Unit – 3 (BEE) R19&R20 Regulations – I ECE II Semester

Synchronous Generators: Principle of operation and construction of alternators – types of alternators Regulation of alternator by synchronous impedance method-EMF equation of three phase alternator. Synchronous Motors: Construction of three phase synchronous motor - operating principle – equivalent circuit of synchronous motor.

ALTERNATOR - WORKING PRINCIPLE

- Synchronous generator or AC generator is a device which converts mechanical power in the form of A.C.
- It works on the principle of ELECTRO MAGNETIC INDUCTION and it is also called as Alternator.
- An alternator consists of armature winding and field magnet, but the difference between the alternator and DC generator is that in the DC generator armature rotates and the field system is stationary.
- This arrangement in the alternator is just reverse of it, the armature is stationary called as stator and field system is rotating called as Rotor.

For generating EMF, three things are essential:

1) Magnetic field
2) System of conductors
3) Relative motion between those two.

- The conductors are mounted on the stator and the field poles are mounted on the Rotor core
- Relative motion between the stator conductors and the field is brought about rotating the field system.
- The rotor is coupled mechanically to a suitable prime mover. When the prime mover runs, the rotor core also rotates and the field flux is cut by the stationary stator conductors and emf's are induced in them.
- If a load is connected across the stator terminals electric power would be delivered to it.

Advantages of Stationary Armature

1. The generated power can be easily taken out from the stator.
2. There is no possibility of the armature conductors flying of, when the machine runs at high speed since they are housed in the stator slots.
3. There is no difficulty in insulating the armature (stationary) winding for very high voltages, i.e, as high as 30000v or more.
4. Two slip rings are required for the supply of DC energy required for rotor field excitation. Since exciting current is to be supplied at low voltage, there is no difficulty in insulating them.

5. Rotating field is competitively light and can run with high speeds.

Differences between stationary and rotating field systems:

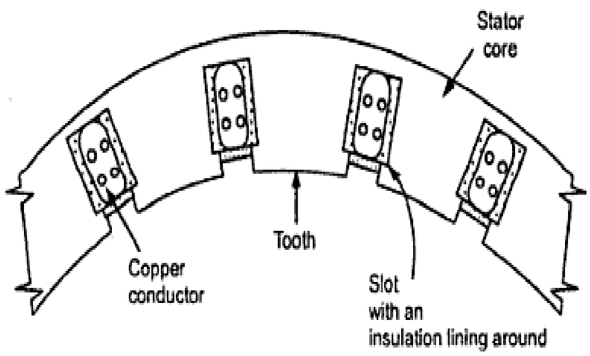
S.No.	STATIONARY FIELD SYSTEM	ROTATING FIELD SYSTEM
1	4 slip rings are required.	100 slip rings are required.
2	Heavy armature current passes through slip rings.	Very low field current passes through slip rings.
3	More sparking at slip rings.	No sparking at slip rings.
4	Armature supply is taken through slip rings.	Armature supply is taken through fixed connections.
5	Capacity is limited to 30KVA.	It can be designed to any capacity.
6	Voltage is limited to 440v.	Voltage is up to 33KV is generated.
7	Low efficiency.	High efficiency.
8	More maintenance.	Less maintenance.

CONSTRUCTION OF ALTERNATOR

An alternator consists of mainly two parts

1. Stator
2. Rotor

Stator:



1. The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel iron alloy, the core is laminated to minimize the loss due to Eddy currents.
2. The laminations are stamped out in complete rings or segments. The laminations are insulated from each other and have space between them for allowing the cooling air to pass through.
3. The inner periphery of the stator is slotted and copper conductors which are joined to one another constituting armature winding housed in these slots.
4. The other ends of the winding are brought out are connected to fixed terminal from which the generator power can be taken out.
5. Different shapes of the armature slots are available
   a. The wide open type slot also used in DC machines has the advantage of permitting easy installation of form-wound colis and there easy removal in case of repair but it has the

disadvantage of distributing the air gaps flux into bunches that produce ripples in the wave of generated EMF.

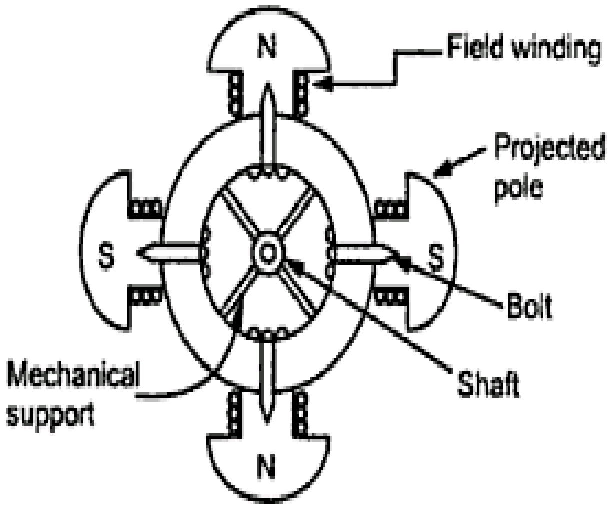
b. The semi closed type slots are better in this respect but do not allow the use of form wound coils.
c. The fully closed slots do not disturb the air gap flux but they try to increase the inductance of the windings. The armature conductors have to be threaded through, thereby increasing the initial labour and cost of the winding. Hence, these are rarely used.

