Introduction to AC machine

Classification of AC Rotating Machines

1) Synchronous Machines:

•Synchronous Generators: A primary source of electrical energy.

•Synchronous Motors: Used as motors as well as power factor compensators (synchronous condensers).

2) Asynchronous (Induction) Machines:

•Induction Motors: Most widely used electrical motors in both domestic and industrial applications.

•Induction Generators: Due to lack of a separate field excitation, these machines are rarely used as generators.

Synchronous machine

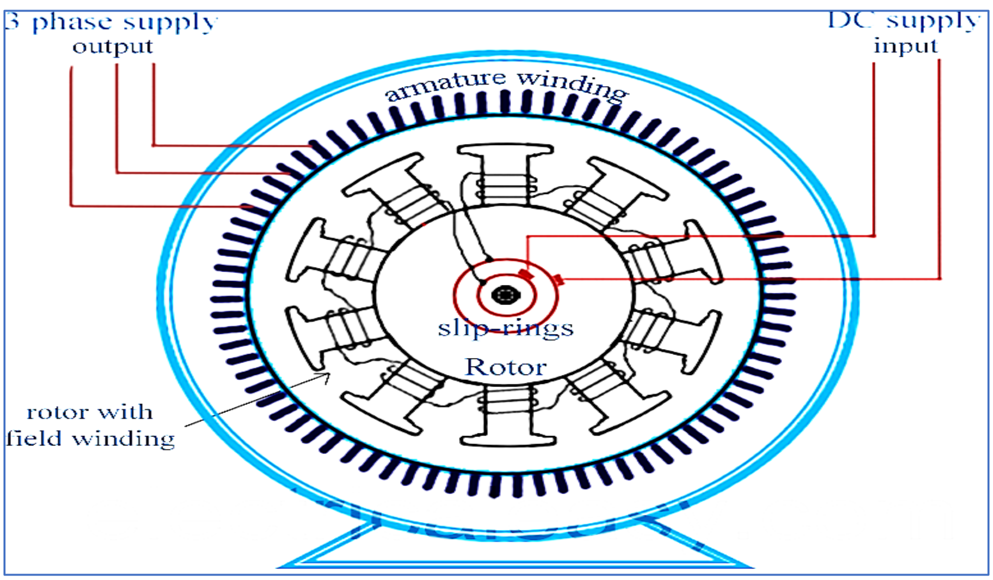
Introduction

- Synchronous machine constitutes of both synchronous motors as well as synchronous generators.
- Under steady state conditions, the rotating air gap field and the rotor in a synchronous machine rotate at the same speed, called the synchronous speed which depends on the frequency of the armature current and the number of field poles. Synchronous machine always operates at a speed equal to synchronous speed i.e., $N_s = 120f/P$ where f = supply frequency P = number of poles
- In case of motor, it automatically rotates at a constant speed at different loads and in case of generator, speed governor is used to control the speed at a constant value.

Construction

The main parts of synchronous machine are

1) Stator
2) Rotor
   i) Salient pole rotor ii) Non salient/cylindrical rotor
3) Excitor



1. **Stator**

- The stator is the stationary part of the machine. It includes various parts like stator frame, stator core, stator windings and cooling arrangement.

- It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator.
- Stator consists of distributed winding embedded in slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF
- The stator/armature is an iron ring formed of lamination of special magnetic iron having slot in it and inner periphery to accommodate armature conductor.

2. **Rotor**

- Rotating part of the machine with number of magnetic poles excited by DC current.
- DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles.
- The rotor produces the main field flux.

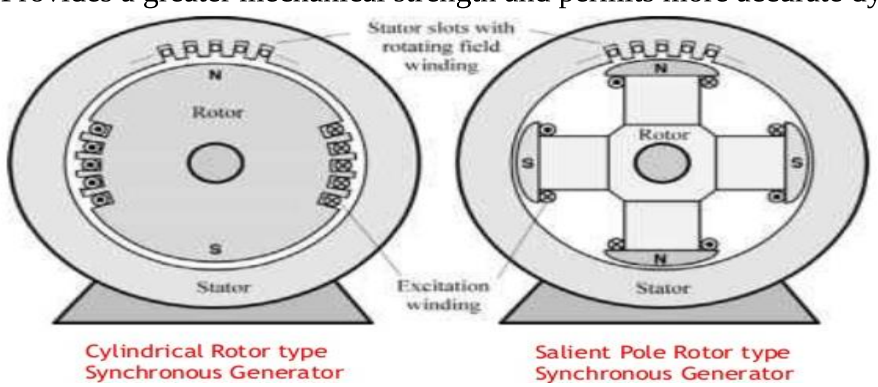
There are two types of rotor construction, namely salient pole type and cylindrical rotor type.

Salient pole rotor

- Construction is easier and cheaper
- This type of rotor has projected magnetic poles i.e., poles projecting out from the surface of the rotor core. It is made up of steel laminations to reduce eddy current losses.
- Constructed for medium & low speeds due to large number of poles i.e., hydraulic turbine, diesel engine.
- A salient pole machine has a non-uniform air gap. The gap is maximum between the poles and is minimum at the pole centers.

Cylindrical pole rotor

- No projected poles i.e. smooth magnetic poles in cylindrical surface.
- A cylindrical rotor is made from solid forgings of high-grade nickel chrome molybdenum steel forgings of high-grade nickel chrome molybdenum steel.
- They are useful in high-speed machines i.e., steam turbine as they have less number of poles. They also produce less noise and windage losses as they have a uniform air gap.
- The cylindrical rotor type alternator has two or four poles on the rotor.
- Provides a greater mechanical strength and permits more accurate dynamic balancing.



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3.**Excitor**

- Excitor produce dc current required for rotor field winding.
- It is a self-excited DC generator mounted on the shaft of synchronous machine.
- DC supply is given to it through slip rings. When direct current flow through the field winding, it produces the required magnetic field.

Main advantages of rotating field and stationary armature

The magnetic field system in synchronous generator is opposite to DC generator as in DC there is rotating armature and stationary field system. But in synchronous there is rotating field and stationary armature. The following are the main advantages of rotating field type synchronous machines.

1) A stationary armature is more easily insulated for the high voltage for which the alternator is designed. This generated voltage may be as high as 33 kV.
2) The armature windings can be braced better mechanically against high electromagnetic forces due to large short-circuit currents when the armature windings are in the stator. The armature windings, being stationary, are not subjected to vibration and centrifugal forces.
3) The output current can be taken directly from fixed terminals on the stationary armature without using slip rings, brushes, etc.
4) The voltage generated in the armature is much higher and therefore greater insulation is required for the armature winding. Thus, it is much easier to insulate the high voltage winding when it is mounted on a stationary structure.
5) Two slip rings are required for the supply of direct current to the rotor while in stationary field type 3 to 4 slip rings would be needed.
6) Rotating field is comparatively light and can be constructed for high-speed operation.
7) The stationary armature may be cooled more easily because the armature can be made large to provide a number of cooling ducts.

