- Three phase synchronous Generator
- Introduction
- Constructional Details,ArmatureWindings,Types of Rotor, Exciter
- Working Principle
- EMF equation, distribution factor, pitch factor
- Armature reaction and its effects
- Alternator with load and its phasor diagram
- Three Phase Synchronous Motor
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- Starting methods
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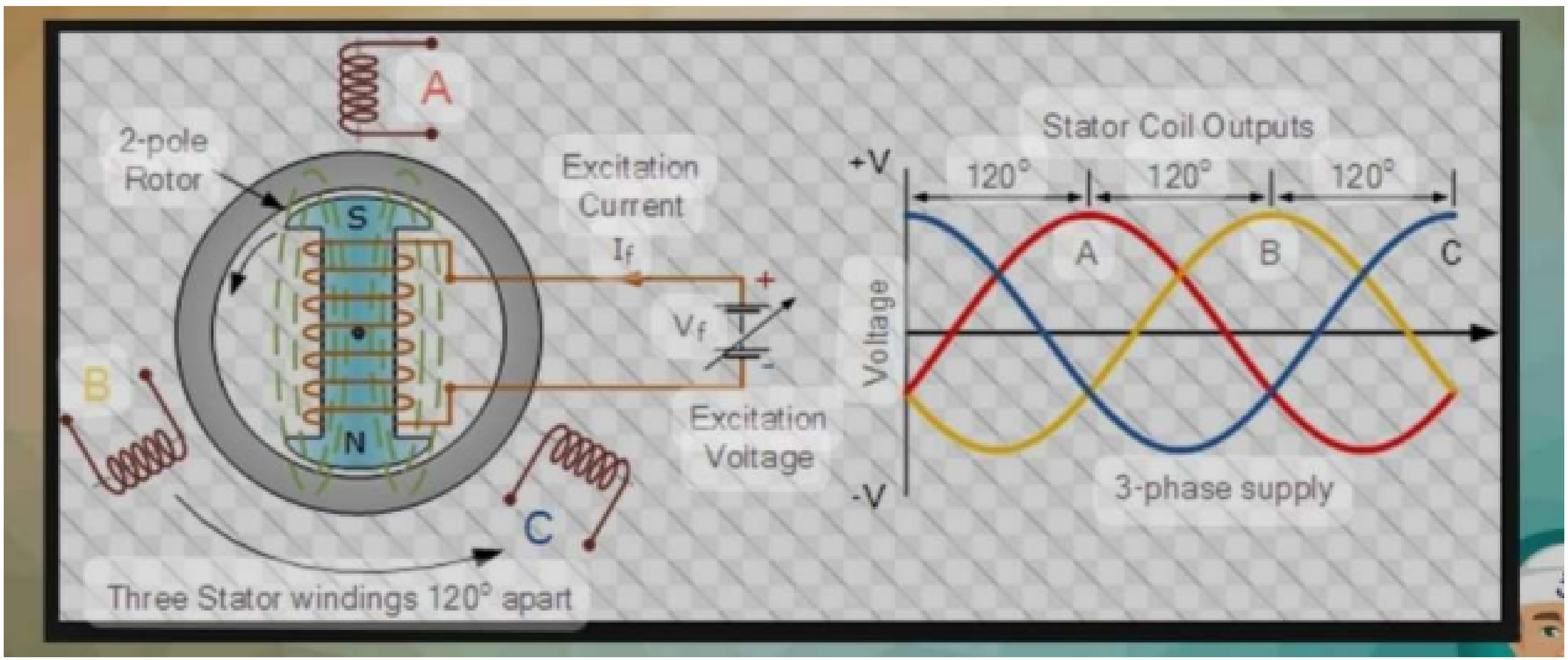
- Effect of Excitation and power factor control

- A synchronous machine is an AC machine in which the rotor moves at a speed which bears a constant relationship to the frequency of currents, in the armaturewinding.

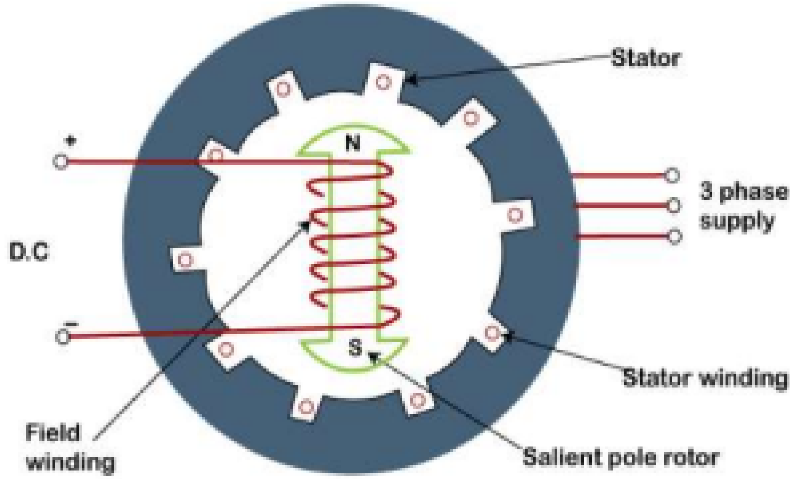
- A synchronous machine is one of the important types of electric machines.
- Synchronous machine are AC rotating machine which can be used as either generator or motor.
- In case of a generator, the machine has to be driven at a constant speed equal to the synchronous speed.Whereas synchronous motor automatically rotates at a constant speed equal to the synchronous speed.
- Large AC network operating at constant frequency rely almost exclusively on synchronous generators (also called the alternators) for the supply of electrical energy.
- Private, standby end peak-load plants with diesel or gas-turbine prime movers also have synchronous generators.

Synchronous machines are generally constructed in largersizes. Small size alternators are not economical.The modern trend is to build alternators of very large size capable of generating 500 MVA or even more. The synchronous motor is rarely built in small sizes owing to superior performance characteristics and economical construction of induction motors.



The main parts of a synchronous machine are:

1. Stator or armature
2. Rotor
3. Exciter



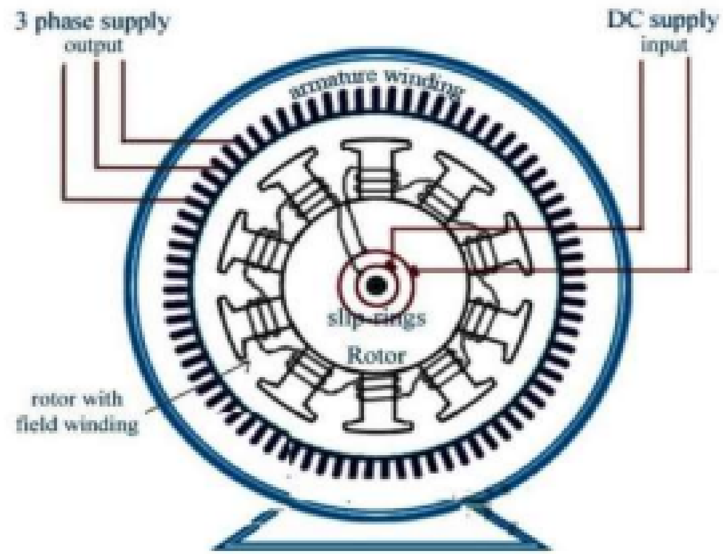
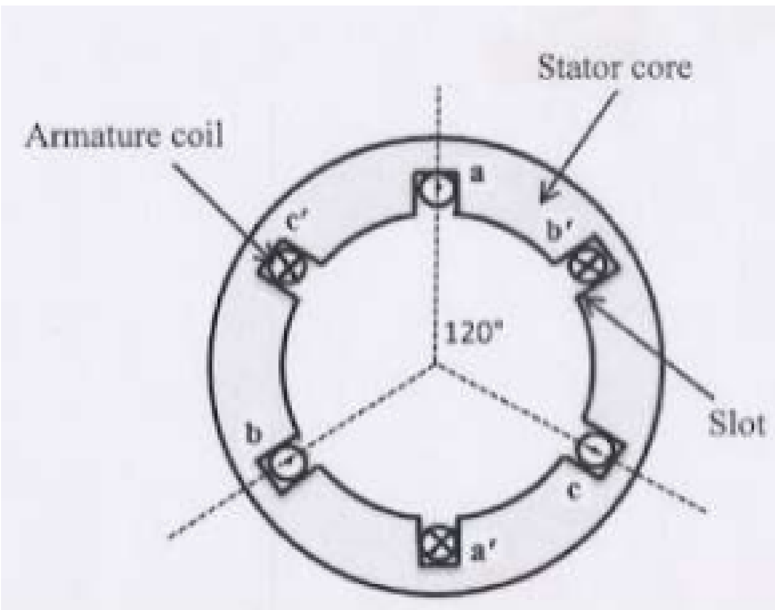


Fig.1: construction of three phase synchronous Motor and Generator

- The armature is an iron ring formed of laminations of special
- magnetic iron or steel alloy (silicon steel) having slots on its inner periphery to accommodate armature conductors and is known as <u>stator</u>.
- The whole structure is held in a frame which may be of cast iron or welded steel plates.
- The field rotates in between the stator; flux of the rotating field cuts the core of the stator continuously and therefore causes eddy current loss in the stator core.To minimize the eddy current loss, the stator core is laminated.