Rotor

Depending upon the type of application, these are classified into two types

1) Salient-pole or projecting pole type
2) Non silent-pole or round rotor or cylindrical rotor

Salient-pole or projecting pole type



1. It is used for low and medium speed alternators used in hydro and diesel power generating station.
2. The poles are made of laminated sheets and fixed to the rotor by dove tail joint.
3. Short circuited damper bars are placed in the slots provided on the pole surfaces.
4. These are used to prevent hunting and to provide starting torque in synchronous motors.
5. The field coils are placed on the poles as shown in the figure

Key features:-

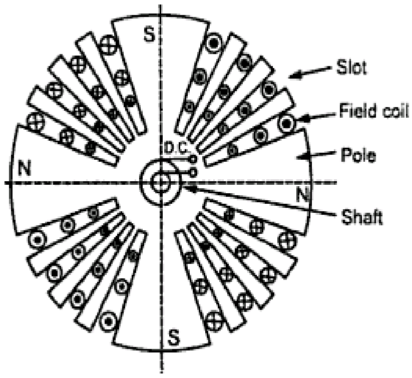
1. It has non-uniform air gap.
2. The diameter of the rotor is more than of the cylindrical rotor.
3. The no. of poles is higher than that of the non salient-pole rotor
4. Axial length is less.
5. The prime mover speed is less and is driven in hydal turbines
6. These generators are used in hydro electric stations so these are called as hydro generators.

Non-Salient pole type (or) Cylindrical type (or) Round rotor:

- Slots are provided in between the poles and these slots are placed with field winding Conductors.

Key Features:

1. No. of poles are less when compared to salient pole type.
2. Diameter is less
3. Axial length is more
4. Air gap is uniform
5. Prime mover speed is more and is driven in thermal turbines.
6. These are used in thermal stations so, these are called as turbo Generators.



FREQUENCY OF THE INDUCED EMF

Consider an alternate whose rotor is driver at a constant speed N rpm.

Let

P = No. of poles in the alternator

f = Frequency of the generated voltage in Hertz (or) Cycles per sec

- $$\text{No. of cycles of the induced EMF per sec} = \frac{\text{No. of Cycles}}{\text{Revolution}} \times \frac{\text{No. of Revolutions}}{\textit{Seconds}}$$

No. of cycles per revolution = No. of pairs of poles = P/2

No. of revolutions per second = N/60

Therefore,

$$\text{Frequency of the induced EMF} = \frac{P/2}{1} \times \frac{N}{60} = \frac{PN}{120}$$

For a given alternator, the no. of poles is fixed. Hence in order to generate power at a specified frequency, the machine is to be run at a definite speed which is termed as synchronous speed.

EMF EQUATION OF ALTERNATOR:

Consider a 3 - Phase alternator with

P = No. of poles

N = Driven speed in rpm.

E = RMS value of the induced emf per pole in Volts.

Ø = Average flux per pole in Webbers

Z_{ph} = No. of stator conductors per phase

T_{ph} = No. of stator turns per phase, also

$T_{ph}=Z_{ph}/2$

"f " is the frequency of induced emf in Hz

- Therefore total flux cut per revolution by any one stator conductor is equal to PØ Webbers.
- Time taken for one revolution is equal to 1/N min or 60/N sec

Therefore rate of cutting of flux is equal to = dØ/dt

= "PØ" / "60/N" (wb/sec) = PØN/60 (wb/sec)

Since, f = PN/120 and 2f = PN/60 , then dØ/dt = 2Øf

- According to faraday's second law of Electro Magnetic Induction,
- The average value of the induced emf per conductor in each phase = 2fØ volts
- The average value of the induced emf per phase $=2fØZ_{ph}$ volts
- The average value of the induced emf per phase $=2fØ(2T_{ph})$ volts
- Therefore, RMS value of emf per phase = Form factor * Average Value

$= 1.11*4fØT_{ph} = 4.44ØfT_{ph}$

- In a practical alternator the space distribution of the filed flux is not purely sinusoidal, it is having some distortion and moreover in a practical alternator short pitch winding is used, therefore by these two reasons, the actual EMF that is induced is somewhat less than the emf that is arrived at.
- Therefore by inserting pitch factor (or) chording factor (or) coil span factor (k_c or k_p) and Distribution or breadth factor (k_d or k_b) in the above emf equation , the actual emf equation is obtained and is given as
- RMS value of emf (E) per phase including the winding factor (k_w) is

$$E = 4.44ØfT_{ph}\, k_w = 4.44ØfT_{ph}\, k_c\, k_d$$

<u>Winding Terminology</u>

<u>Pole pitch:</u> Distance between two adjacent opposite main poles by the no. of armature conductors.