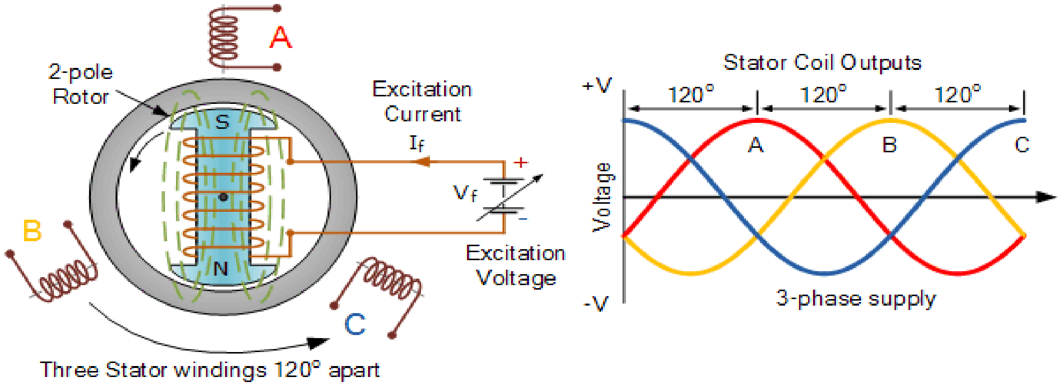
Operating principle of synchronous generator

- The synchronous generator works on the principle of Faraday laws of electromagnetic induction.
- 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 is the alternator is just reverse of it there the armature is stationary called as stator and field system is rotating called as Rotor.
- The electromagnetic induction states that electromotive force induced in the armature coil if it is rotating in the uniform magnetic field. The EMF will also be generated When the field is rotated by a prime mover, voltages are induced in the stator coils because they are cutting the flux of the rotor field.
- Thus, the relative motion between the conductor and the field induces the EMF in the conductor.
- Thus, 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 stators 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.

  So, if we plot the magnitudes of the induced emf against the time, we get an alternating nature of the induced emf

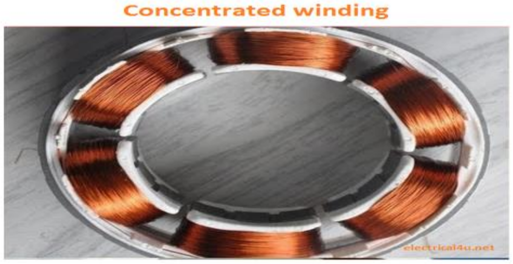


Distributed winding & Concentrated Winding

1. **Concentrated Winding**: Concentrated type of winding can be done when the total number of poles in the armature is equal to the number of slots of the armature coil. Look at the image, the winding the total coils is wound in the single slots.

- All the turns of this type of winding have the same magnetic axis, for example, the transformer winding. This type of winding gives maximum output voltage but not exact sinusoidal because it is independent of pitch and distribution factor.
- i.e., all the coil of one phase is placed in one slot of each phase under each pole. Or Winding Will be done in a single slot
- Induced voltage is arithmetic sum since no phase difference
- This type of winding is used in transformer, electromagnets etc.

Concentrated winding



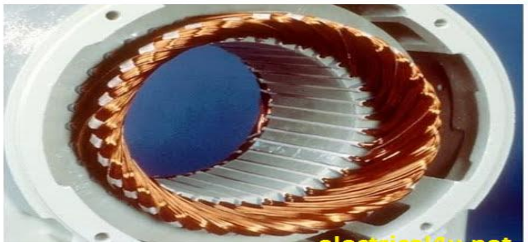
2. **Distribution Winding**: Here, coil sides are placed in different sides under each pole. Or Winding will be done throughout the slot

- Distributed winding is distributed along the air gap. In these winding poles are not equal to the number of slots. It does not have the same magnetic axis.
- The emf induced in the distributed winding is less due to the presence of pitch factor and distribution factor.
- Distributed windings are used in DC machine, synchronous machine and induction machine.
- The voltage induced is vector sum of each slot.

Advantages of Distributed Winding:

1. It reduces harmonics present in the generated emf which also improves the sine waveform.
2. It reduces armature reaction and improves cooling.
3. The coil is distributed over the slots, so the core (copper and iron) is fully used.
4. It improves the mechanical strength of the winding.

Distributed Winding



EMF EQUATION

- Consider a 3Ø alternator with

  Φ = flux per pole in Wb

  P = Number of poles

  Ns = Synchronous speed in rpm

  f = frequency of induced emf in Hz

  Z = total number of stator conductors or armature conductors or coil sides in series/phase

  = 2T (because one turn or coil has two side or as 2 conductors constitute 1 turn)

  T = no. of turns or coils per phase

  According to Faradays Law electromagnetic induction,

  The average value of emf induced per conductor in one revolution $E_{avg} = d\Phi/dt$

  where, Total flux cut per revolution by any one stator conductor = dΦ

  =PØ Wb

  Time taken for one revolution = dt= 1/N min or 60/N sec

- Average value of emf induced per conductor = dΦ/dt = PØ / (60/N) (wb/sec)

  = PØN/60 (wb/sec)

  But we have N=120f/P

- So, the average value of the induced emf per conductor = 2FØ volts
- In any one phase Z conductors are joined in series,
- Therefore, average induced emf per phase = (2FØ) Z volts = 2FØ(2T) volts
- Avg. value of induced emf per phase = 4FØT volts
- For a sine wave form factor = rms value/avg value = 1.11

  RMS value of induced emf per phase = 1.11 × average value

  E_{rms} = 4.44FØT volts

  This is the general EMF equation for the machine having concentrated and full pitched winding

  In a practical alternator the space distribution of the field 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 derived.

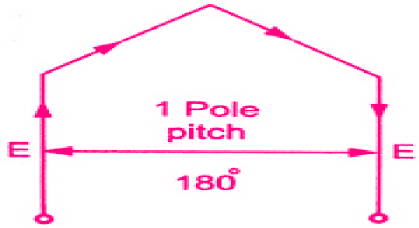
  Therefore, by inserting pitch factor (or) chording factor (or) coil span factor (Kc or K_p) and Distribution or breadth factor (K_d or K_b) in the above emf equation, we with get the actual emf equations as

  $E_{rms} = 4.44\ f\ Ø\ T\ K_c\ K_d$ volts.

  Pitch Factor or Coil Span Factor (Kc)

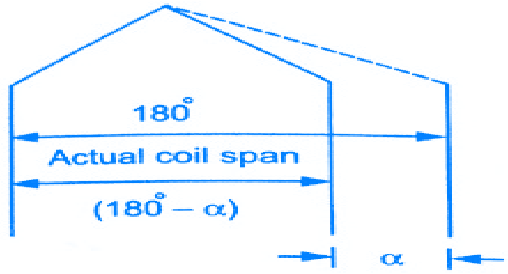
- **In** practice, short pitch coils are preferred. So, coil is formed by connecting one coil side to another which is less than one pole pitch away. So actual coil span is less than 180°. The coil is generally shorted by one or two slots.

- Let, E be the induced emf in each coil side. If the coil is full pitch coil,



the resultant emf across a coil is. $E_R = E + E = 2E$

- Now, as coils are shorted in terms of the number of slots i.e., either by one slot, two slots and so on and slot angle is β then the angle of short pitch is always a multiple of the slot angle β.

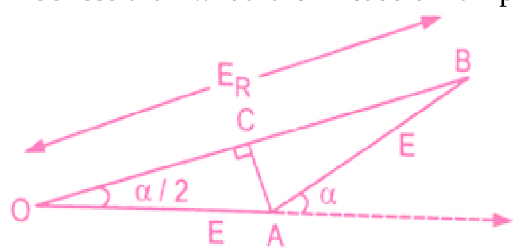


- Let, α = Angle by which coils are short pitched.

  α = β x Number of slots by which coils are short pitched

  or α = (180° - Actual coil span of the coils)

- Now the coil is short pitched by angle α, the resultant emf is also no longer remains the algebraic sum of the two but becomes a phasor sum of the two as shown in the figure. Obviously, E_R in such a case will be less than what it is in case of full pitch coil.

