I_{ph} \dots (\text{ohm's law})$$

$$\therefore Z_{ph} = \frac{1732}{150} = 11.547 \Omega$$

$$X_s = \sqrt{(Z_{ph})^2 - R_{ph}^2}$$

$$= \sqrt{(11.547)^2 - (1)^2}$$

$$\boxed{X_s = 11.503 \Omega}$$

③ Find E_{ph} & % regulation for P.F = 0.8 lagging:

$$\cos \phi = 0.8 \dots (\text{Given})$$

$$\sin \phi = 0.6$$

$$(E_{ph})^2 = (V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi + I_a X_s)^2$$

$$E_{ph}^2 = (2078.46 \times 0.8 + 80.188 \times 1)^2 + (2078.46 \times 0.6 + 80.188 \times 11.503)^2$$

$$\boxed{\therefore E_{ph} = 2782.9 \text{ V}}$$

$$\% \text{ Regulation} = \frac{E_{ph} - V_t}{V_t} \times 100 \%$$

$$= \frac{2782.9 - 2078.46}{2078.46} \times 100$$

$$\boxed{\therefore \text{Regulation} = 33.89 \%}$$

④ Find E_{ph} and % regulation for PF = 0.8 leading.

$$E_{ph}^2 = (V_t \cos \phi + I_a R_a)^2 + (V_t \sin \phi - I_a X_s)^2$$

$$E_{ph}^2 = (2078.46 \times 0.8 + 80.188)^2 + (2078.46 \times 0.6 - 80.188 \times 11.503)^2$$

$$E_{ph} = 1772.94V$$

$$\begin{aligned} \% \text{ Regulation} &= \frac{E_{ph} - V_t}{V_t} \times 100\% \\ &= \frac{1772.94 - 2078.46}{2078.46} \times 100 \end{aligned}$$

$$\% \text{ Regulation} = -14.7\%$$

Note: Regulation for the lagging P.F. loads is positive, whereas that for leading P.F. load is negative.

- ③ A certain 3 ϕ Alternator is rated at 5 kVA, 110V, 26.3A, 50 Hz and 1200 rpm. The stator resistance between terminals as measured with dc is 0.2 Ω . With no load and rated speed, the stator line voltage is 160V for a field current of 4A. At rated speed, the short circuit stator current per terminal is 60A for a field current of 4A. Calculate:
1. Synchronous impedance per phase
 2. The voltage regulation of alternator at 0.8 P.F. lagging
 3. The alternator is star connected.

Soln: Given:

Rated output = 5 kVA

Rated output voltage = $V_L = 110V$.

$F = 50\text{Hz}$,

$N_s = 1200 \text{ rpm (rated)}$

$R_a = 0.2$

$$\therefore R_a \text{ per phase } (R_{ph}) = \frac{R_a}{2} = \frac{0.2}{2} = 0.1 \Omega$$

$$V_{oc} = 160V, I_f = 4A$$

$$I_{sc} = 60A, I_a = 26.3A$$

$$\cos\phi = 0.8 \text{ (lag)}$$

① Find $Z_{ph} = ?$

$$V_{oc(ph)} = \frac{V_{oc(Line)}}{\sqrt{3}} = \frac{160}{\sqrt{3}} = 92.38V$$

$$\therefore Z_{ph} = \frac{V_{oc(ph)}}{I_{sc}} = \frac{92.38}{60} = 1.54\Omega$$

$$X_s = \sqrt{(Z_{ph})^2 - (R_{ph})^2}$$

$$= \sqrt{(1.54)^2 - (0.1)^2}$$

$$X_s = 1.53$$

② Voltage Regulation = ?

$$E_{ph}^2 = (V_t \cos\phi + I_a R_a)^2 + (V_t \sin\phi + I_a X_s)^2$$

$$\text{Let } V_t = V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{110}{\sqrt{3}} = 63.5V$$

$$\therefore E_{ph}^2 = (63.5 \times 0.8 + 26.3 \times 0.1)^2 + (63.5 \times 0.6 + 26.3 \times 1.53)^2$$

$$E_{ph} = 94.83V$$

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

$$= \frac{94.83 - 63.5}{63.5} \times 100$$

$$\% \text{ Regulation} = 49.34\%$$

* Maintenance of An alternator:

* preventive maintenance:

- For a proper maintenance of an alternator, it is necessary to keep the unit clean and that all electrical connections are tight and in good conditions.
- Because of the durability of diesel engines, most maintenance is preventive in nature and consists of the following operations:
 1. General inspection
 2. Lubrication service
 3. Cooling system service
 4. Fuel system service
 5. Servicing and testing starting batteries
 6. Regular engine exercise

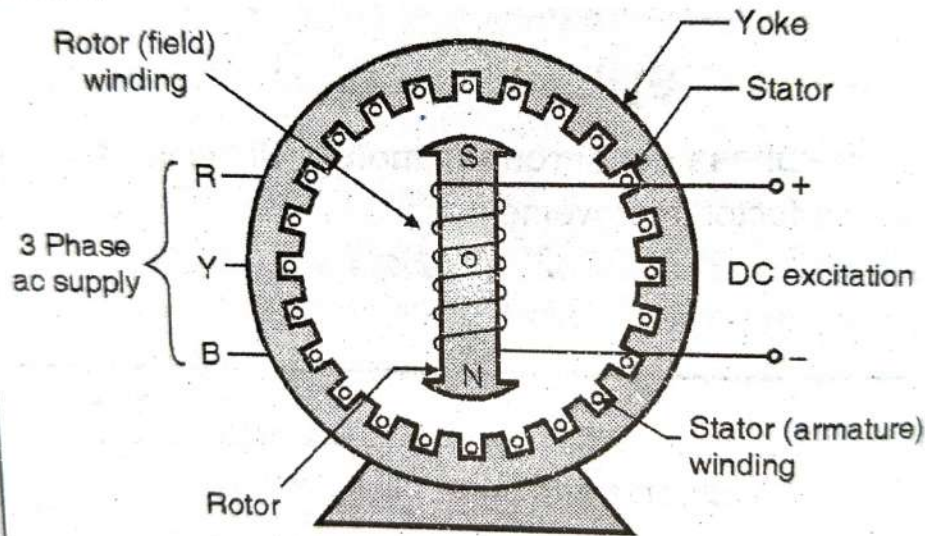
* General inspection:

The general periodic inspection and maintenance of an alternator involves the following:

1. Check the wiring, the brushes, and the drive unit for faults.
2. Check the exciter for its residual magnetism.
3. If the residual magnetism is low, it can be restored by flashing the field.
4. Clean the alternator excitor with an approved fluid.
5. Smooth a rough or pitted exciter commutator or slip ring with 000 sandpaper, then clean and polish it with a clean, dry cloth.
6. Check the brushes periodically for length and general condition.

* 3 ϕ synchronous motor:

* Construction:



- synchronous motor has two windings:
 - 1) stator winding (Armature winding)
 - 2) field winding (Rotor winding)
- stator winding or armature winding is connected to 3 ϕ AC supply.
- The rotor winding (field winding) is placed on rotor shaft.
- field winding is connected to DC supply via two slip rings.
- The rotor used is of salient pole or cylindrical pole.
- Normally, salient pole is preferred.
- stator winding is made of copper and is wound for 3 phase.
- Rotor winding is also made of copper.
- slip rings are made of phosphor bronze or hard drawn copper.
- Brushes are used to give supply to stator winding.
- Brushes are made of carbon or graphite.

* Working:

1. When 3 ϕ supply is given to 3 ϕ stator winding, 3 ϕ current flows and rotating magnetic field (RMF) is produced in the air gap between stator and rotor. Rotating magnetic poles are

AM created in stator core.