<u>Coil span:</u> Distance between two coils starting and ending conductors

The distance between any two conductors is called slot angle (β),

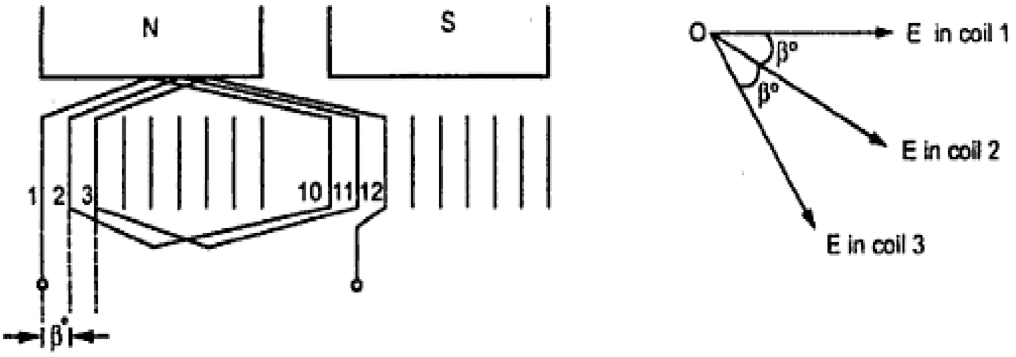
Short pitch angle (α) = short chorded slots × B

- If the distance b/w two coils sides of a coil, i.e. coil span is equal to one pole pitch, i.e. 180°E , it is called as full pitch winding.
- If the distance b/w two coils sides of a coil, i.e. coil span is less than one pole pitch i.e 180°E, it is called short pitch (or) fractional chorded winding.
- If the winding is short pitched by one slot then the short pitch angle α is equal to slot angle β.

- If it is short pitched by two slots, then $\alpha = 2\beta$ and so on.

Pitch Factor (or) Chording Factor (or) Coil Span Factor

It is the ratio of vector sum of the emfs induced in the two coil sides of coil to their arithmetic sum .



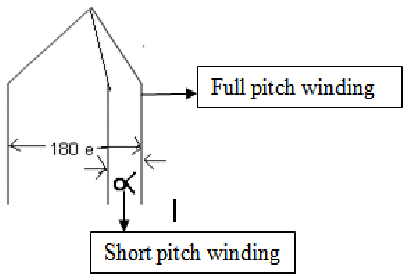
(a) Distributed winding

(b) Phase difference between induced e.m.f.

$$kc = \frac{\text{vector sum of induced emf per coil}}{\text{arthimetic sum of induced emf per coil}}$$

(or)

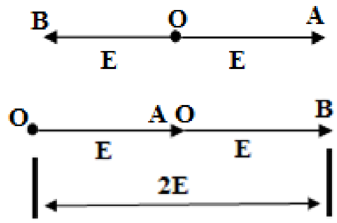
$$kc = \frac{\text{voltage induced in short pitch winding}}{\text{voltage induced in full pitch winding}}$$



Arithmetic sum:-

Let, The coil span of the short pitch winding is less than one pole pitch (180°) by an angle α.

The emf induced per coil side namely OA = E volts



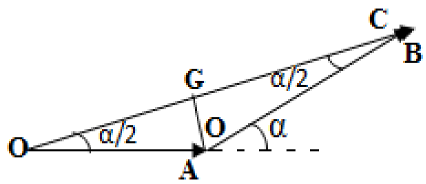
The emf induced in another coil side namely OB = E volts

Then, ***Arithmetic sum*** of emfs induced = OA + OB = **2E** volts

Vector sum:-

The emf induced per coil side namely OA = E volts

The emf induced in another coil side namely OB = E volts short pitched by α



Then, ***Vector sum*** of emfs induced is OC = OG + GC

From Δ OGA, OG = OA cos(α/2) = E cos(α/2) and

From Δ OGC, GC = OB cos(α/2) = E cos(α/2)

Therefore, ***Vector sum*** of emfs induced = OC = E cos(α/2) + E cos(α/2) = **2E cos(α/2)**

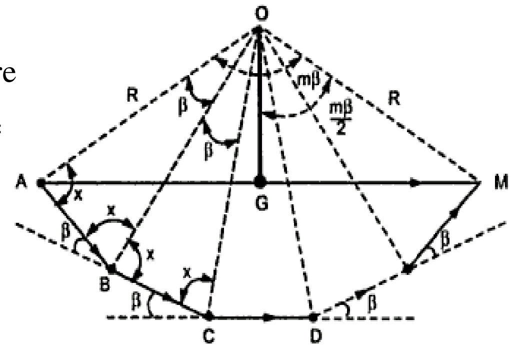
$$k_c = \frac{2E\cos\left(\frac{\alpha}{2}\right)}{2E} = \cos\left(\frac{\alpha}{2}\right) \Rightarrow k_c = \cos\left(\frac{\alpha}{2}\right)$$

Distribution Factor (or) breadth factor:- (k_d or k_b)

- The ratio of the vector sum of the e.m.fs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the e.m.fs induced (or to the resultant of the e.m.fs induced in all the coils concentrated in one slot under one pole) is known as distributed factor $k_{d.}$

$$k_d = \frac{\text{vector sum of induced emf in all coils under one pole}}{\text{arthimetic sum of induced emf in all coils under the same pole}}$$

- It is the ratio of voltage induced in a distribution winding to the voltage induced in the concentric winding.