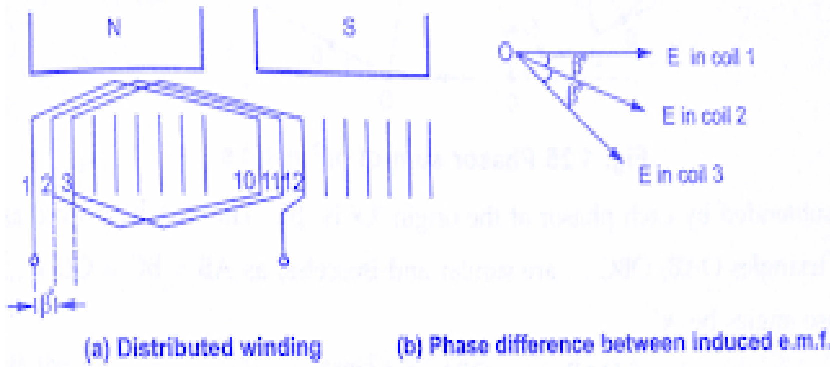


Here, $E_R = 2E\cos(\alpha/2)$

Pitch factor $K_p = \dfrac{\text{emf induced in a short pitched coil}}{\text{emf induced in a full pitched coil}} = \dfrac{(2E\cos\alpha/2)}{2E} = \cos\alpha/2$

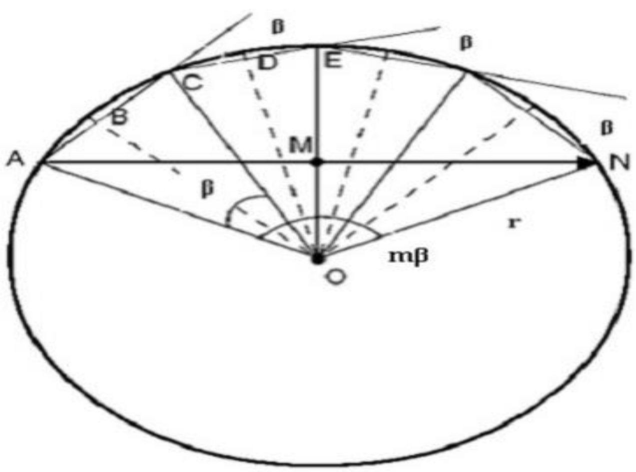
<u>Distribution Factor (K_d)</u>

- Similar to full pitch coils, concentrated winding is also rare in practice. Attempt made to use all the slots available under a pole for the winding which makes the nature of the induced emf more sinusoidal. Such a winding is called distributed winding.
- In concentrated winding the emf induced in all the coil sides will be same in magnitude and in phase with each other. In case of distributed winding the magnitude of emf will be same but the emfs induced in each coil side will not be in phase with each other as they are distributed in the slots under a pole. Hence the total emf will not be same as that in concentrated winding but will be equal to the vector sum of the emfs induced. Hence it will be less than that in the concentrated winding.
- Distribution factor $K_d = \dfrac{\text{EMF induced in a distributed winding}}{\text{EMF induced in a concentrated winding}} = \dfrac{\text{vector sum of the EMF}}{\text{arithmetic sum of the EMF}}$



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

- Let E = emf induced per coil side
  m = number of slots per pole per phase,
  n = number of slots per pole
  β = slot angle = 180/n
- The emf induced in concentrated winding with m slots per pole per phase = m E volts.
- Fig below shows the method of calculating the vector sum of the voltages in a distributed winding having a mutual phase difference of β. When m is large curve ACEN will form the arc of a circle of radius r.
- Now,



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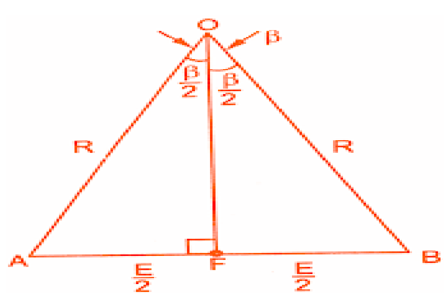


- From the figure below AC = 2 * r * sin β/2 where, β = 180/slots/poles
- Hence arithmetic sum = m * 2r sin β/2 where, m=slot/(pole*phase)
- Now the vector sum of the emfs is AN as shown in figure below = 2 * r * sin mβ/2
- Hence distribution factor $K_d = \frac{\text{vector sum of the EMF}}{\text{arithmetic sum of the EMF}} = \frac{(2r \sin m\beta/2)}{(m * 2r \sin \beta/2)} = \frac{(\sin m\beta/2)}{(m * \sin \beta/2)}$

Numerical

1. A 3Φ, 50 Hz, star connected salient pole alternator has 216 slots with 5 conductors per slot. All the conductors of each phase are connected in series; the winding is distributed and full pitched. The flux per pole is 30 mwb and the alternator runs at 250 rpm. Determine the phase and line voltages of emf induced.

Slon: $N_s = 250$ rpm, f = 50 Hz,

$P = 120 \times f/N_s = 120 \times 50/250 = 24$ poles

m = number of slots/pole/phase = 216/(24 x 3) = 3

$\beta = 180^0$ / number of slots/pole $= 180^0 / (216/24) = 20^0$

Hence distribution factor $K_d = (\sin m\beta/2) / (m \sin \beta/2)$

$= (\sin 3 \times 20 / 2) / (3 \sin 20/2)$

$= 0.9597$

Pitch factor $K_p = 1$ for full pitched winding.

We have emf induced per conductor

$T_{ph} = Z_{ph}/2$; $Z_{ph} = Z/3$

Z = conductor/ slot x number of slots

$T_{ph} = Z/6 = 216 \times 5 /6 = 180$

Therefore $E_{ph} = 4.44 K_p K_d f \Phi T_{ph}$ vlolts

$= 4.44 \times 1 \times 0.9597 \times 50 \times 30 \times 10^{-3} \times 180$

= 1150.488 volts

Hence the line Voltage $E_L = \sqrt{3}$ x phase voltage $= \sqrt{3} E_{ph}$

$= \sqrt{3} \times 1150.488$

= 1992.65 volts

2. A 3Φ, 16 poles, star connected salient pole alternator has 144 slots with 10 conductors per slot. The alternator is run at 375 rpm. The terminal voltage of the generator found to be 2.657 KV. Determine the frequency of the induced EMF and the flux per pole.

Solution:

Ns = 375 rpm, P =16, slots = 144, Total no. of conductors = 144 x 10 = 1440

$E_L = 2.657$ kV, $f = P N_s/120 = 16 \times 375/120 = 50$ Hz

Assuming full pitched winding $k_p = 1$

Number of slots per pole per phase = 144/(16 x 3) = 3

Slot angle β = 1800 / number of slots/pole = 1800 /9 = 200

Hence distribution factor $K_d = (\sin m\beta/2) / (m \sin \beta/2) = (\sin 3 \times 20 / 2) / (3 \sin 20/2) = 0.9597$

Turns per phase $T_{ph} = 144 \times 10/ 6 = 240$

$E_{ph} = E_L/\sqrt{3} = 2.657/\sqrt{3} = 1.534$ kV

$E_{ph} = 4.44 K_p K_d f \Phi Tph$ volts

$1534.0 = 4.44 \times 1 \times 0.9597 \times 50 \times \Phi \times 240$

Φ = 0.03 wb = 30 mwb

3. A 4 pole, 3 phase, 50 Hz, star connected alternator has 60 slots with 4 conductors per slot. The coils are short pitched by 3 slots. If the phase spread is 60^0, find the line voltage induced for a flux per pole of 0.943 wb.

Slon: p = 4, f = 50 Hz, Slots = 60, cond/slot = 4 , short pitched by 3 slots, phase spread = 60^0, Φ = 0.943 wb

Number of slots/pole/phase m = 60/(4 x 3) = 5
Slot angle β = phase spread/ number of slots per pole/phase
= 60/5 = 12
Distribution factor $k_d = (\sin m\beta/2) / (m \sin\beta/2)$
= sin (5 x 12/2) / 5 sin(12/2)
= 0.957
Pitch factor = cos α/2

Coils are short chorded by 3 slots
Slot angle = 180/number of slots/pole
= 180/15 = 12
Therefore coil is short pitched by α = 3 x slot angle = 3 x 12 = 36^0
Hence pitch factor $k_p = \cos \alpha/2 = \cos 36/2 = 0.95$

Number of turns per phase $T_{ph} = Z_{ph}/2 = (Z/3)/2 = Z/6 = 60 \times 4/6 = 40$

EMF induced per phase $E_{ph} = 4.44\, k_p\, k_d\, f\ \Phi\, T_{ph}$ volts
= 4.44 x 0.95 x 0.957 x 50 x 0.943 x 40
= 7613 volts
Line voltage $E_L = \sqrt{3} \times E_{ph}$
= $\sqrt{3}$ x 7613 = 13185 volts

4. In a 3 phase star connected alternator, there are 2 coil sides per slot and 16 turns per coil. The stator has 288 slots. When run at 250 rpm the line voltage is 6600 volts at 50 Hz. The coils are shot pitched by 2 slots. Calculate the flux per pole.