- The stator is exactly same as the stator of 3 – ø induction motor. It has uniformly distributed three phase armature winding.

Figure 2: Cross-section of stator of synchronous Machines



- The field system is just like that of a d.c. generator which is excited from a separate source of 125 or 250V dc supply.
- The excitation is usually provided from a small dc shunt or compound generator, known as an exciter, mounted on the

shaft of the alternator itself.

- The field system of the alternator is rotated within the armature ring and is known as rotor.
- The exciting current is supplied to the rotor through two slip-rings and brushes.
- Rotor is the rotating part of the machine with number of magnetic poles excited by the dc source from exciter.
- There are two types of rotor :

1) cylindrical type rotor and
2) salient type rotor

- This type of rotor has got smooth magnetic poles in form of aclosed cylinder.
- These types of rotors are used in very high speed alternators (driven by steam turbines).
- To reduce the peripheral velocity, the diameter of the rotor is reduced and axial length is increased. Such

rotors have two orfour poles.

- The cylindrical rotor (or also known as non salient pole type) has the following special features:
- They are of small diameter and of very long axial length
- Less windage loss
- High operating speed i.e. 1500 to 3000 RPM
- Robust construction and noiseless operation

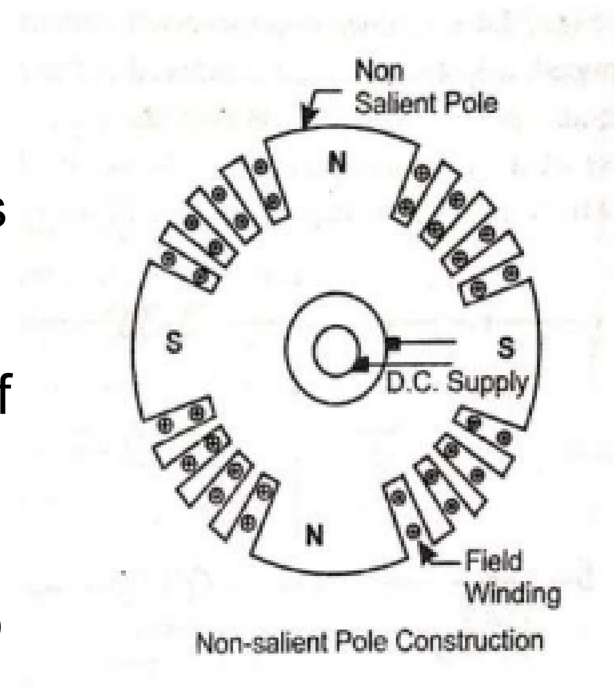


Figure 3: Cylindrical type Rotor

Figure 3: Cylindrical type Rotor

- The rotor of this type is used almost entirely for low and moderate speed alternators, since it is least expensive and provides ample space for the field ampere-turns.

- Salient poles cannot be employed in high speed generators on account of very high peripheral speed (100 to 170 meters per second) and the difficulty of obtaining sufficient magnetic strength.
- The salient poles are made of thick steel laminations riveted together and are fixed to rotor by a dovetail joints.
- The salient pole field structure have large diameter and short axial length, the pole shoes cover almost 2/3 of pole pitch and salient poles are employed with hydraulic turbines or diesel engines.
- The speed is 50 to 1000 RPM .

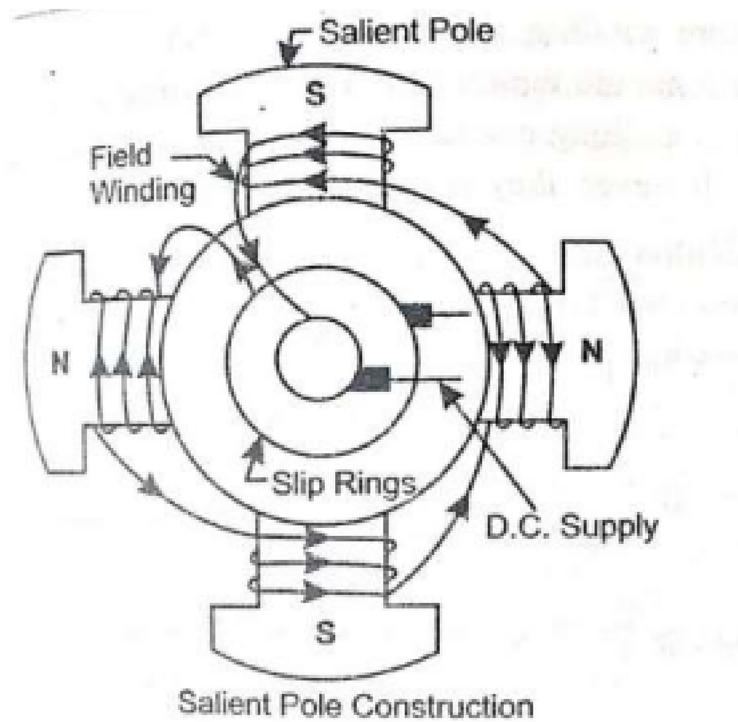
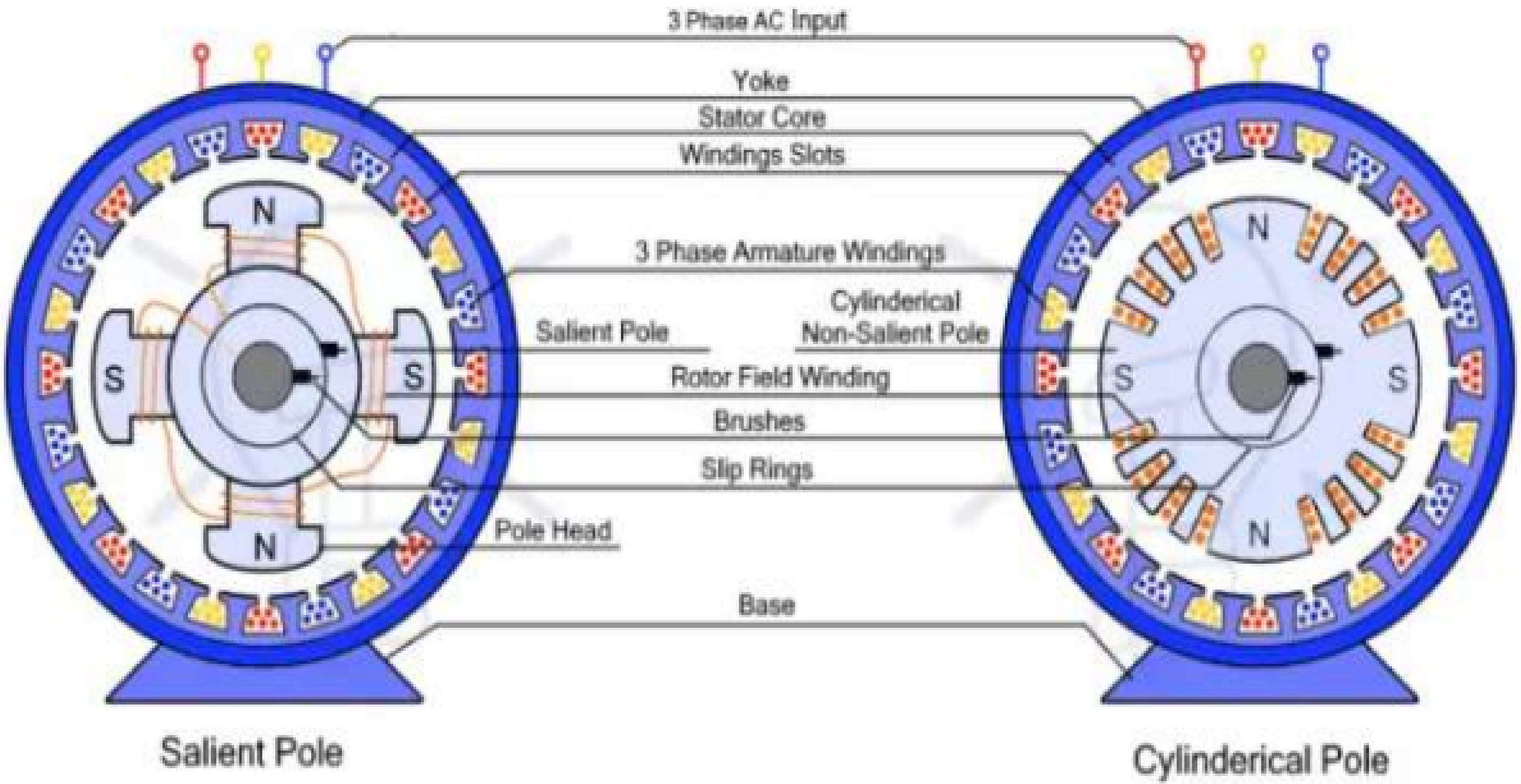


Figure 4: Salient type Rotor



- It is a self excited dc generator mounted on the shaft of the main machine.
- The function of the exciter is to supply dc current to the field winding of the rotor.