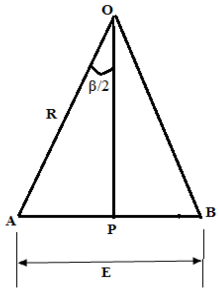
- Let ‘m’ be the no. of stator slots per pole per phase, where no. of slots per pole is defined as pole pitch (n), then m = n/3.
- The slot angle ‘β’ =180°/no.of slots/pole. $B = 180^0 / n$

  Let,

  E = EMF induced per conductor.

  R = radius

  O = centre of the circle is drawn to pass through the points ABCD



- Arithmetic sum of emf induced in the conductors of ‘m’ no. of slots per pole per phase = m*E

  From Δ OAB, induced EMF AB = AP +PB

  In Δ OPA, AP = E/2 = R sin(β/2) and PB = E/2 = R sin(β/2)

  Therefore AB = induced emf E = 2R sin (β/2)

Arithmetic sum of emf induced in the conductors = 2mR sin (β/2)

- Vector sum of emf induced in the conductors of ‘m’ no. of slots per pole per phase = AM

  From Δ OAM,

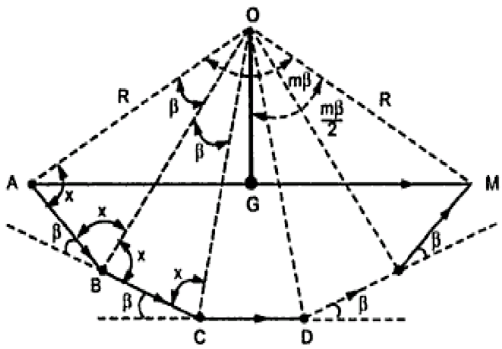
  Angle between OA and OM is mβ

  Drawing an perpendicular bisector of OG to AM, then

  AM = AG + GM (AG = GM)

  In a right angled triangle OGM,

  GM = AG = R Sin (mβ)/2



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Therefore,

AM = AG + GM =R Sin (mβ)/2+ R Sin (mβ)/2 = 2R Sin (mβ)/2

Vector sum of emf induced in the conductors = 2R Sin (mβ)/2

Thus, the distribution factor k_d is

$$k_d = \frac{2RSin\left(\frac{m\beta}{2}\right)}{2mRSin\left(\frac{\beta}{2}\right)} \Rightarrow K_d = \frac{Sin\left(\frac{m\beta}{2}\right)}{m\,Sin\left(\frac{\beta}{2}\right)}$$

Concentration Winding:

- Each coil side containing a no. of conductors, and if all the conductors of a coil side are placed in a single slot, it is called concentrated coil
- It gives more voltage but the sine wave will not be smooth

Distribution Winding:

- When the conductors of the coil side are distributed in different slots, it is called as distributed slots.
- It gives less voltage but the wave form will be smooth.

Advantages of Short Pitch Winding:

- Copper in end connection can be saved.
- Harmonics are reduced
- Iron losses will be reduced
- Efficiency will be increased
- Generated voltage waveform will be improved is more sinusoidal.

Disadvantages of Short Pitch Winding:

- The magnitude of the induced voltage will be reduced

VOLTAGE REGULATION OF ALTERNATOR:

- When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine.
- When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.
- Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation.

(or)

- The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.

  Hence regulation can be expressed as

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

where
E_{ph} = induced emf per phase,
V_{ph} = rated terminal voltage per phase

EMF method (or) Synchronous impedance method:

This method is also known as synchronous impedance method.

Here the magnetic circuit is assumed to be unsaturated.

In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following information is to be determined.

Open circuit characteristics of the alternator.

Short circuit characteristics of the alternator.

The voltage drop in an alternator is mainly due to the following reasons

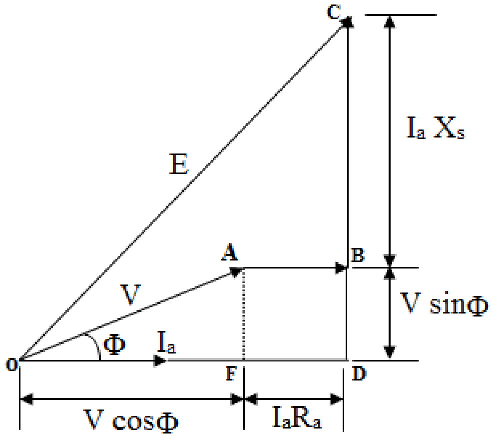
1. Voltage drop due to armature winding resistance ($I_a R_a$)
2. Voltage drop due to armature winding leakage reactance ($I_a X_L$)
3. Voltage drop due to armature reaction drop ($I_a X_a$)

   - The combination of 2 and 3 leads to the voltage drop due to armature winding leakage reactance and armature reaction drop called as voltage drop due to synchronous reactance (X_s)= $I_a (X_L+X_a) = I_a X_s$
   - Combination of the drops due to R_a and X_s is known as voltage drop due to synchronous impedance drop ($I_a Z_s$)

Calculation of no load induced emf (E) from the terminal voltage (V)

The calculation of no load induced emf (E) from the terminal voltage (V) at rated load depends on the nature of the load

For Lagging pf loads (inductive loads):