Slon: N_s = 250 rpm, f = 50 Hz, slots = 288, E_L= 6600 volts, 2 coilsides/slot, 16 turns /coil
Short pitched by 2 slots

Number of poles = 120f/ N_s = 120 x 50/250 = 24
Number of slots /pole/phase m = 288 / (24 x 3) = 4
Number of slots /pole = 288 / 24 = 12
Slot angle β = 180/ number of slots per pole
= 180 / 12 = 15^0

Distribution factor $k_d = (\sin m\beta/2) / (m \sin\beta/2)$
= sin (4 x 15/2) / 4 sin(15/2)
= 0.9576

Coils are short chorded by 2 slots
Slot angle = 15
Therefore coil is short pitched by α = 2 x slot angle = 2 x 15 = 30^0
Hence pitch factor $k_p = \cos \alpha/2 = \cos 30/2 = 0.9659$

Two coil sides per slot and 16 turns per coil
Total number of conductors per slot = 2 x 16 = 32 turns
Total conductors = 32 x 288
Turns per phase = 32 x 288 / 6
= 1536

$E_{ph} = 6600 / \sqrt{3} = 3810.51$ volts,

We have EMF induced per phase $E_{ph} = 4.44\, k_p\, k_d\, f\ \Phi\, T_{ph}$ volts
3810.51 = 4.44 x 0.9659 x 0.9576 x 50 x Φ x 1536
Φ = 0.02 wb

Armature Reaction in a Synchronous Machine

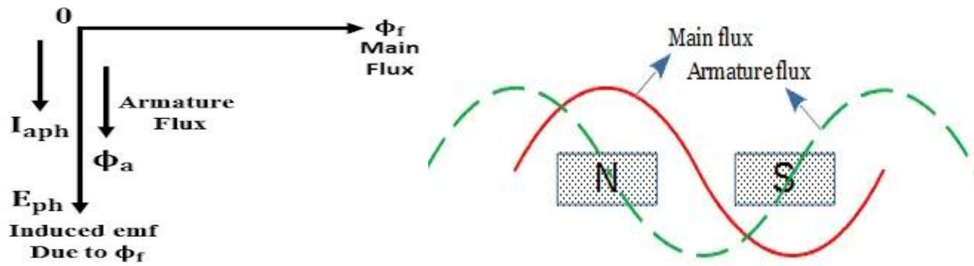
- Whenever the synchronous generator is loaded, current will start flowing through armature winding. This current carrying armature winding will setup its own magnetic flux which is also rotating in nature. The effect of armature field on the field produced by the rotor is known as armature reaction.
- When the current flows through the armature winding of an alternator, a flux is produced by the resulting MMF. This armature flux reacts with the main pole flux, causing the resultant flux to become either less than or more than the original main field flux.

- Thus, Effect of Armature (stator) flux on flux produced by rotor field poles is called Armature Reaction.
- The nature of armature reaction in synchronous machine depends on power factors of the load\ nature of load. The power factor can be defined as the cosine of the angle between the armature phase current and the induced EMF in the armature conductor in that phase.
  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.
- Here armature reaction is discussed for following three conditions, namely unity power factor, zero power factor lagging and zero power factor leading.

Effect of Load Power Factor on Armature Reaction

i) Armature reaction at unity power factor load/ purely resistive load

Consider an alternator is supplying to a purely resistive load. The current is in phase with the voltage i.e., unity power factor, and therefore the position of the coil for maximum current will be the same as the position for maximum voltage. The armature current produces armature flux lags behind the main flux by 90°.

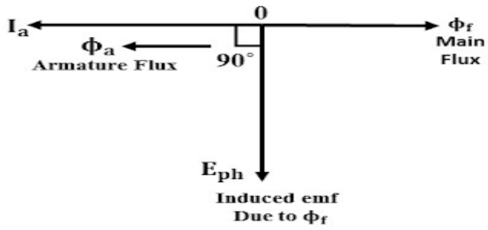


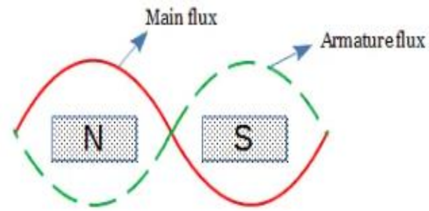
- As the armature flux act on the main field flux perpendicularly, the distribution of main field flux under a pole face does not remain uniformly distributed.
- The waveform of armature flux will cross and distorts the main field flux at one point, thereby weakening the main flux. This effect is called **cross magnetizing effect**.
- Also, the armature flux also assists the main flux at another point. In this case, the armature reaction strengthens the main field flux. Due to these effects, the main field flux will get distorted, without causing much change to the generated voltage.
- Thus, flux density at the trailing tip of the pole is increased while flux at the leading tip of the pole decreases. Due to this, the armature reaction at resistive load is said to have a distorting effect maintaining the constant average field strength.
- The effect on the alternator due to armature reaction for unity power factor load causes a small terminal voltage drop of an alternator. The effect of armature reaction under unity power factor load is called 'Cross Magnetising Effect'.

ii) Armature reaction at zero power factor lagging load/purely inductive load

When the load is purely inductive, the current lags by 90° behind the voltage, and therefore, the coil has to advance 90° (electrical) from the earlier position as shown in the below figure. The armature current will be delayed by 90^0 and so the armature flux produced will also be shifted by 90^0 with respect to the poles.

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

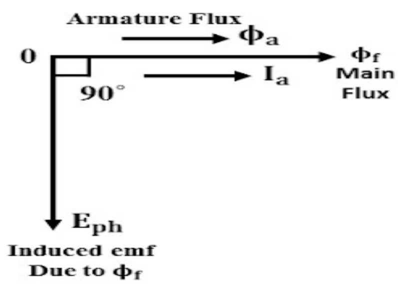


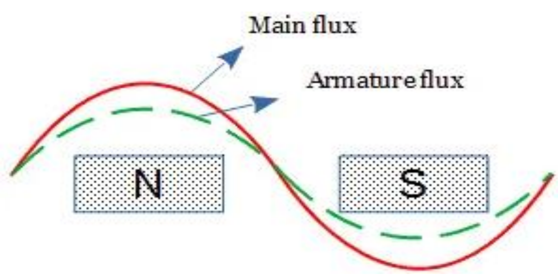


Thus, the main flux gets decreased in this loading condition. This effect of armature reaction on this load is said to be a **demagnetizing effect**.
Due to this, the main field flux gets weaken and so the emf induced will be reduced. To maintain the same value of generated emf, filed excitation will have to be increased to overcome the demagnetizing effect.

iii) <u>Armature reaction at zero power factor leading load/purely capacitive load</u>

When the load is purely capacitive, Current lead by 90° to the voltage, and therefore, the coil carries its maximum current by 90° before it reaches the position as shown below.
The armature current due to emf induced by main field flux leads by 90° as shown in the below phasor diagram. Thus, the armature winding flux and main field flux will be in the same direction and add-up each other, resulting in strengthening of the field flux. Thus, the main flux gets increased in this loading condition.