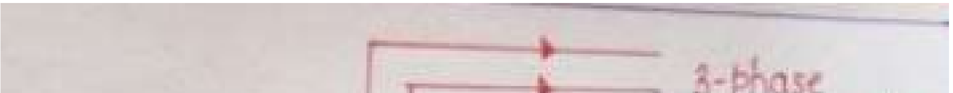
- The dc current generated by the exciter is fed to the field winding of the alternator through slip ring and carbon brushes.

- The magnetic field system in synchronous generator is opposite to that in a DC generator.
- A DC generator has stationary magnetic field pole and rotating armature conductor whereas a synchronous generator has rotating magnetic system & stationary armature

conductors.

- The rotating magnetic system has the following advantages:
  - The output current can be sent to the load directly from the fixed terminals on the stator without slip ring & brushes.
  - It is easier to insulate stationary armature winding for high voltage (usually 11 KV or higher) rather than rotating armature.
  - The field winding deals with low current at low voltage.Therefore, the rotating magnetic field winding can be easily insulated. Also, slip rings & brushes do not have to handle large currents so that the sparking problems at slip rings are minimum.

- Synchronous generator is

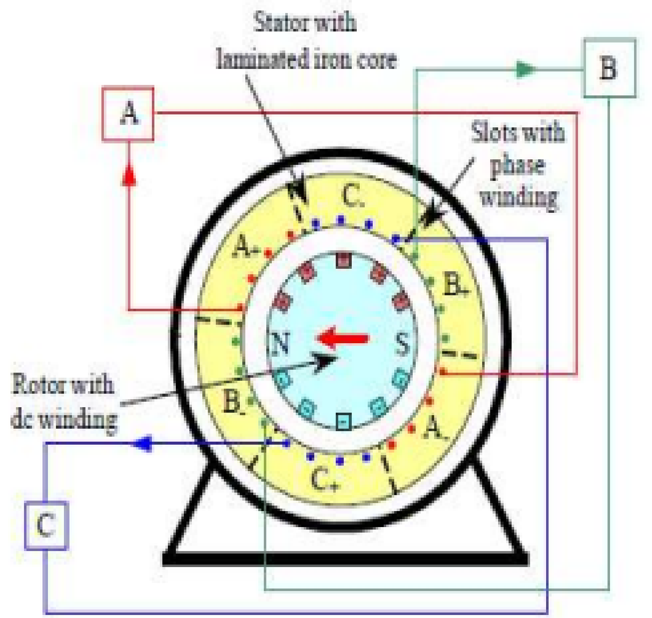


also known as alternator as it produces alternating voltage.

- The shaft of the machine is driven by the prime mover at a constant speed equal to the synchronous speed (i.e. N_S=120f/P).
- Like the dc generator a synchronous generator functions on the basis of Faraday's Law.
- The exciter (dc generator) builds up its voltage and supplies dc current to the field winding of the main generator.

- The magnetic flux produced by the rotor pole will cut the stationary three phase statorwinding.
- Hence, according to the Faraday's Law of electromagnetic induction, three phase emf will induce in the statorwinding.
- In an actual power generating station, speed governor is used to keep the speed of the machine constant automatically at any load condition so that the frequency of generated emf is constant.
- Like DC generator,synchronous generator also operates in the principle of electromagnetic induction. But there is one important difference between the two.
- In DC generator, the field poles are stationary and armature conductor are rotating.
- But in synchronous generator, the field poles are rotating and armature conductor (i.e.statorconductors) are stationary.

Synchronous Machines



Major components of a round rotor two-pole generator

Figure 5:AThree Phase Round Rotor

- Considering the machine as shown in Figure 5 and assuming that the flux density in the air gap is uniform implies that sinusoidally varying voltages will be induced in the three coils RR,YY, and BB if the rotor carrying dc rotates at a constant speed,Ns.

- If ø is the flux per pole, ω is the angular frequency & N is the number of turns in phase (coil RR') then the voltage induced in phase R is given by:

- $e_R=\omega N ø \sin wt=E_m \sin\omega t$

- Here, $E_m = 2\pi f N ø$ & $f = (\omega/2\pi)$ is the frequency of the induced voltage.As phases 'Y' & 'B' are displaced from phase R by ± 120° then the corresponding voltage may be written as, $e_Y= E_m \sin(\omega t – 120°)$

$e_B=E_m \sin(\omega t + 120°)$

- After an AC generator is brought up to its proper speed (for 50 Hz, 3 –ø, if P = 2 then, N_S= 120f/P = 3000 RPM and if P = 4, then N_S = 1500 RPM) by its prime mover, its field is excited from a DC generator.
- As the poles move under the armature conductors on the stator, the field flux cutting across the conductors induces an emf in them.
- Since, no commutator are used this alternating emf generated appears at the stator winding terminals.
- The amount of emf depends in the field strength and speed of the rotor. The speed is controlled by the governor attached to the prime mover. Since, most generators are operated at constant speed, the amount of emf generated becomes dependent on the field excitation.

Let Z = No. of conductors or coil sides in series per phase Or, Z = 2.T, whereT = No. of turns in series per phase. P = No. of magnetic pole in the rotor

f = frequency of induced emf

ø = magnetic flux per pole

N = speed of the rotor in RPM

- In one revolution of the rotor (i.e., in 60/N sec) each stator conductor is cut by a flux of ø. P,webers.

- Therefore, average emf induced per conductor

  $= d\phi/dt =$

  $\phi.P/(60/N)$, volts
- But $f = (P.N)/120$

  or, $N = 120f/P$
- Therefore, average emf induced perconductor

  $= (\phi.P/60)*(120f/P) = 2.f.\phi$, volts

- Then, average emf induced per phase $= 2.f.\phi.Z$

  (Where, $Z=2T$)

  $= 2.f.\phi.2T = 4.f.\phi.T$, volts
- We know that form factor for sine wave

  = RMS value/ Averagevalue

  = 1.11
- Therefore, RMS value of induced emf per phase

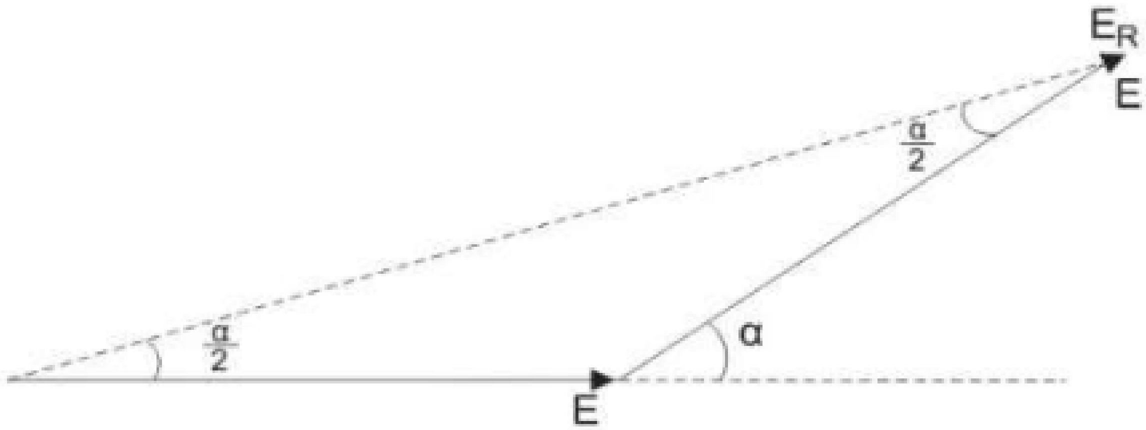
  $= 1.11 * 4.f.\phi.T$

  $= 4.44\ f.\phi.T$, volts…………..(1)

- Besides the factor indicated by the equation (1), there are some other factors which affects the magnitude of emf induced in stator windings. These factorsare known as winding factor and they are :
  - pitch factor &
  - distribution factor of the stator winding.

- The coil span of the armature winding ideally equals to a pole pitch (i.e., spacing over 180° electrical).
- But in actual machine, the span may be less than 180°electrical, such winding is known as “short pitchwinding”.
- The ratio of phasor sum of induced EMFs per coil to the arithmetic sum of induced EMFs per coil is known as pitch factor Kp or coil span factor Kc. Its value is always less than unity.

- Let us consider, the coil has a pitch short by an angle α electrical degrees from the full pitch. The induced emf in each coil side be E. Now, if the coil is said to be full pitch, then total induced emf in the coil would be 2E.
- For a coil, that is short-pitched by α electrical degrees, the resultant induced emf ER is the phasor sum of two voltages α electrical degrees.