Let the known quantities are

V = Terminal voltage under rated load in Volts = OA

I_a = Rated armature current in Ampere

R_a = Armature resistance in ohms

X_s = synchronous reactance in ohms

E = No load induced emf in Volts = OC

From the KVL

$\vec{E} = \vec{V} + I_a(R_a + jX_s)$

1. Draw the phasor diagram for the above KVL equation as shown in the figure with known quantities
2. Take the reference phasor as OA = terminal voltage (V), since the load is inductive the current is lagging to phasor OA by its load phase angle Φ lag.
3. Add I_aR_a drop = AB = FD to the terminal voltage V which is inpase to I_a
4. From point B add I_aX_s drop = BC which is leading to I_a by 90^0
5. Join points O and C i.e OC = E no-load induced emf
6. From ΔODC

$$OC = \sqrt{OD^2 + DC^2} \quad \Rightarrow \text{OD} = \text{OF} + \text{FD} = \text{V}\cos\Phi + \text{I}_a\text{R}_a$$

$$\Rightarrow \text{DC} = \text{DB} + \text{BC} = \text{V}\sin\Phi + \text{I}_a\text{X}_s$$

$$E = \sqrt{(\text{V}\cos\Phi + \text{I}_a\text{R}_a)^2 + (\text{V}\sin\Phi + \text{I}_a\text{X}_s)^2} \text{ ------ LAGGING PF}$$

For Unity pf loads (resistive loads):

Since phase angle Φ = 0 degrees, the power factor cosΦ = 1

Then from ΔOBC

$$OC = \sqrt{OB^2 + BC^2} \quad \Rightarrow \text{OB} = \text{OA} + \text{AB} = \text{V} + \text{I}_a\text{R}_a$$

$$\Rightarrow \text{BC} = \text{I}_a\text{X}_s$$

$$E = \sqrt{(V + \text{I}_a\text{R}_a)^2 + (\text{I}_a\text{X}_s)^2} \text{ ----- UPF LOADS}$$

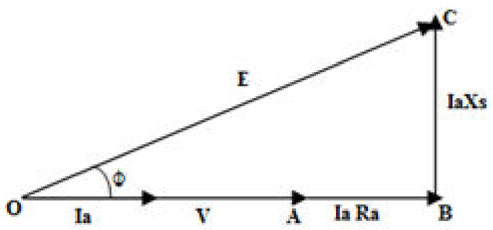
For Leading pf loads (capacitive loads):

From ΔODC

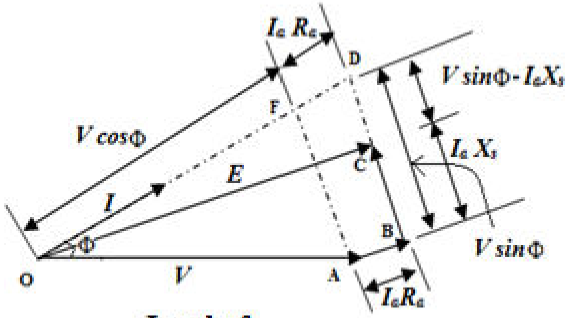
$OC = \sqrt{OD^2 + DC^2} \Rightarrow OD = OF + FD = V\cos\Phi + I_a R_a$

$\Rightarrow DC = DB - BC = V\sin\Phi - I_a X_s$

$E = \sqrt{(V\cos\Phi + I_a R_a)^2 + (V\sin\Phi - I_a X_s)^2}$ ------LEADING PF



UPF



Lead pf

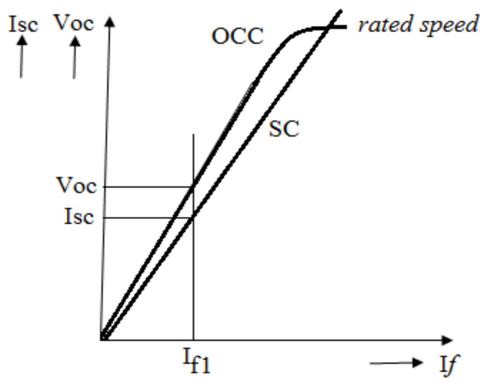
Open circuit characteristics on the alternator

1. The alternator is made to run at no-load or with the terminals kept ***opened.***
2. The alternator is operated with constant speed at rated value.
3. A voltmeter is connected in parallel to the opened terminals.
4. A variable excitation is applied to the field winding in a step wise.
5. As the voltage induced in the alternator is directly proportional to the excitation.
6. Tabulate the values of field currents and the corresponding induced voltages up to 125% of rated voltage.
7. Plot the graph between field current and open circuit voltage as shown in the below figure.
8. The open circuit characteristic is linear at the lower portion and is almost constant at the rated excitation values.

Short circuit characteristics on the alternator

1. The alternator is made to run with the terminals shorted
2. The alternator is operated with constant speed at rated value
3. An ammeter is connected in series to the shorted terminals.
4. An excitation is applied to the field winding such a way that rated short circuited current passes through it
5. As the current in the alternator under short circuit is directly proportional to the excitation, so the plot of the Short circuit characteristic is a straight line passing through the origin.