2. When DC supply is given to the field winding on rotor, magnetic poles are created on rotor.
3. opposite magnetic poles on stator and rotor locked due to force of attraction and rotor rotates with same speed as that of rotating magnetic field produced by stator i.e. synchronous speed.
4. As soon as 3 ϕ supply is given to stator winding, immediately stator magnetic field starts rotating at synchronous speed. Every time stator poles sweep over rotor poles, rotor pole experiences pull and push. so rotor poles can not pick up speed. Thus motor is not self starting.
5. To make it starting, rotor is rotated by some means to synchronous speed and then field winding is excited, so that rotor is pulled into synchronism and further rotates at constant synchronous speed.

* Working principle of synchronous motor:

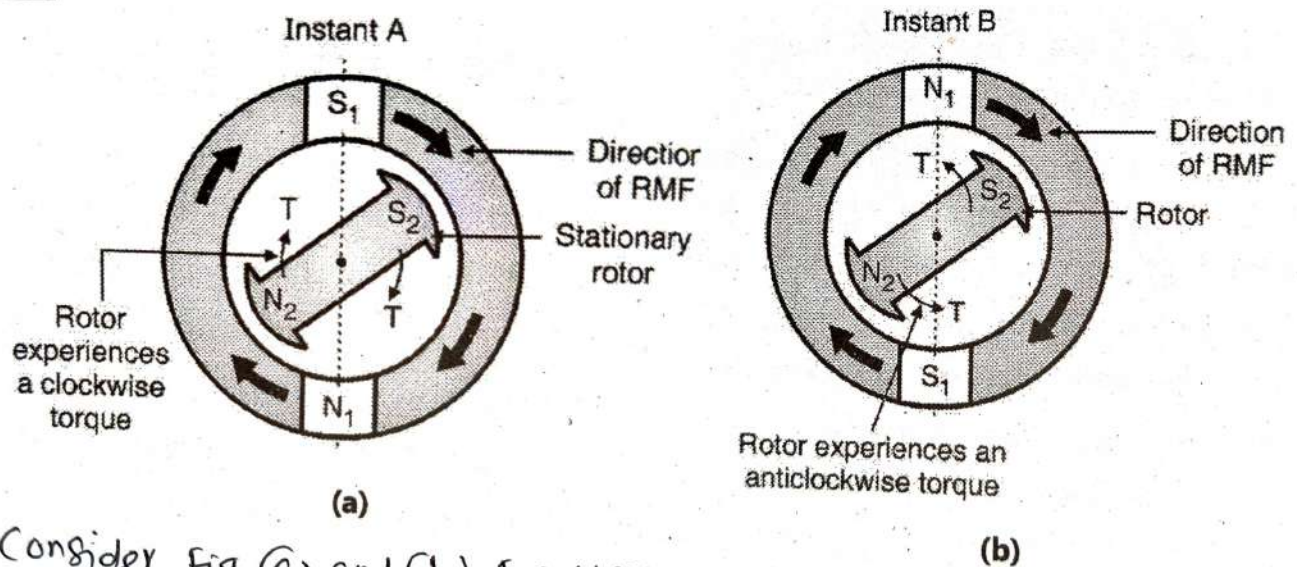
- A synchronous motor works on the principle of magnetic locking between the rotating magnetic field of stator and rotor magnetic field.
- The speed of motor is synchronous speed of RMF.
- It is given by

$$N_s = \frac{120F}{P} \text{ rpm}$$

Where N_s = synchronous speed in rpm
 F = Supply Frequency in Hz
 P = No. of poles.

Q. Why synchronous motor is not self starting?

Ans:

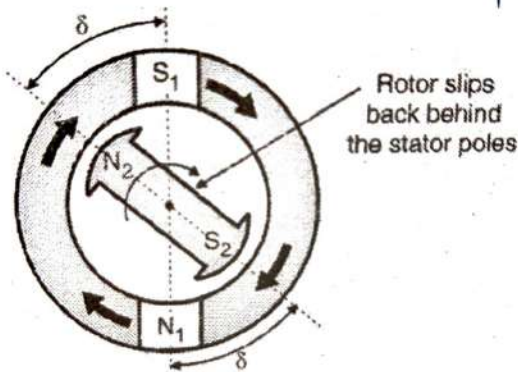


- Consider fig. (a) and (b) for working of synchronous motor.
- Assume that rotor is not driven by any external prime mover.
- Initially, the rotor is in random position as shown in fig (a).
- Fig (a) shows the situation at an instant 'A'. The rotor is in at random position. The stator poles S_1 and N_1 are rotating in the clockwise direction.
- Due to force of attraction between the unlike poles N_1-S_2 and S_1-N_2 , the standstill rotor (stationary) experiences a torque in the clockwise direction as shown in fig (a).
- Before the rotor can accelerate in clockwise direction, the stator poles change their position fastly as shown in fig (b).
- At instant B, which occurs half a period after instant A, the stator poles complete half revolution to acquire new position as shown in fig (b).
- Due to force of attraction between unlike poles N_1-S_2 and S_1-N_2 , the standstill rotor experiences a torque in anticlockwise direction as shown in fig (b).
- Thus the standstill rotor is subjected to torque which is changing its direction at very rapid rate.

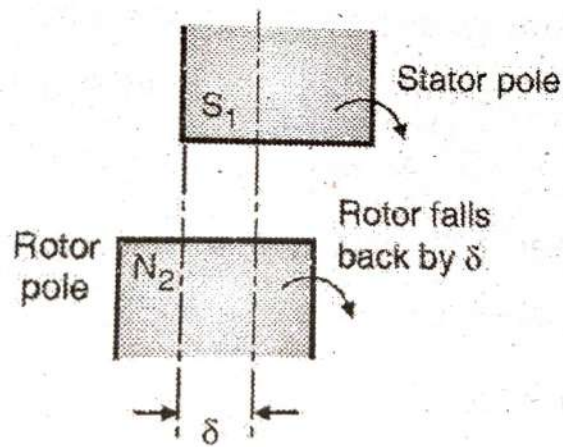
- Due to inertia of the rotor, rotor cannot respond to the torque exerted on it which changes its direction rapidly and hence remains stationary.
- This is why synchronous motor is not self starting.

* Load Angle:

- Defn: The load angle (δ) is the angle between the rotor magnetic field and the stator rotating magnetic field.
- It is also known as torque angle or power angle.



(a) Rotor slips back



* Significance of Load Angle:

- The load angle (torque angle) is important in operation of 3 ϕ synchronous motors.
- The load angle in synchronous motor is a key indicator of:
 1. Torque output
 2. System stability
 3. Load adaption
 4. Power transfer efficiency.
- Significance of load angle is as follows:

1. Torque production:

- The electromagnetic torque in synchronous motor is proportional to the sine of the load angle.

$$T \propto \sin(\delta)$$

- Higher load angle means more torque is produced.

2. Power transfer:

- The power developed by the motor is also dependent on the load angle.
- $P \propto V \cdot E \cdot \sin(\delta)$ where, V = stator V_{tg}
 E = Rotor induced EMF.
- This shows that power output increases with δ . (up to 90°).

3. Stability:

- stable operation: δ should remain within a certain limit ($< 90^\circ$)
- loss of synchronism: If δ exceeds the stability limit, the rotor falls out of synch with the stator field and the motor will stop.

4. Load adaptation:

- As mechanical load on motor increases, the rotor tends to lag behind the stator field, increasing the load angle.
- The motor adjusts the load angle to match the torque demand without changing speed.

5. Control Indicator:

- In control system, monitoring the load angle helps in:
 1. predicting overloads
 2. preventing instability
 3. optimizing motor performance.

* Different torques in synchronous motor:

- There are following torques in synchronous motor:
 1. starting torque
 2. Running torque
 3. pull in torque
 4. pull out torque.

1. starting torque:

- It is defined as the torque ~~for~~ developed by the motor when full voltage is applied to its stator winding.

2. Running torque:

- It is the torque developed by the motor under the running condition.