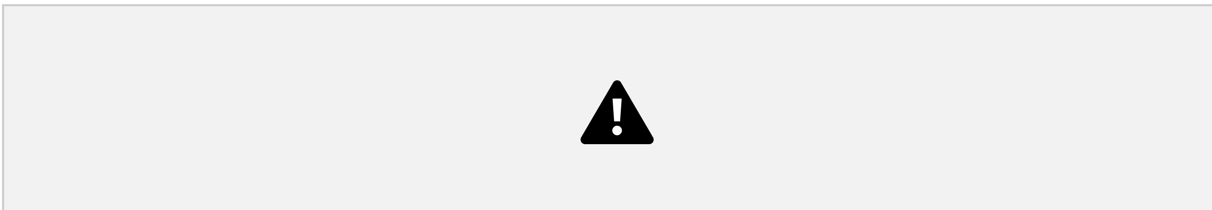


$$E_R = 2E\cos\frac{\alpha}{2}$$

The formula for pitch factor is given by

$$K_p = \frac{Resultant\ emf\ of\ short\ pitched\ coil}{Resultant\ emf\ of\ full\ pitched\ coil}$$
$$= \frac{Phasor\ sum\ of\ coil\ side\ emfs}{Arithmetic\ sum\ of\ coil\ side\ emfs}$$
$$= \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$

- The pitch factor in the above equation is for fundamental component of emf.If the coil span is reduced by one slot, then the phase angle α between the induced EMFs in the two sides of the coil is given as



- If all the coil sides of any one phase under one pole are bunched in one slot, the winding obtained is known as concentrated winding.
- The ratio of the phasor sum of the EMFs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the EMFs induced(or to the resultant of EMFs induced in all coils concentrated in one slot under one pole) is known as breadth factor Kb or distribution factor Kd. Its value is always less than unity.

- Let n be the number of slots per pole.
- m be the number of slots per pole per phase.
- Ec be the induced emf in each coil side.
- Angular displacement between the slots

- The EMFs induced in different coils of one phase under one pole are represented by side AC, CD, DE, EF,… which are equal in magnitude but differ in phase.[Say the magnitude be E and phase difference be 180 degrees]

The distribution factor can be obtained as

- The magnitude of actual emf induced per phase is given by, $E = 4.44\ Kp.\ K_d.f\varnothing T$ volt per phase

K_d = distribution factor
K_p= pitch factor coil span factor
f = frequency of emf generated in Hz
ø = flux per pole in weber

- Note: K_d = 1 for concentrated Coils
  K_c = 1 for full -pitched Coils

- When the synchronous generator is loaded with external load,current will flow through the armaturewindings.

- These current carrying armature winding will set up its own magneticfield which is also rotating in nature.
- **The effect of this armature field on the field produced by rotor is known as armature reaction**.The nature of armature reaction depends upon the power factor of the load.
- For unity power factor of load, the armature reaction is

cross magnetizing in nature. For pure inductive load (lagging), the armature reaction is **demagnetizing in nature**.

- For pure capacitive load (leading), the armature reaction is **magnetizing in nature**.

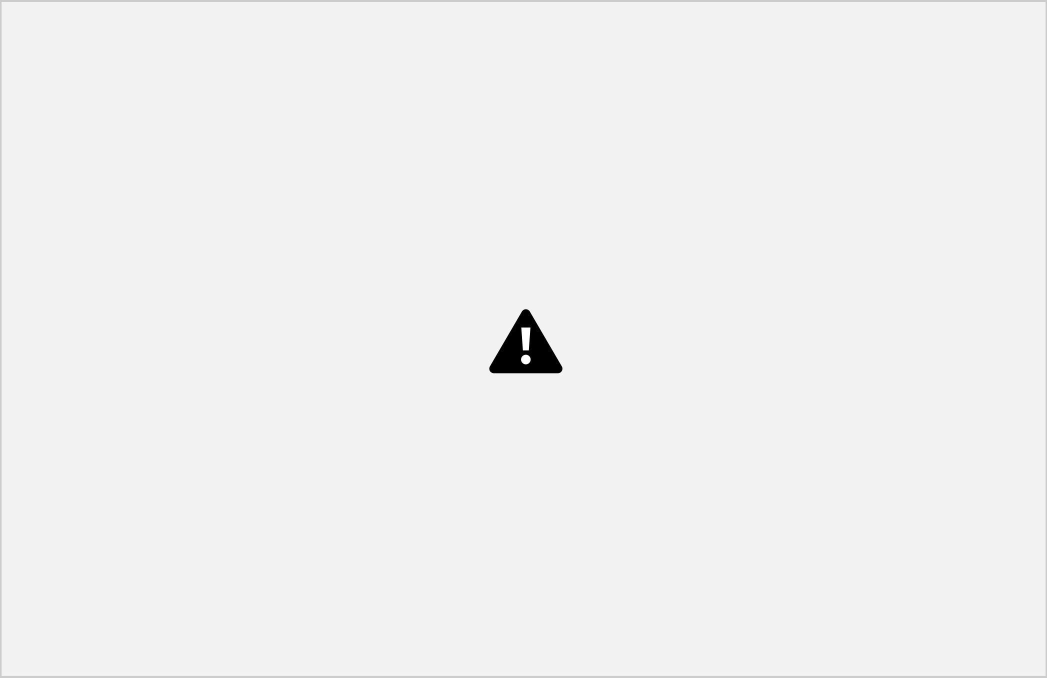


Fig : Phasor diagram of generated

voltage

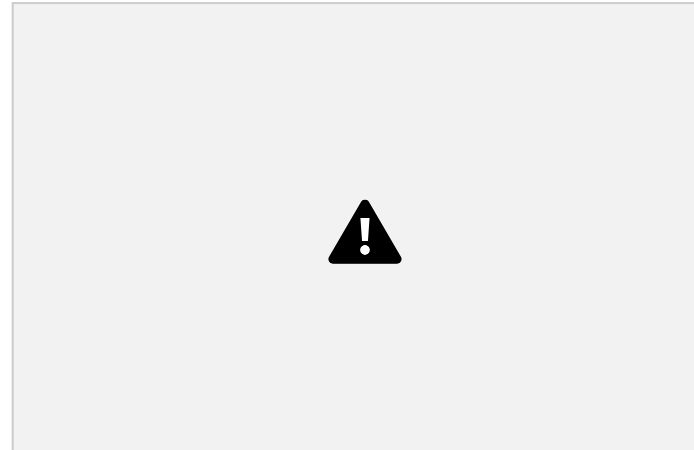


Fig : Phasor diagram of

armature flux

- If the load is purely resistive (p.f.=1), there will be no phase difference between the terminal voltage (V) & the armature current.Since, the nature of flux will be in phase with armature current, the magnetic flux produced by three phase windings will have similar waveform as that of the terminal voltage as shown in fig a & b.
- The mathematical equation of three flux can be

written as: - $ø_R = ø_m \operatorname{Sin} \omega t$

- $\text{ø}_Y = \text{ø}_m \, \text{Sin}\,(\omega t - 120°)$
- $\text{ø}_B = \text{ø}_m \, \text{Sin}\,(\omega t - 240°)$
- When the magnet rotates 90° from its zero position, voltage & current in the R-coil will be positive maximum & voltage & current in theY-coil & B coil will be negative

Fig E: Resultant of armature flux

According to fig E, the resultant flux $ø_A$= 1.5 $ø_m$, whose direction lags by an angle of 90° with the direction of main flux ($ø_M$) produced by the rotor. Both of these flux rotates with the same speed in the same direction.Therefore, at every instant the armature reaction flux ($ø_A$) try to distort the main flux ($ø_M$).