Calculation of synchronous impedance of an alternator:



1. From the plots of OCC and SC, V_{oc} and I_{sc} corresponding to the field current of I_{f1} is identified and the ratio of these V_{oc} to I_{sc} is defined as the synchronous impedance Z_s.

   $$Z_s = \frac{V_{oc} \text{ at } I_{fl}}{I_{sc} \text{ at same } I_{fl}}$$

2. From the obtained synchronous impedance Z_s, the synchronous reactance X_s is calculated with the known value of armature resistance R_a

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

3. Due to this synchronous impedance Z_s there is a fall in terminal voltage when the load on the alternator is increased from no load to rated load.
4. The difference of the voltage from no-load (E) to rated load (V) expressed in terms of rated voltage (V) is known as voltage regulation

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

   Where
   E = No-load voltage in Volts
   V = Rated load Voltage in Volts
5. The no-load voltage E is calculated using the above defined formula after obtaining the value of X_s from point no.2
6. The formula for no-load voltage E is

$$E = \sqrt{(V\cos\Phi + I_a R_a)^2 + (V\sin\Phi \pm I_a X_s)^2}$$

(+) Sign is for lagging power factor and (-) Sign is for leading power factor.

Since the regulation is estimated from the calculation of EMF value hence method is known as ***EMF method*** or from the calculation of synchronous impedance value hence called ***synchronous impedance method***

Synchronous Motors: Construction of three phase synchronous motor - operating principle –equivalent circuit of synchronous motor.

INTRODUCTION

- It may be recalled that a d.c. generator can be run as a d.c. motor. In like manner, an alternator may operate as a motor by connecting its armature winding to a 3-phase supply. It is then called a synchronous motor.
- As the name implies, the synchronous motor runs at synchronous speed (Ns = 120f/P) i.e., in synchronism with the revolving field produced by the 3-phase supply.
- The speed of rotation is, therefore, tied to the frequency of the source. Since the frequency is

fixed, the motor speed stays constant irrespective of the load or voltage of 3- phase supply.

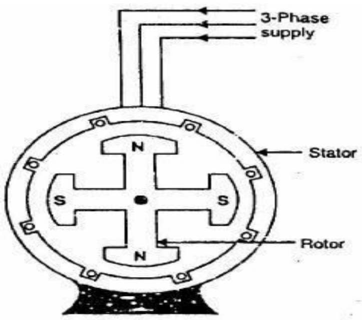
- However, synchronous motors are not used so much because they run at constant speed (i.e., synchronous speed) but because they possess other unique electrical properties.

CONSTRUCTION

- A synchronous motor is a machine that operates at synchronous speed and converts electrical energy into mechanical energy.
- It is fundamentally an alternator operated as a motor. Like an alternator, a synchronous motor has the following two parts:

i. Stator which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply

ii. Rotor that has a set of salient poles excited by DC to form alternate N and S poles.



- The exciting coils located on the rotor shaft are connected in series to two slip rings and DC is fed into the winding from an external exciter mounted on the same shaft.
- The stator is wound for the same number of poles as the rotor poles and its speed of rotation is given
- Synchronous speed $N_s = \frac{120f}{p}$

  Where, f = frequency of supply in Hz

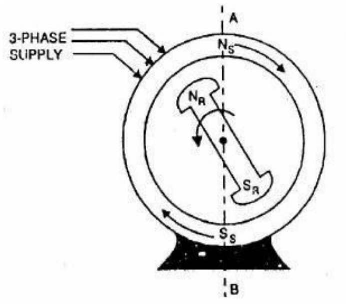
  p = number of poles
- An important drawback of a synchronous motor is that it is not self-starting and auxiliary means have to be used for starting it.

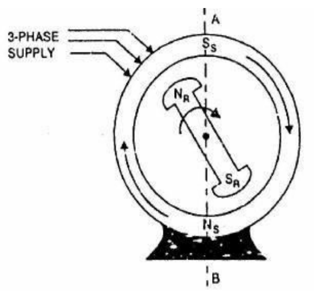
Salient features of a synchronous motor:

1. Synchronous motor runs only at synchronous speed or it doesn't runs at all.
2. Its speed is constant (synchronous speed) at all loads.
3. Synchronous motor can be made to operate over a wide range of power factors (lagging, unity or leading) by adjustment of its field excitation. Therefore, a synchronous motor can be made improve the power factor of the system.
4. Synchronous motors are generally of the salient pole type.
5. Synchronous motor is not self-starting and an auxiliary means has to be used for starting it.

OPERATING PRINCIPLE

- The fact that a synchronous motor has no starting torque can be easily explained.
- Consider a 3-phase synchronous motor having two rotor poles NR and SR. Then the stator will also be wound for two poles NS and SS.
- The motor has direct voltage applied to the rotor winding and a 3-phase voltage applied to the stator winding.