3. pull-in torque:

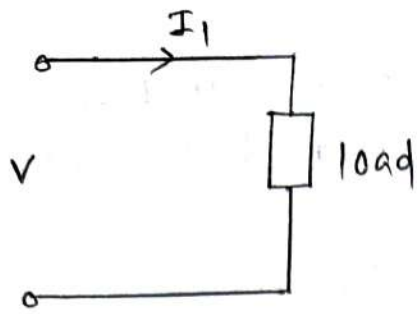
- The amount of torque at which the motor will pull into synchronization is called as pull-in torque.

4. pull-out torque:

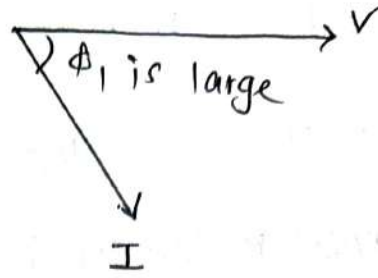
- The maximum torque which the motor can develop without pulling out of step or out of synchronism is called the pull-out torque.

* Synchronous motor For power factor improvement

- When a synchronous motor is operated without mechanical load and is over excited, it draws a leading current from the supply.
- Such a motor is called as 'synchronous condenser or synchronous compensator'.
- Its main purpose is to improve power factor and provide reactive power compensation.
- Consider a lagging p.f. load connected across a single phase ac supply as shown in Fig (a).

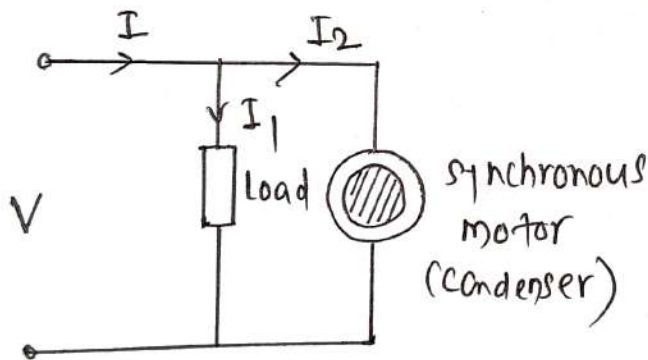


(a)

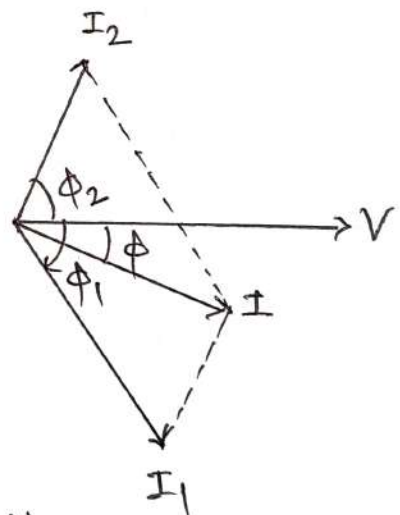


(b)

- The phasor diagram for this load is shown in Fig (b), which shows that the current I_1 lags the supply voltage V by a large angle ϕ_1 . Therefore the power factor $\cos \phi_1$ is small, i.e. poor.
- To improve the power factor, we have to reduce the angle ϕ towards zero.
- This can be achieved by connecting a synchronous condenser across the load as shown in Fig. (c)



(c) Connection of synchronous condenser.



(d) phasor diagram.

- The synchronous motor is on no load and overexcited, so it is taking a leading current I_2 . This current leads the supply voltage by an angle ϕ_2 .
- The net current I drawn from the supply is equal to the vector sum of I_1 and I_2 as shown in Fig. (d).
- From Fig. (d), it is clear that angle ϕ between V and I is

Much less than ϕ_1 .

- Hence the value of $\cos\phi$ will be higher than that of $\cos\phi_1$, which means that the power factor improvement has taken place.

* starting Methods of synchronous motor:

- As synchronous motors are not self starting, we need to make it start by different methods. as follows:

1. Using a small dc machine
2. Using a small induction motor
3. Using a damper winding
4. As a slip ring induction motor.