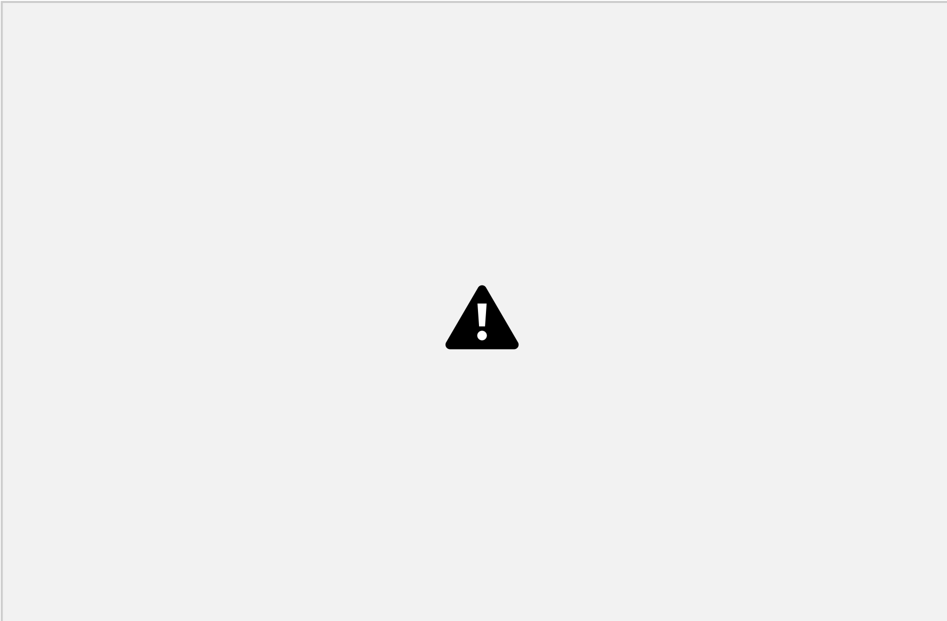


Fig.Phasor diagram of main flux & armature reaction flux for resistive load

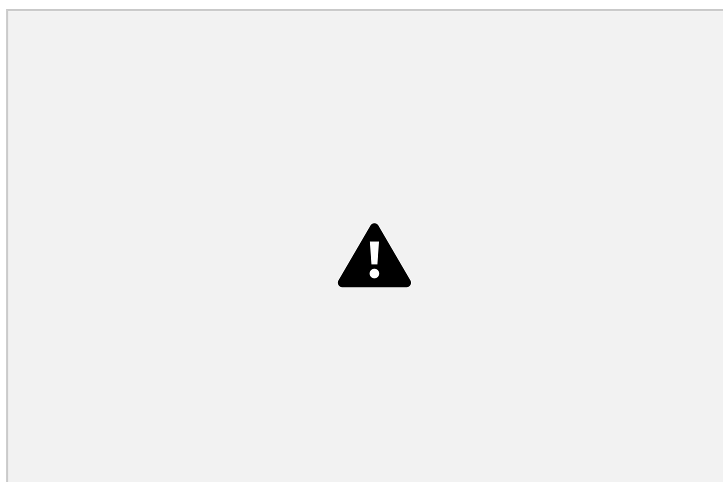


Fig. Phasor diagram of main flux & armature reaction flux for inductive load

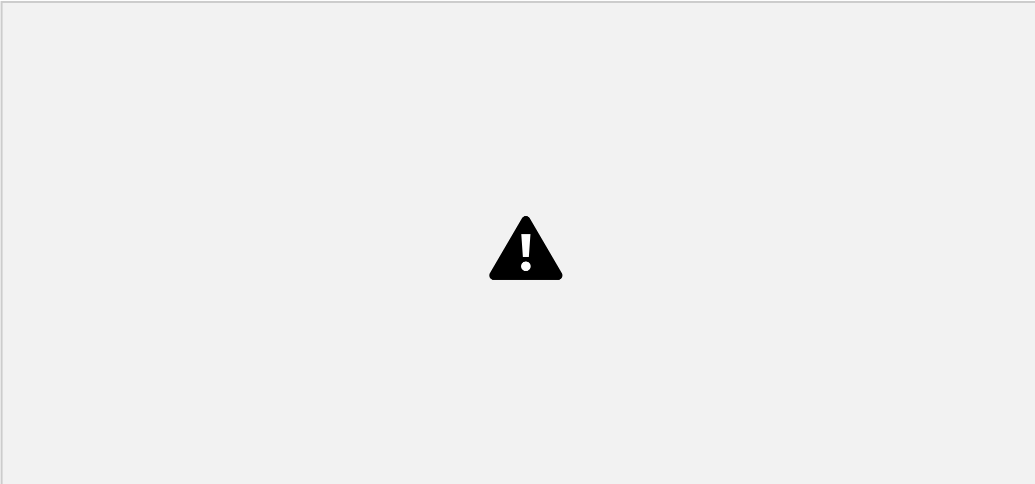


Fig.Phasor diagram of main flux & armature reaction flux for capacitive load

- When current flows through the stator conductors, the flux is set up, a portion of this flux does not cross the air-gap, but completes its path in the stator. Such a flux is known as the **leakage flux.**
- This leakage flux is proportional to stator or armature current, since the magnetic path it covers is not normally saturated.
- It also depends on the phase angle between the stator current and voltage applied across the stator.
- The leakage flux sets up an emf of self inductance leading the load current I by π/2 and proportional to load current I in

magnitude.

- Hence,armature winding is assumed to possess leakage reactance X_L such that the voltage drop due to it, IX_L is equal to an emf set up by leakageflux.
- A part of the generated emf is used up to overcome this leakage reactance drop in addition to armature resistance drop.

- i.e. generated emf = phasor sum of terminal voltage, armature resistance drop and leakage reactance drop.
- i.e. $E = V + IR_e + jX_L = V + I(R_e + jX_L)$

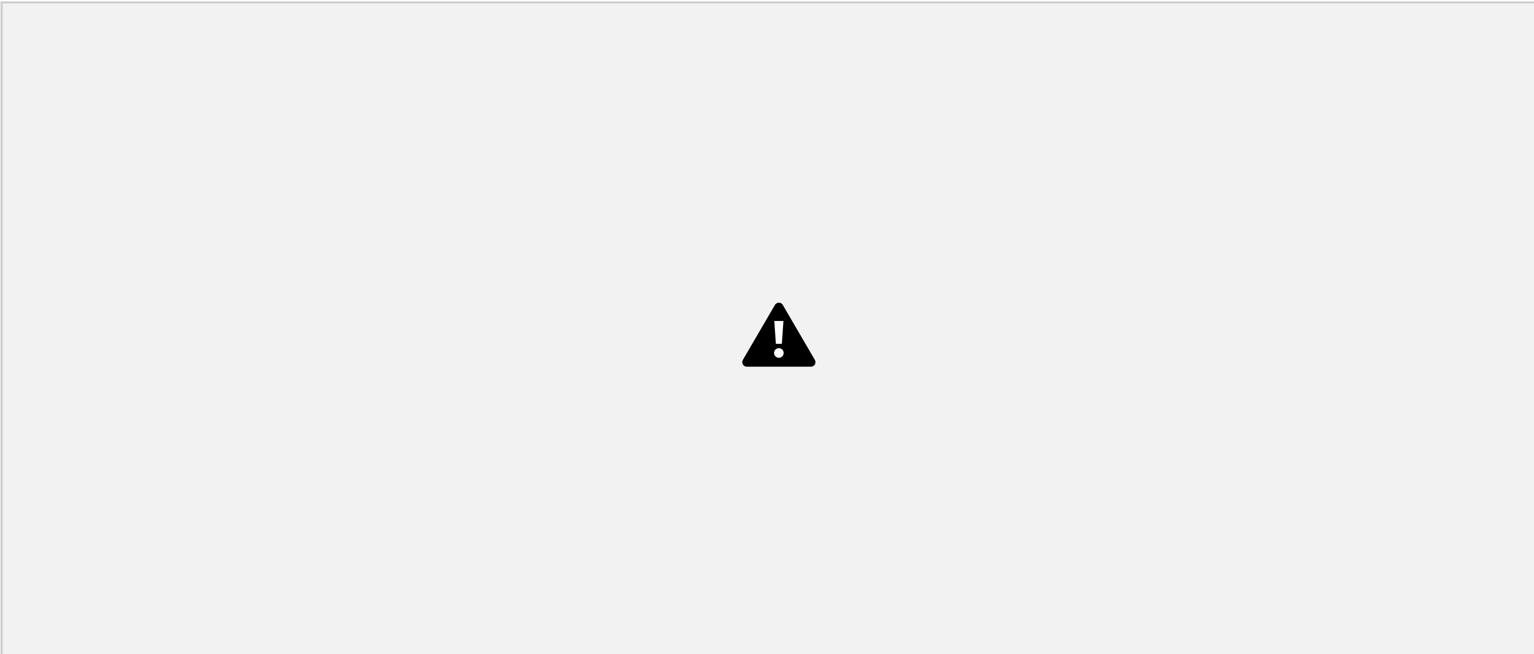


Figure: Phasor Diagram

- **EffectiveResistance:**
  - The effective resistance of the armature winding is somewhat greater than the conductor resistance, called the dc resistance, as measured by direct current.
  - This is due to additional loss, over the purely I^2R loss, inside

and sometimes outside the conductor, owing to alternating current.

- When the synchronous reactance X_S is combined with the armature effective resistance R_e, the quantity obtained is called the **synchronousimpedance.** i.e. $Z_S = R_e + jX_S$
- Armature winding effective resistance R_a in alternators is usually very small in comparison to synchronous reactance X_S, and therefore, synchronous impedance Z_S may be assumed equal to the synchronous reactance for many purposes.

- **SynchronousReactance:**
  - The emf setup due to armature reaction mmf is always in quadrature with the load current I and is proportional to it.
  - Thus, it is equivalent to an emf induced in an inductive coil

and the effect of armature reaction can, therefore, be considered equivalent to reactance drop IX_a where X_a is the fictitious reactance which takes care of the armature reaction effect.

- The armature winding possesses a certain leakage reactance X_L.
- Thus, the sum of leakage reactance X_L and fictitious reactance X_a is called **the synchronous reactance**.
- i.e., $X_S = X_L + X_a$

- It is known that the stator of the synchronous generator has three sets of winding on which emfs are induced. Usually these three windings are 'star'connected & the neutral is earthed as shown in the figure.
- When the generator is loaded

as shown in figure, current will flow through the stator winding & some voltage drop will take place in the stator winding. Therefore, the terminal voltage across the load will not be equal to the emf induced in the statorwinding.