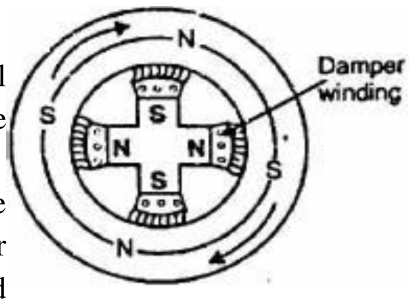




- The stator winding produces a rotating field which revolves round the stator at synchronous speed Ns(= 120 f/P).
- The direct (or zero frequency) current sets up a two-pole field which is stationary so long as the rotor is not running.
- Thus, we have a situation in which there exists a pair of revolving armature poles (i.e., NS - SS) and a pair of stationary rotor poles (i.e., NR - SR).
- Suppose at any instant, the stator poles are at positions A and B as shown in figure below, It is clear that poles NS and NR repel each other and so do the poles SS and SR.
- Therefore, the rotor tends to move in the anticlockwise direction. After a period of half-cycle (or ½ f = 1/100 second), the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in below figure Now SS and NR attract each other and so do NS and SR.
- Therefore, the rotor tends to move in the clockwise direction. Since the stator poles change their polarities rapidly, they tend to pull the rotor first in one direction and then after a period of half-cycle in the other. Due to high inertia of the rotor, the motor fails to start.
- Hence, the synchronous motor has no self-starting torque i.e., a synchronous motor cannot start by itself.

<u>Making Synchronous Motor Self-Starting</u>

- A synchronous motor cannot start by itself. In order to make the motor self-starting, a squirrel cage winding (also called damper winding) is provided on the rotor.



- The damper winding consists of copper bars embedded in the pole faces of the salient poles of the rotor as shown in Fig.
- The bars are short-circuited at the ends to form in effect a partial squirrel cage winding. The damper winding serves to start the motor.
- To start with, 3-phase supply is given to the stator winding while the rotor field winding is left unenergized. The rotating stator field induces currents in the damper or squirrel cage winding and the motor starts as an induction motor.
- As the motor approaches the synchronous speed, the rotor is excited with direct current. Now the resulting poles on the rotor face poles of opposite polarity on the stator and a strong magnetic attraction is set up between them. The rotor poles lock in with the poles of rotating flux. Consequently, the rotor revolves at the same speed as the stator field i.e., at synchronous speed.
- Because the bars of squirrel cage portion of the rotor now rotate at the same speed as the rotating stator field, these bars do not cut any flux and,
- Therefore, have no induced currents in them. Hence squirrel cage portion of the rotor is, in effect, removed from the operation of the motor.
- It may be emphasized here that due to magnetic interlocking between the stator and rotor poles, a synchronous motor can only run at synchronous speed. At any other speed, this magnetic interlocking (i.e., rotor poles facing opposite polarity stator poles) ceases and the average torque becomes zero. Consequently, the motor comes to a halt with a severe disturbance on the line.

  Note: It is important to excite the rotor with direct current at the right moment.

  For example, if the d.c. excitation is applied when N-pole of the stator faces N pole of the rotor, the resulting magnetic repulsion will produce a violent mechanical shock. The motor will immediately slow down and the circuit breakers will trip. In practice, starters for synchronous motors are designed to detect the precise moment when excitation should be applied.

EQUIVALENT CIRCUIT OF SYNCHRONOUS MOTOR

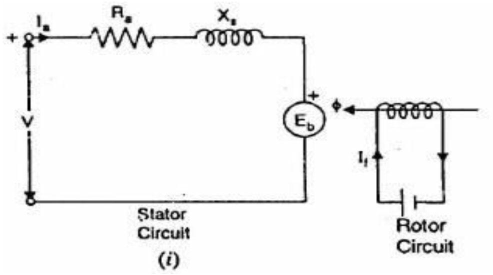
Unlike the induction motor, the synchronous motor is connected to two electrical systems;

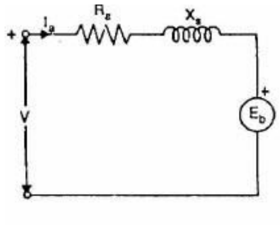
i. DC source to the rotor terminals

ii. AC source to the stator terminals

1. Under normal conditions of synchronous motor operation, no voltage is induced in the rotor by the stator field because the rotor winding is rotating at the same speed as the stator field.

2. In the stator winding, two effects are to be considered, the effect of stator field on the stator winding and the effect of the rotor field cutting the stator conductors at synchronous speed.





i. The first effect of stator field on the stator (or armature) conductors is accounted for by including an inductive reactance in the armature winding. This is called synchronous reactance X_s. A resistance R_a must be considered to be in series with this reactance to account for the copper losses in the stator or armature winding. This resistance combines with synchronous reactance and gives the synchronous impedance of the machine.

ii. The second effect is that a voltage is generated in the stator winding by the synchronously-revolving field of the rotor. This generated e.m.f. Eb is known as back e.m.f. and opposes the stator voltage V. The magnitude of Eb depends upon rotor speed and rotor flux per pole. Since rotor speed is constant; the value of Eb depends upon the rotor flux per pole i.e. exciting rotor current I_f.