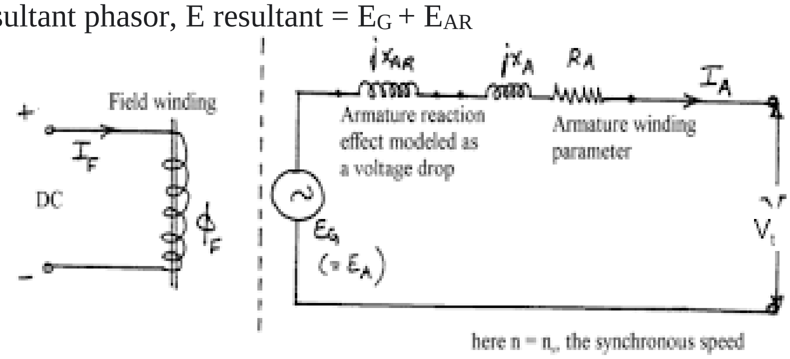




Hence, in this case, the armature reaction exerts a wholly magnetizing effect due to the addition of both fluxes. This results in greater induced emf, and the terminal voltage of the alternator. To keep up the same emf the excitation to the field has to be reduced. Since the armature flux assists field flux, therefore the effect is called as **'Magnetising effect'** of armature reaction.

<u>Equivalent circuit of synchronous Generator</u>

- Dc current is supplied to the field winding which produces main field flux Φ_f
- Φ_f induces an emf E_G, in the armature winding
- Depending upon the loaded condition, armature current I_A induces
- IA induces its own flux due to armature reaction; E_{AR} is induced by Φ_{AR}.
- The resultant phasor, E resultant = $E_G + E_{AR}$

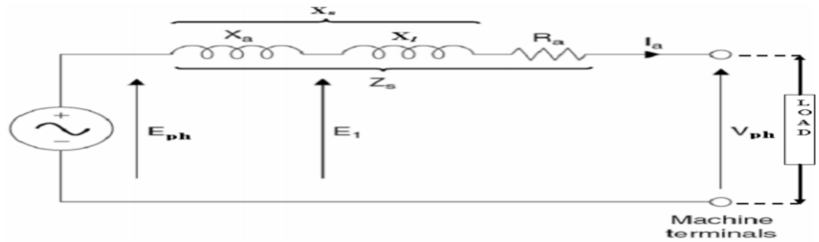


Prepared By: Damodar Bhandari

$V_t = E_G – I_a R_a - jI_a X_{AR} + jI_a X_A$
$V_t = E_G - I_aR_a – jI_a X_s$
$V_t = E_G – I_a(R_a - jX_s)$ where, $X_s = X_{AR} + X_A$ = synchronous reactance

Equivalent Parameters

- So, we can see that, armature flux distorts the main field flux. The nature of armature reaction depends upon the power factor of the load. Armature reaction thus causes the additional voltage drop.
- The voltage drop due to armature reaction may be modelled in the equivalent circuit by a reactance X_a. The voltage drop I_aX_a thus simulates the voltage drop due to armature reaction. The leakage reactance is the true reactance and the armature reaction reactance is a fictitious reactance.



- The sum of leakage reactance and armature reaction reactance is called synchronous reactance X_s. Therefore, synchronous reactance $X_s = X_l + X_a$ **Ω** per phase
- and synchronous impedance $Z_s = R_a + j X_s$ **Ω** per phase
- Armature winding effective resistance Ra in alternators is usually very small in comparison to synchronous reactance X_S, & therefore, synchronous impedance Z_s may be assumed equal to the synchronous reactance for many purposes. And usually, Ra≈1.25 to 1.75 of $R_{d.c.}$

- **Phasor Diagram of synchronous generator**

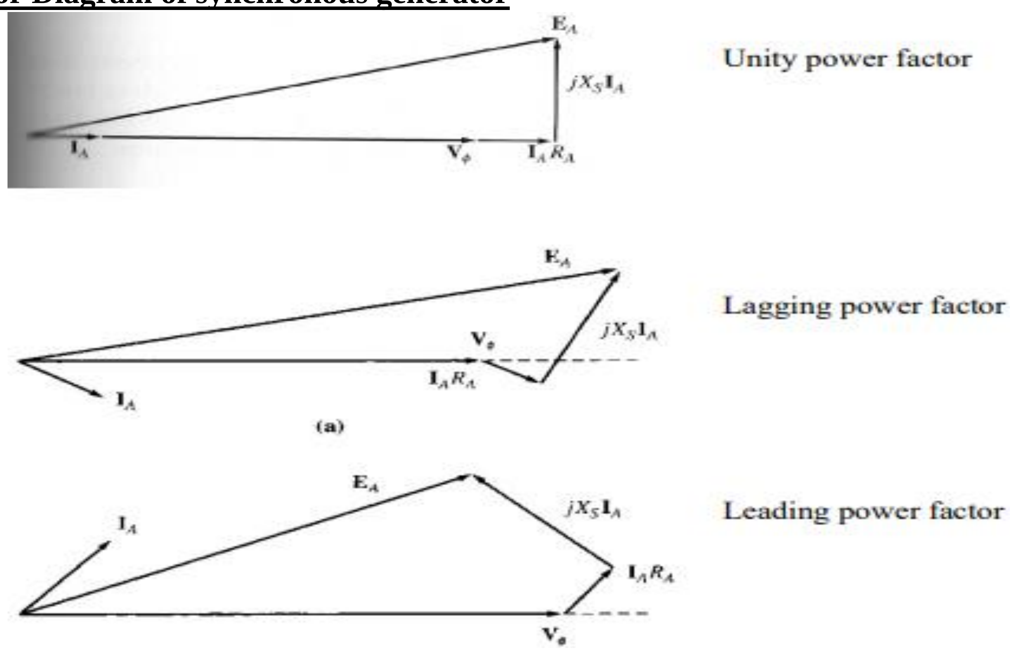


Fig: i) Unity power factor/ resistive load
ii) Inductive load/lagging power factor
iii) Capacitive load/leading power factor

Voltage Regulation

- 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 $\% \text{ Regulation} = \frac{Eph - Vph}{Vph} * 100$

  Where E_{ph} = Induced EMF /phase, V_{ph} = Rated terminal voltage/phase

Methods of finding Voltage Regulation

- The voltage regulation of an alternator can be determined by different methods. In case of small generators, it can be determined by direct loading whereas in case of large generators it cannot determine by direct loading but will be usually predetermined by different methods.
- Following are the different methods used for predetermination of regulation of alternators.
  1. Direct loading method
  2. EMF method or Synchronous impedance method
  3. MMF method or Ampere turns method
  4. ASA modified MMF method
  5. ZPF method or Potier triangle method
- All the above methods other than direct loading are valid for non-salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

1. Voltage regulation of Alternator by Synchronous Impedance Method/EMF method

- In EMF method, the voltage drops due to armature resistance (R_a) and the drop due to synchronous reactance (X_S) is considered, both the drops are emf quantities. The impedance of armature winding is expressed as $Z_S = R_a + jX_S \ \Omega/phase$, which is nothing but the synchronous impedance of an alternator and since the drop due to the synchronous impedance is considered, this method is called *synchronous impedance method*.
- Before calculating the voltage regulation, we need to calculate the following data.

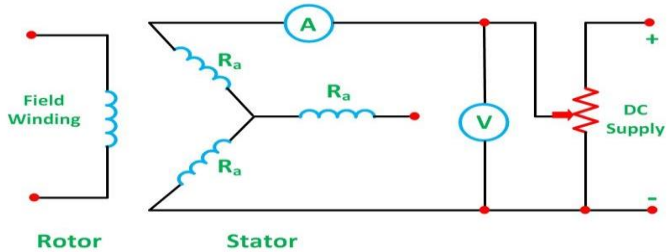
  1.Armature Resistance per phase [R_a]

  2. Open Circuit characteristics which is a graph between open circuit voltage [$V_{o.c.}$] and field current.

  3.Short circuit characteristics which is a graph between short circuit current [$I_{s.c.}$] and field current.