Fig: Alternator withload

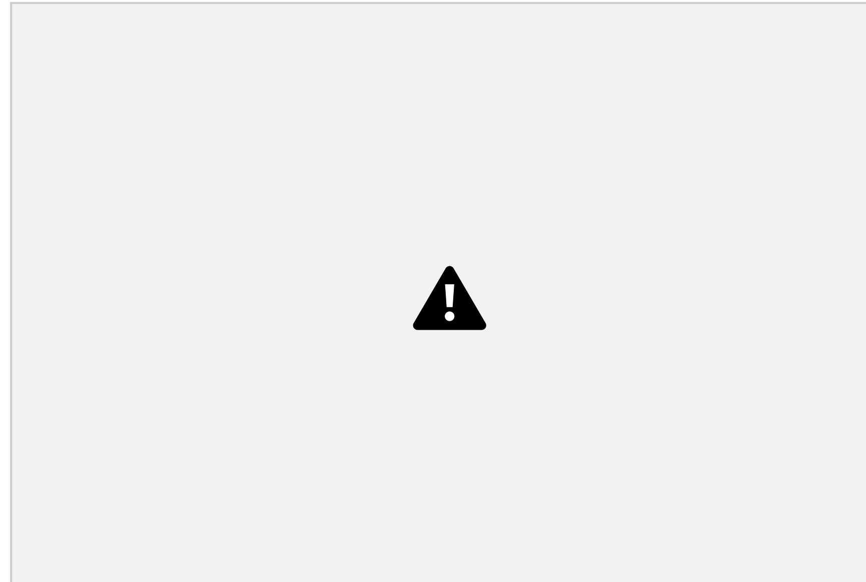
Fig: Equivalent circuit of Alternator with load

- Let E_0 = emf induced per phase in the stator winding V = terminal voltage across the load per phase

- At no- load operation, the terminal voltage (V) will be equal to the emf induced (E_0).
- But at loaded operation, the terminal voltage (V) will be less than the emf induced (E_0) due to following three reasons:
  - Voltage drop due to armature winding resistance.
  - Voltage drop due to leakage reactance of armature winding
  - Voltage drop on account of armature reaction

- Let R_e= effective armature resistance of an alternator
  X_L = Leakage reactance

- Let the voltage drop due to armature reaction be equal to voltage drop on account of fictitious reactance X_a.
- Let the terminal voltage per phase be V volts and load current per phase be I amperesand power factor cos ø.
- The voltage drop due to the armature effective resistance, IR_e will be in phase with current I, the voltage drop due to leakage reactance, $IX_L$and voltage drop due to armature reaction IX_awill be in quadrature with the load current I.
- The terminal voltage V differs from the terminal voltage on no- load, also called the excitation voltage, E_0 by the phasor sum of above voltage drops i.e. IZ_S, where $Z_S$is the synchronous impedance.



From the phasor diagram, the total

voltage drop on load

$$= IR_e + j\,(IX_L + IX_a)$$

$$= I\,[R_e + j\,(X_S)]$$

$$= IZ_S$$

The voltage on no-load, $E_0 = V + IZ_S$

$$E_0 = V + I\,[R_e + j\,(X_L + X_a)]$$

- Synchronous motor are ac motor which always rotates at a constant speed equal to synchronous speed.
- The construction of synchronous motor is exactly same as that of a synchronous generator.

- Infact,a given synchronous generator also can be used as a synchronous motor.
- Some characteristics features of synchronous motor are as follows:

- It runs either at synchronous speed or not at all i.e. while running it maintains a constant speed equal to synchronous speed.
- It is not self starting.Some auxillary means has to be used to start motor. The motor can be operated at wide range of power factors both lagging and leading

- A synchronous motor has the following two parts (refer

Figure-1)

- Consider a 3-phase, 2-pole synchronous motor having two rotor poles N_R and S_R as shown in Figure-2. The stator is also being wound for two poles N_S and S_S. A three-phase AC supply is connected to the stator winding and a DC voltage is applied to the rotor field winding.

- The stator winding produces a rotating magnetic field which revolves around the stator at synchronous speed. The DC voltage applied to the rotor sets up a two-pole field which is stationary so long as the rotor is not running. Hence, under this condition, there exists a pair of revolving stator poles (N_S-S_S)and a pair of stationary rotor poles (N_R-S_R).

- Now, suppose at any instant, the stator poles are at positions as shown in Figure-2. From Figure-2, it is clear that poles $N_S$and $N_R$repel each other and so do the poles $S_S$and S_R.

Hence, the rotor experiences a torque in the anticlockwise direction

- After a period of half-cycle of the AC supply, the polarities of the stator poles are reversed but the polarities of the rotor poles remain the same as shown in Figure-3. Under this condition, the poles S_S and N_R attract each other and so do the poles N_S and S_R. Due to this, 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 direction. But the rotor has high inertia, consequently, the rotor does not move and we say that the starting torque is zero. In other words, a synchronous motor is not self starting.

- As seen earlier, synchronous motor is not self starting. It is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible by various method in practice. The various methods to start the synchronous motor are:

1. Using pony motors
2. Using damper winding
3. As a slip ring induction motor
4. Using small d.c. machine coupled to it.

1. Using pony motors

- In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called ‘pony motor’.
- Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled.The motor then continues to rotate as synchronous motor.

2. <u>Using DamperWinding</u> • In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called damper winding. This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor. The schematic representation of such damper winding is shown in the Fig.4.

Fig.4. Starting as a squirrel cage induction motor

- Once the rotor is excited by a three phase supply, the motors starts rotating as an induction motor at sub synchronous speed. Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed.
- As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero. Hence when motor is running as synchronous motor, there can not be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start.Afterwards it is out of the circuit.
- As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

3. <u>As a Slip Ring Induction Motor</u>

- The above method of starting synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper winding, it is designed to a form a three phase star or delta connected winding. The three ends of this winding are brought out through slip

rins.

- An external rheostat then can be introduced in series with the rotor circuit. So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque. The resistance is then gradually cut off, as motor gathers speed.
- When motor attains speed near synchronous. d.c. excitation is provided to the rotor, then motors gets pulled into synchronism ans starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a motor resistance starter.
- The synchronous motor started by this method is called a slip ring induction motor is shown in the Fig.5.

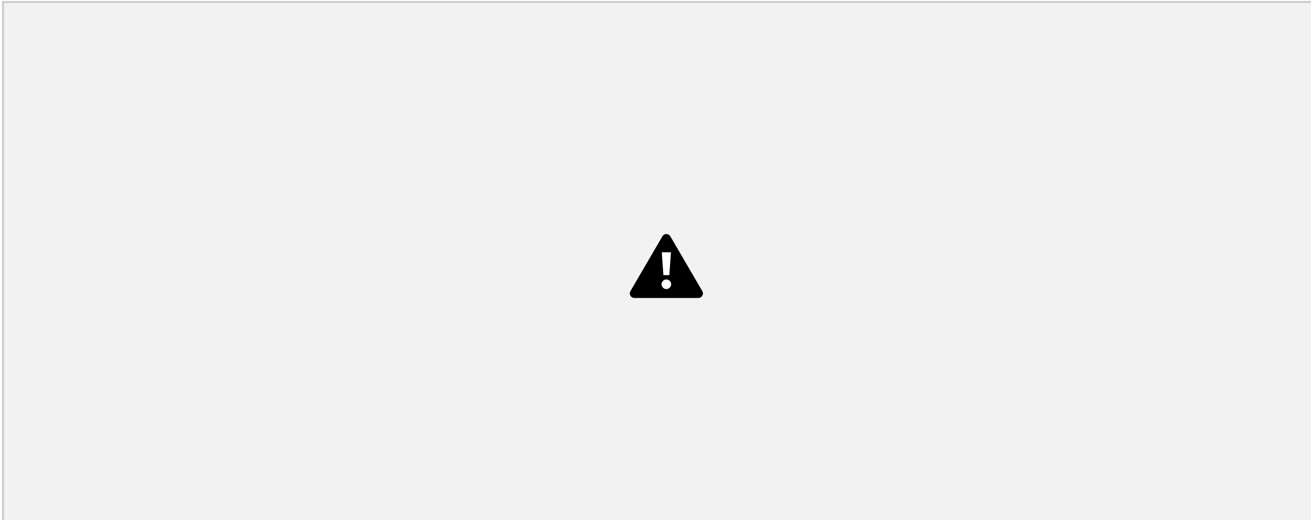


Fig.5. Starting as a slip ring induction motor

- It can be observed from the Fig.5. that the same three phase rotor winding acts as a normal rotor winding by shorting two of the phases. From the positive terminal, current ‘I’ flows in one of the phases, which divides into two other phases at start point as 1/2 through each, when switch is thrown on d.c. supply side.

4. <u>Using Small D.C. Machine</u>

- Many a times, a large synchronous motor are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.