Above fig. shows the schematic diagram for one phase of a star-connected synchronous motor. Referring to the equivalent circuit,

Net voltage per phase in stator winding is Er = V - Eb

Armature current per phase in stator winding is $I_a = \frac{E_r}{Z_s} = \frac{V - E_b}{\sqrt{R_a^2 + X_s^2}}$

A synchronous motor is said to be

Normally excited if the field excitation is such that $E_b = V$

Under-excited if the field excitation is such that $E_b < V$

Over-excited if the field excitation is such that $E_b > V$

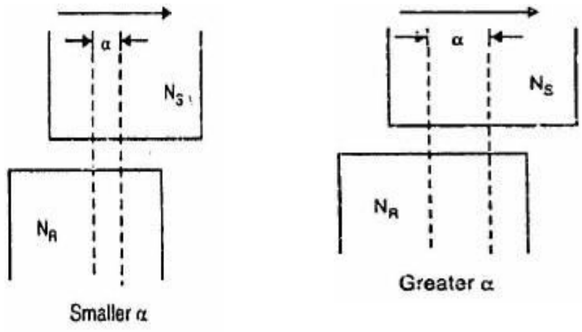
- As we shall see, for both normal and under excitation, the motor has lagging power factor. However, for over-excitation, the motor has leading power factor.

  Note: In a synchronous motor, the value of Xs is 10 to 100 times greater than Ra. Consequently, we can neglect Ra unless we are interested in efficiency or heating effects.

MOTOR ON LOAD

- In d.c. motors and induction motors, an addition of load causes the motor speed to decrease. The decrease in speed reduces the counter e.m.f. enough so that additional current is drawn from the source to carry the increased load at a reduced speed. This action cannot take place in a synchronous motor because it runs at a constant speed (i.e., synchronous speed = 3000 rpm) at all loads.

- Whereas when the mechanical load on synchronous motor is increased the rotor poles fall slightly behind the stator poles while continuing to run at 2990 r.p.m synchronous speed. The angular displacement between stator and rotor poles (called torque angle α) causes the phase of back e.m.f. E_b to change w.r.t. supply voltage V. This increases the net e.m.f. E_r in the stator winding. Consequently, stator current Ia (= Er/Zs) increases to carry the load.



The following points may be noted in synchronous motor operation:

1. A synchronous motor runs at synchronous speed at all loads. It meets the increased load not by a decrease in speed but by the relative shift between stator and rotor poles i.e., by the adjustment of torque angle α.
2. If the load on the motor increases, the torque angle α also increases (i.e., rotor poles lag behind the stator poles by a greater angle) but the motor continues to run at synchronous speed. The increase in torque angle α causes a greater phase shift of back e.m.f. Eb w.r.t. supply voltage V. This increases the net voltage Er in the stator winding. Consequently, armature current Ia (= Er/Zs) increases to meet the load demand.
3. If the load on the motor decreases, the torque angle a also decreases. This causes a smaller phase shift of Eb w.r.t. V. Consequently, the net voltage Er in the stator winding decreases and so does the armature current Ia (=Er/Zs).

Pull-Out Torque

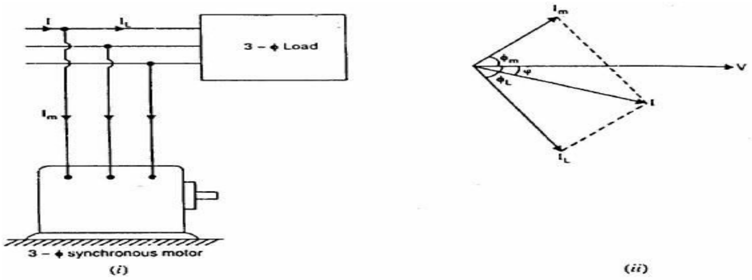
- There is a limit to the mechanical load that can be applied to a synchronous motor. As the load increases, the torque angle α also increases so that a stage is reached when the rotor is pulled out of synchronism and the motor comes to a standstill.
- This load torque at which the motor pulls out of synchronism is called pull—out or breakdown torque. Its value varies from 1.5 to 3.5 times the full— load torque.

SYNCHRONOUS CONDENSER

- A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor.
- An over-excited synchronous motor running on no-load in known as synchronous condenser.
- When such a machine is connected in parallel with induction motors or other devices that operate at low lagging power factor, the leading kVAR supplied by the synchronous condenser partly neutralizes the lagging reactive kVAR of the loads. Consequently, the power factor of the system is improved.
- Fig. below shows the power factor improvement by synchronous condenser method. The 3 - Φ load takes current I_L at low lagging power factor cos Φ_L. The synchronous condenser takes a current I_m which leads the voltage by an angle Φ_m. The resultant current I is the vector sum of I_m and I_L and lags behind the voltage by an angle Φ. It is clear that Φ is less than Φ_L so that cos Φ is greater than cos Φ_L. Thus the power factor is increased from cos Φ_L to cos Φ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement

Advantages

1. By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving step less control of power factor.
2. The motor windings have high thermal stability to short circuit currents.
3. The faults can be removed easily.



Disadvantages

1. There are considerable losses in the motor.
2. The maintenance cost is high.
3. It produces noise.
4. Except in sizes above 500 RVA, the cost is greater than that of static capacitors of the same rating.
5. As a synchronous motor has no self-starting torque, then-fore, an auxiliary equipment has to be provided for this purpose.

Applications of Synchronous Motors

1. Synchronous motors are particularly attractive for low speeds (< 300 r.p.m.) because the power factor can always be adjusted to unity and efficiency is high.
2. Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads.
3. They are used to improve the voltage regulation of transmission lines.