  1. **Armature Resistance per phase [Ra]**

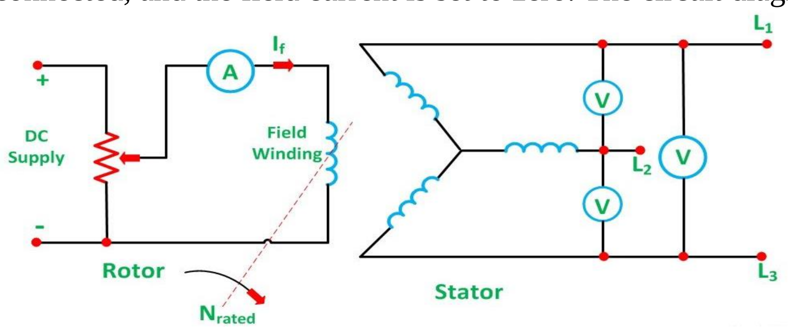
  In this test, it is assumed that the alternator is star connected with the DC field winding open as shown in the circuit diagram below.



It measures the DC resistance between each pair of terminals either by using an ammeter – voltmeter method or by using the Wheatstone's bridge. The average of three sets of resistance value R_t is taken. The value of R_t is divided by 2 to obtain a value of DC resistance per phase. Since the effective AC resistance is larger than the DC resistance due to skin effect. Therefore, the effective AC resistance per phase is obtained by multiplying the DC resistance by a factor 1.20 to 1.75 depending on the size of the machine. A typical value to use in the calculation would be 1.25.

2. **Open Circuit Test**

In the open circuit **test** for determining the synchronous impedance, the alternator is running at the rated synchronous speed, and the load terminals are kept open. This means that the loads are disconnected, and the field current is set to zero. The circuit diagram is shown below.

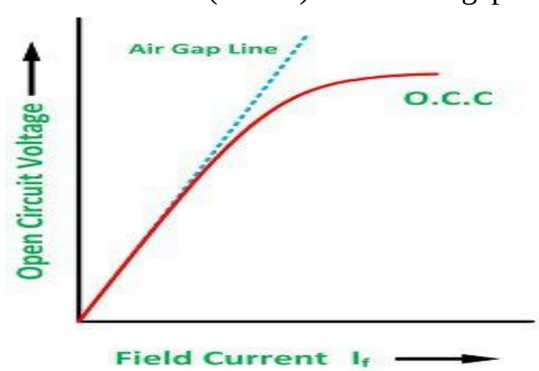


After setting the field current to zero, the field current is gradually increased step by step. The terminal voltage E_t is measured at each step. The excitation current may be increased to get 25% more than the rated voltage.

A graph is drawn between the open circuit phase voltage $E_p=E_t/\sqrt{3}$ and the field current I_f.

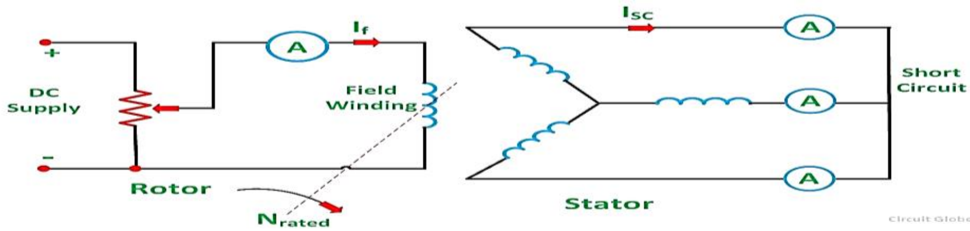
The curve so obtains called Open Circuit Characteristic (O.C.C). The shape is same as normal magnetization curve. The linear portion of the O.C.C is extended to form an air gap line.

- The Open Circuit Characteristic (O.C.C) and the air gap line is shown in the figure below.

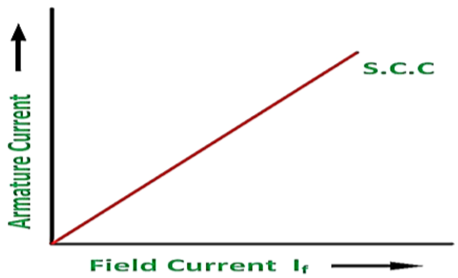


3. **Short Circuit Test**

In short circuit test, the armature terminals are shorted through three ammeters as shown in figure below.

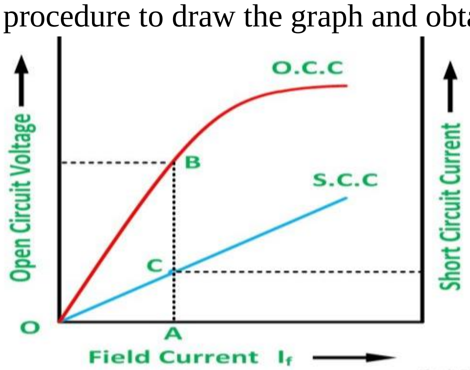


- The field current should first be decreased to zero before starting the alternator. Each ammeter should have a range greater than the rated full load value. The alternator is then run at synchronous speed. Same as in an open circuit test that the field current is increased gradually in steps and the armature current is measured at each step. The field current is increased to get armature currents up to 150% of the rated value.
- The value of field current If and the average of three ammeter readings at each step is taken. A graph is plotted between the armature current I_a and the field current I_f. The characteristic so obtained is called Short Circuit Characteristic (S.C.C).



<u>Determination of Z_s from the graph</u>

- The value of Z_s to be determined for the "SAME VALUE OF FIELD EXCITATION". Follow the simple procedure to draw the graph and obtain the voltage regulation.



1. Plot the OCC and SCC curve in a graph.
2. For the rated full load current (I_{sc}) of alternator [which is to be found from the rating of alternator], draw a line that cuts the SCC curve, from that draw a vertical line towards the x-axis and find the field current (I_f).
3. For that field current, extend the line so that it cuts the OCC curve and find the open circuit voltage V_{oc} volts (phase value).
4. Now, we know the open circuit voltage V_{oc} volts and short circuit current I_{sc}. From this, determine the value of Z_S using the formula, $Z_S = \frac{Voc}{Isc}$
5. From the known resistance value and determined Z_S found the value of X_s using the formula,
   $X_s = \sqrt{Zs^2 - Ra^2}$
6. Now, using the following formulas, obtain the value for E_{ph}, [obtained from phasor diagram]
   For Lagging Power factor,

$E_{ph} = \sqrt{(Vph\ cos\Phi + IaRa)^2 + (Vphsin\Phi + IaXa)^2}$

For Leading Power factor,

$E_{ph} = \sqrt{(Vph\ cos\Phi + IaRa)^2 + (Vphsin\Phi - IaXa)^2}$

For unity power factor,

$E_{ph} = \sqrt{(Vph\ + IaRa)^2 + (IaXa)^2}$

7. Finally, the voltage regulation of alternator can be determined from the formula,

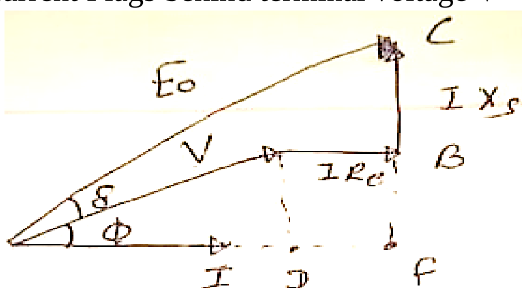
$\%\ Regulation = \frac{Eph - Vph}{Vph} * 100$

Condition for voltage regulation

Q. Derive the formula for voltage regulation of transformer at lagging pf.

Solution, drawing the phasor diagram

let, load current I lags behind terminal voltage V



So,

$OC^2 = OF^2 + FC^2$

$E_0^2 = (OD+DF)^2 + (FB+BC)^2$

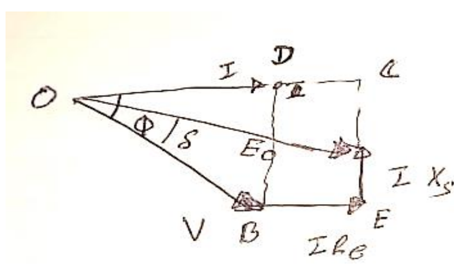
$E_0^2 = (V\cos\Phi + IR_e)^2 + (V\sin\Phi + IX_s)^2$

$E_0 = \sqrt{(V\ cos\Phi + IRe)^2 + (Vsin\Phi + IXs)^2}$

Exercise:

Q.1) **Derive the relation for voltage regulation of alternator for leading power factor.**

Hints:



$E_{ph} = \sqrt{(Vph\ cos\Phi + IaRa)^2 + (Vphsin\Phi - IaXa)^2}$

Q.2) Derive the relation for voltage regulation of alternator for unity power factor.