- Let us consider the motor is operated at no-load condition. Assume the ideal condition, that is the motor has no losses.

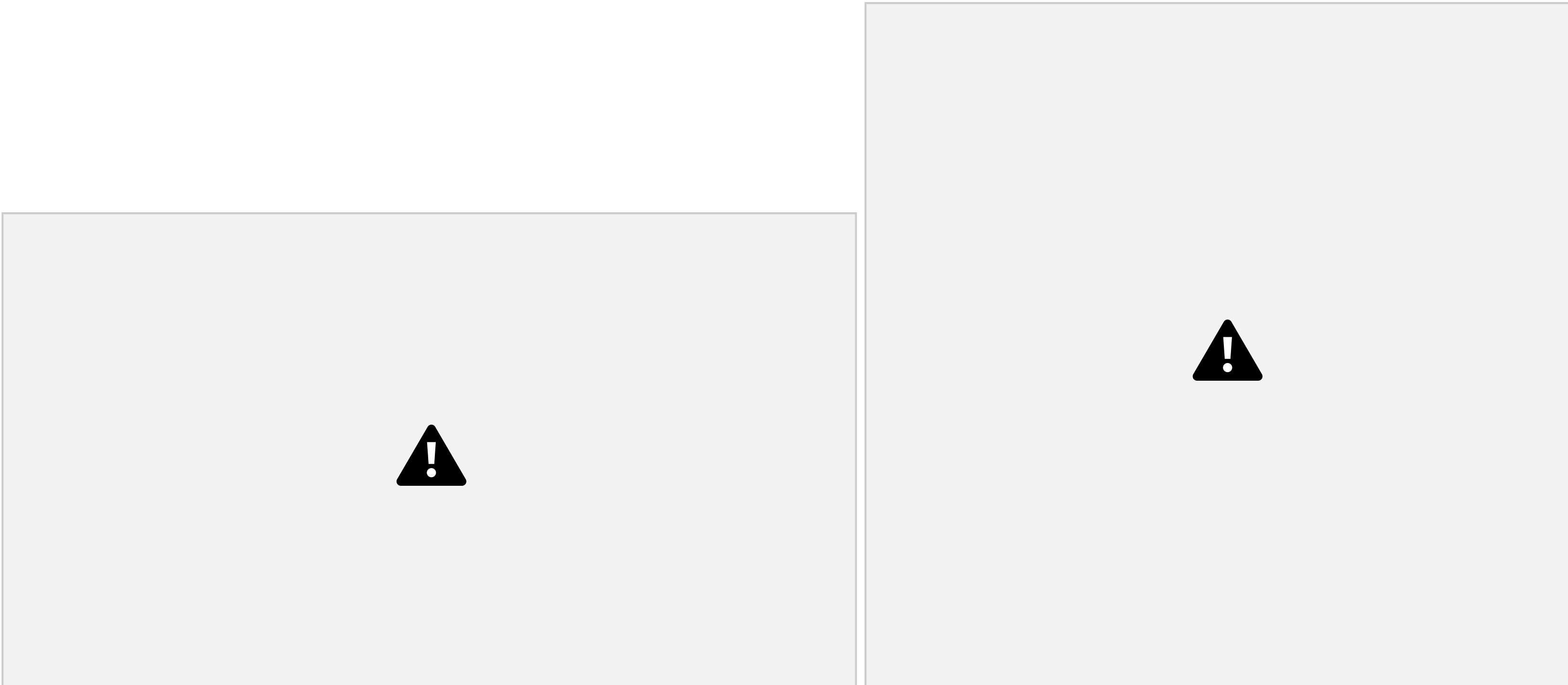


Fig.6. Synchronous motor on no- load

- Since there is no load and no losses, the armature current will be zero. Hence, there will not be any stress for the rotor to rotate. In this condition, the magnetic locking between the stator field and rotor field will be established in such a way that, both the magnetic axes coincide with each other.

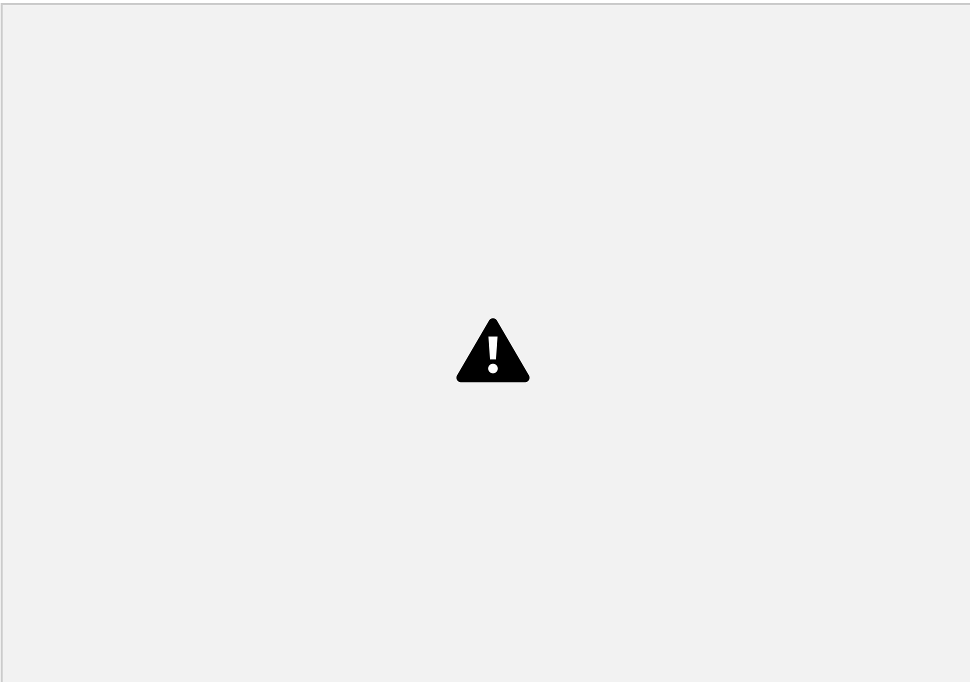
- As the armature current is zero, the voltage equation will become, $V = E_b$.

- The back emf E_b is equal and opposite to the supply voltage V as shown in the above phasor diagram.

- However, this condition is not possible in practical conditions. Because the motor has a mechanical loss, iron loss, and a small amount of copper loss even in no-load condition.

- Let us consider the motor is operated at no-load condition. Assume the practical or real case, which means the motor losses are considered.
- Due to the losses, the rotor and stator axis do not coincide with each other. Instead, the rotor axis falls behind the stator axis by

an angle δ. It is called load angle or power angle or coupling angle or angle of retardation or torque angle δ.



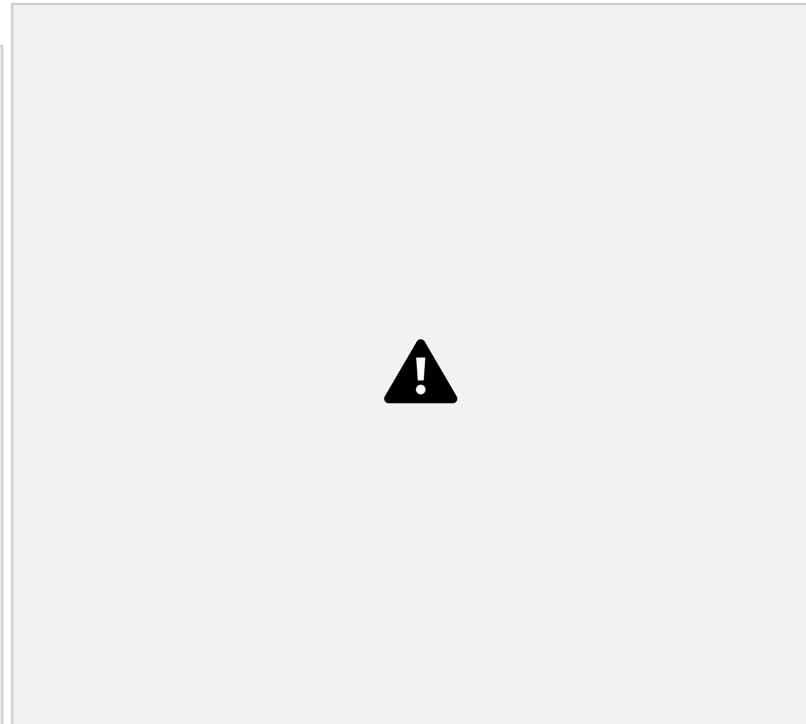


Fig.7. Synchronous motor on no- load with losses

- It causes a voltage E_R across the armature circuit and the motor draws no-load current from the mains. This no-load current lags behind the resultant voltage by an angle θ.
- However, magnetic locking still exists between the magnetic fields of

the rotor and stator. As a result, the rotor rotates at constant synchronous speed with a rotating magnetic field while maintaining an angle difference between the axes of the two fields, as illustrated in the figure below. Because of the rotor axis retardation, the flux lines between the two become stretched.