Numerical:

Q.1) The data obtained on 100 kVA, 1100 V, 3-phase alternator is :

DC resistance test: E between line = 6 V dc, I in lines = 10 A dc.

Open circuit test: field current = 12.5 A dc, line voltage = 420 V ac.

Short circuit test: field current = 12.5 A, line current = rated value, Calculate the voltage regulation of alternator at 0.8 pf lagging.

Soln:

Assume alternator to be star-connected, as usually

$$\text{Phase voltage, } V_p = \frac{1100}{\sqrt{3}} = 635.1 \text{ A}$$

$$\text{Full load phase current, } I_p = I_L = \frac{100 \times 1000}{\sqrt{3} \times 1100} = 52.5 \text{ V}$$

$$\text{Armature dc resistance per phase, } R_{dc} = \frac{E_{dc}}{2 \times I_{dc}} = \frac{6}{2 \times 10} = 0.3\Omega$$

($\because$ dc voltage is connected across two phases)

$$\text{Armature effective ac resistance per phase, } R_a = 1.667 \times 0.3 = 0.5\ \Omega$$

(assuming 66.7% of dc resistance for skin effect)

Synchronous impedance per phase,

$$Z_s = \frac{OC \text{ voltage per phase}}{SC\text{current per phase}} \text{ for same excitation}$$

$$= \frac{\frac{420}{\sqrt{3}}}{52.5} = 4.62\ \Omega$$

$$\text{Synchronous reactance per phase, } X_s = \sqrt{(4.62)^2 - (0.5)^2} = 4.59\Omega$$

At 0.8 lagging power factor, $\cos\phi = 0.8$ and $\sin\phi = 0.6$

Open circuit voltage per phase,

$$E_{op} = \sqrt{(V_p \cos\phi + I_p R_A)^2 + (V_p \sin\phi + I_p X_s)^2}$$

$$= \sqrt{(635.1 \times 0.8 + 52.5 \times 0.5)^2 + (635.1 \times 0.6 + 52.5 \times 4.59)^2}$$

$$= 820 \text{ V}$$

$$\text{Percentage regulation} = \frac{820 - 635.1}{635.1} \times 100$$

$$= 29.11\%$$

$= -13.54\ \%$

Ex.2. A 3-phase star connected alternator is rated at 1600 kVA, 13500 volts. The armature resistance and synchronous reactance are 1.5 Ω and 30 Ω per phase respectively. Calculate the percentage voltage regulation for a load of 1280 kW at a pf of 0.8 leading.

Soln: Full load current = $1600 \times 10^3 / (\sqrt{3} \times 13500 \times 0.8) = 68.4$ amps;

Voltage per phase $V_{ph} = 13500/\sqrt{3} = 7795$volts

0.8 pf leading: $E_{ph} = \sqrt{[(V \cos\Phi + IR_a)^2 + (V \sin\Phi - IX_S)^2]}$

$= \sqrt{[(7795 \times 0.8 + 68.4 \times 1.5)^2 + (7795 \times 0.6 - 68.4 \times 30)^2}$

$= 6861$ volts

Voltage regulation $= [(E_{ph} - V_{ph} / V_{ph})] \times 100$

$= [(6861 - 7795) / 7795] \times 100$

$= -12\ \%$

3) A 1200 kVA, 3300 volts, 50 Hz, three phase star connected alternator has an armature resistance of 0.25 Ω per phase. A field current of 40 Amps produces a short circuit current of 200 Amps and an open circuit emf of 1100 volts line to line. Find the % regulation at full load 0.8 pf lagging and leading by using emf method.

Soln:

Full load current = 1200 x 103 / (√3 x 3300) = 210 amps;

Voltage per phase Vph = 3300/√3 = 1905 volts

Synchronous impedance Zs =(OC voltage per phase/ SC current per phase) …….. for same excitation

= (1100/√3) / 200 = 3.17 Ω

Synchronous reactance = Xs = $\sqrt{(Zs)^2 - (Ra)^2}$ = $\sqrt{(3.17)^\wedge 2 + (0.25)^2}$ = 3.16 Ω

For 0.8 pf lagging: referring to the phasor diagram

$E_{ph} = \sqrt{(Vph\,cos\Phi + IaRa)^2 + (Vphsin\Phi + IaXa)^2}$

$E_{ph} = \sqrt{(1905 \text{ x } 0.8 + 210 \text{ x } 0.25)^2 + (1905 \text{ x } 0.6 + 210 \text{ x } 3.16)^2}$ = 2398 volts

Voltage regulation = [(Eph – Vph)/ Vph] x 100 = [(2398 – 1905) / 1905] x 100 = 25.9 %

For 0.8 pf leading:

Eph = $\sqrt{(Vph\,cos\Phi + IaRa)^2 + (Vphsin\Phi - IaXa)^2}$

= $\sqrt{[(1905 \text{ x } 0.8 + 210 \text{ x } 0.25)^2 + (1905 \text{ x } 0.6 - 210 \text{ x } 3.16)^2}$ = 1647 volts

Voltage regulation = [(Eph – Vph / Vph)] x 100 = [(1647 – 1905) / 1905] x 100 = - 13.54 %

Advantages and Disadvantages of synchronous impedance method

Advantages:

• Simple no load tests (for obtaining OCC and SCC) are to be conducted

• Calculation procedure is much simpler

Disadvantages:

• The value of voltage regulation obtained by this method is always higher than the actual value.

Numerical on synchronous machine (synchronous impedance method)

1) A three-phase star connected alternator is rated at 1600KVA, 13.5 kV. The Ra and Xs are 1.5 ohm and 30 ohms respectively. Calculate the value of emf generated and voltage regulation for a load of 1.28MW at i) 0.8 pf lagging ii) unity pf iii) 0.8 pf leading

2) A 2000 KVA, 11 KV, 50HZ three phase star connected alternator has effective armature resistance of 0.3 ohm and reactance of 5 ohm. It delivers full load current at 0.8 lagging pf at rated voltage. Compute the terminal for the same excitation and load current at 0.8 power factor lagging.

3) A 150 KVA, 3300kV, 50 HZ 3 phase star connected synchronous generator has effective armature resistance of 0.2 ohm. The field current of 40A produce short circuit current of 200A and an open circuited emf of 1040 V (line value). Calculate the full load voltage regulation at 0.8 pf lagging by synchronous impedance method. Also draw the phasor diagram. Ans:

4) A 3-phase alternator is rated at 15 MVA 11 kV with Ra = 1.2ohm and Xs = 25 ohm. Calculate the % voltage regulation and load angle for the load of 1.4375 MVA at 0.8 PF lagging. Also, find out the power factor at which voltage regulation becomes zero.