- In this case, the magnitude of supply voltage and induced back emf will be the same but they will not be in exact opposition. Rather, it is displaced from its position by an angle δ.
- Thus the vector difference between the input voltage and back emf is not zero but gives rise to a resultant phasor E_R as shown.

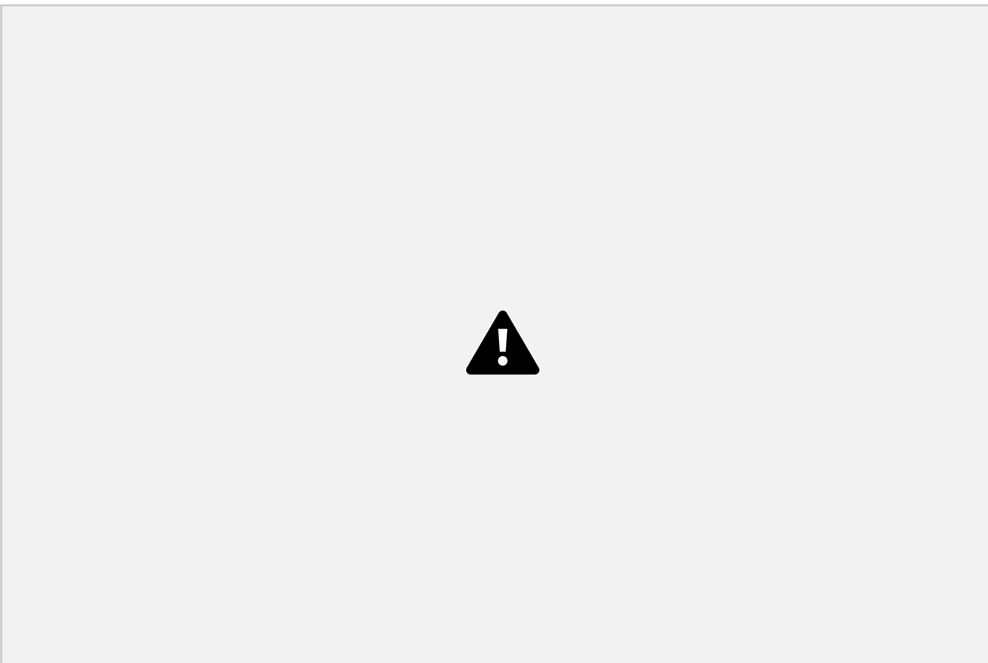
$$V - E_b = I_a Z_s = E_R$$

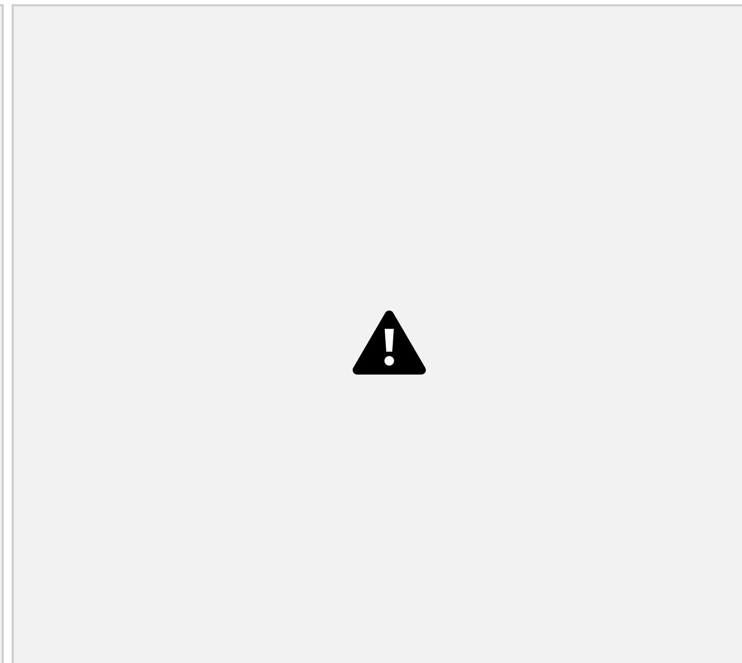
- Under the no-load condition, δ is very small and hence E_R is also very small. Hence the current drawn by the motor is also very small. It will be sufficient to produce the torque.

- Consider a mechanical load is applied to the synchronous motor. A steady increase in load will make the rotor poles fall back a little more relative to the stator poles, as shown below.

Hence the torque angle δ increases further with an increase in load.

- This increases the resultant voltage E_R which in turn increases the current $(I_a = E_R/Z_S)$ drawn by the motor from the mains.





on load

Fig.8. Synchronous motor

- Thus,a synchronous motor is able to supply the necessary torque to the increased mechanical load, by shifting the position of the rotor pole axis with respect to the stator pole axis, maintaining a constant speed or synchronous speed.

- Further increase in load will make the induced emf fall back further, which will make the load angle to increase. When the torque angle increases, the voltage E_R increases and does the armature current Ia.
- When too much mechanical load is applied to a synchronous motor, the rotor is pulled out of synchronism and comes to a halt or standstill. The maximum torque that a motor can develop without losing its synchronism is called pull out torque.

❑ One of the most important characteristics of a synchronous motor is that, by changing the field excitation of the motor, its power factor can be made both lagging and leading. The change in the power factor of the synchronous motor with the change in excitation can be explained with the help of its phasor diagram.

- Consider a synchronous motor having a constant supply voltage and driving a constant mechanical load.The input power to the motor is given by, $P_i=VE_f/X_sSin\delta=3VI_aCos\varphi$
  - Since V and XS are constant for a given synchronous motor, thus for constant power output,

$$E_f Sin\delta=Constant$$

$$I_a Cos\varphi=Constant$$

  - When the field excitation (E_f) of the motor is changed, the armature current (I_a) changes. But the product (Iacosφ) must remain constant. For this to happen, the power factor angle (φ) adjusts itself in such a way that product ($I_a cos\varphi$) remains constant. That is, the power factor of the motor will change. For ($I_a Cos\varphi$)to remain constant, the locus (represented by line XY) of tip of the phasor I_a must trace a straight line perpendicular to the phasor (see the phasor diagrams shown in the
    e).

figur

Fig.9. Under Excitation Excitation
Fig.10. Normal

Excitation Fig.11. Over

- Form the figure, it is clear that as the value of excitation (E_f)

increases, the magnitude of the armature current (I_a) first decreases and then increases again. The armature current is minimum at unity power factor and more at lagging or leading power factors.

1) **Case 1 − Under-Excitation of Synchronous Motor** The synchronous motor is said to be under-excited if the field excitation is such that (E_f<V). Under this condition, the armature current (I_a) lags behind the supply voltage (V) and consumes lagging reactive power (Q) i.e. the motor power factor is lagging as shown in Figure.9.

2) **Case 2 − Normal Excitation of Synchronous Motor** If (E_f=V), the synchronous motor is said to be normally excited. Under this condition, the reactive power of the motor is zero (i.e., Q = 0), that is the motor is neither absorbing nor delivering reactive power. Thus, the power factor of the motor is unity. For a given load, at unity power factor, the resultant voltage (E_r) and hence, the armature current (I_a) are minimum as shown in

Figure.10.

3) <u>Case 3 − Over-Excitation of Synchronous Motor</u>

The synchronous motor is said to be over-excited if the field excitation is such that (E_f>V). Under such conditions, the armature current (I_a) leads the supply voltage (V) and the motor supplies lagging reactive power to the system. Hence, motor power factor is leading as shown in Figure.11.

<u>Conclusion</u>

From the above discussion, it is concluded that,

i. If the synchronous motor is under-excited, it has a lagging power factor. ii. If the synchronous motor is normally-excited, it has unity power factor. iii. If the synchronous motor is over-excited, it has a leading power factor.

- The performance characteristics of a synchronous motor are obtained by v-curves and inverted v-curves. Synchronous machines have parabolic type characteristics (the graph drawn is in the shape of parabolic).

- If the excitation is varied from low (under-excitation) to high (over excitation) value, then the current Ia also changes i.e., becomes minimum at unity PF and then again increases.

- But at starting lagging current becomes unity and then becomes leading in nature. V-curves and inverted V-curves of a synchronous motor are used to analyze efficiency on no-load and on-load conditions.

- If the armature current Ia is plotted against excitation or field current for various load conditions, we obtain a set of curves known as 'V-Curves' clue to their shape similar to english letterV.
- In the below figure V-Curve of a synchronous motor shows how armature current Ia changes with excitation for the same input, at no-load, half full-load,

and full-load.

- From V-Curves it is observed that the armature current has large values both for low and high values of excitation (though it is lagging for low excitation and leading for higher excitation). In between, it has a minimum value corresponding to the unity power factor (normal excitation).

- If the power factor is plotted against excitation for various load conditions, we obtain a set of curves known as InvertedV-Curves.
- The inverted V-Curves of synchronous motor shows how the power factor varies with excitation. From inverted V-curves, it is observed that the power factor is lagging when the motor is under excited and leading when it is over excited. In between, the power factor is unity.