5) From the following test results, determine the voltage regulation of a 2000V, single phase alternator delivering a current of 100A at i) unity pf ii) 0.8 leading pf iii) 0.71 lagging pf

Test result: full load current of 100A is produced or short circuited by a field excitation of 2.5A. an emf of 500V is produced on open circuit by the same excitation. The armature resistance is 0.8 ohms.

6) A 10 MVA 6.6 kV, 3 phase star connected alternator gave open circuit and short circuit data as follows.

Field current in amps: 25 50 75 100 125 150

OC voltage in kV (L-L):	2.4		4.8	6.1	7.1	7.6	7.9
SC Current in Amps:	288	528	875	-	-	-

Find the voltage regulation at full load 0.8 pf lagging by emf method. Armature resistance per phase =0.13 Ω.

2. *Voltage Regulation of Synchronous Generator by MMF method*

The ampere-turn /MMF method is the converse of the EMF method in the sense that instead of having the phasor addition of various voltage drops/EMFs, here the phasor addition of MMF required for the voltage drops are carried out. Further the effect of saturation is also taken care of.

Data required for MMF method are:

- Effective resistance per phase of the 3-phase winding R
- Open circuit characteristic (OCC) at rated speed/frequency
- Short circuit characteristic (SCC) at rated speed/frequency

Compared to the EMF method, MMF method, involves more number of complex calculation steps. Further the OCC is referred twice and SCC is referred once while predetermining the voltage regulation for each load condition. Reference of OCC takes care of saturation effect. As this method requires more effort, the final result is very close to the actual value. Hence this method is called optimistic method.

Numerical Problems

1. A 3.5 MVA, 50 Hz, star connected alternator rated at 4160 volts gave the following results on oc test

Field current: amps	50	100	150	200	250	300	350	400
OC voltage (L-L):	1620	3150	4160	4750	5130	5370	5550	5650

A filed current of 200 amps was found necessary to circulate full load current on short circuit of the alternator. Calculate voltage regulation by mmf method at 0.8 pf lagging. Neglect stator resistance.

Soln: Draw oc and sc characteristics as shown in figure below

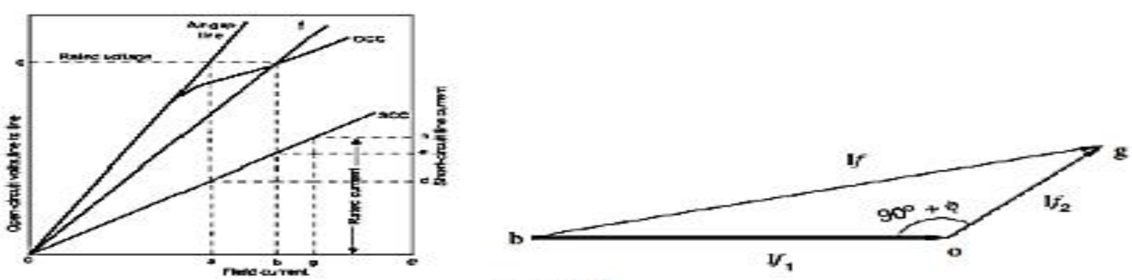


Figure 38

Full load current = $3.5 \times 10^6 / (\sqrt{3} \times 4160)$ = 486 amps.

From occ the field current required to produce rated voltage of 4160 volts is 150 amps. From the characteristics it is ob (I_{f1}). The field current required to circulate full load current on short circuit is og (I_{f2}), from the characteristics and is equal to 200 amps. This filed current is drawn at an angle of 90+Φ w r t ob. The two field currents can be vectorially added as shown in the vector diagram above.

From the above phasor diagram the total field current bg can be computed using cosine rule as

$$bg = \sqrt{(I_{f1})^2 + (I_{f2})^2 + (I_{f1}) \times (I_{f2}) \times \cos(180 - (90+\Phi))}$$

$$= \sqrt{(150)^2 + (200)^2 + (150) \times (200) \times \cos(180 - (90+36.86))}$$

= 313.8 volts.

Corresponding to this filed current of 313.8 amps the induced emf E_0 form the occ is 3140 volts.

Hence % regulation = (3140 – 2401)/ 2401 x 100 = 30.77%

Ex 6. A 10 MVA, 50 Hz, 6.6 kV, 3-phase star connected alternator has the following oc and sc test data

Field current: amps	25	50	75	100	125	150	175	200	225
OC voltage (L-L) :	2400	4800	6100	7100	7600	7900	8300	8500	8700
SC Current amps :	288	582	875						

Calculate the voltage regulation of the alternator by emf and mmf method at a pf of 0.8 lagging. The armature resistance is 0.13 Ω per phase.

Soln: Draw oc and sc characteristics as shown in figure below(already solved by emf method)

Full Load current $I_a = 10 \times 10^6 / (\sqrt{3} \times 6.6 \times 10^3) = 875$ amps

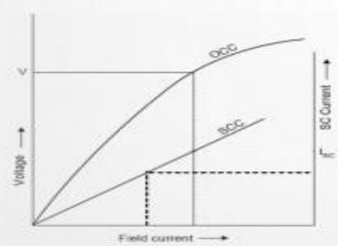
Phase voltage = $6600/\sqrt{3} = 3.81$ kV

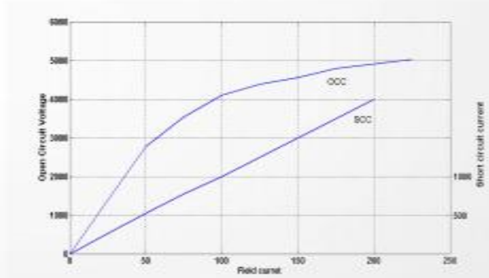
MMF Method: Normal voltage including resistive drop = $V + I_aR_a\cos\phi$

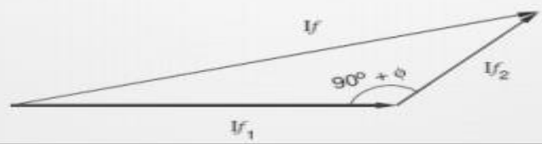
$= 3810 + 875 \times 0.13 \times 0.8$

$= 3901$ volts

From OCC the field current required to produce this normal voltage is 98 amps and is represented as I_{f1} as shown in the phasor diagram. The field current required to produce the rated current of 875 amps on short circuit is 75 amps and is drawn at an angle of 90+ϕ as I_{f2} as shown. The total field current required to obtain the emf E_0 is I_f.







Using cosine rule

$I_f = \sqrt{(I_{f1})^2 + (I_{f2})^2 + (I_{f1}) \times (I_{f2}) \times \cos(180 - (90+\Phi))}$

$= \sqrt{(98 + (75 + (98x (75x \cos (180 - (90+36.86))}$

= 155 amps.

Corresponding to this filed current of 155 amps the induced emf E_0 form the occ is 4619 volts.

Hence % regulation = (4619 – 3810)/ 3810 x 100 = 21.2 %

3. *<u>Voltage Regulation of Synchronous Generator By Zero Power Factor (ZPF) or Potier Triangle Method</u>*

- This ZPF method is based on the separation of armature leakage reactance and armature reaction effects. The armature leakage reactance XL is called Potier reactance in this method, hence ZPF method is also called Potier reactance method.
- To determine armature leakage reactance and armature reaction MMF separately two tests are performed on the alternator. The two tests are
    1. Open circuit test
    2. Zero power factor test

Q. A 11 kV, 1000 kVA, 3 phase star connected alternator has a resistance of 2 Ω per phase. The open circuit and full load ZPF characteristics are given below. Determine the full load voltage regulation at 0.8 pf lagging by Potier triangle method.

Field current (amps):	40	50	80	110	140	180
OC voltage (L-L):	5800	7000	10100	12500	13750	15000
ZPF voltage(L-L):	0	1500	5200	8500	10500	12200

Draw the OCC and ZPF characteristics as shown in figure. Phase voltage = 11000 = 6350 volts. Rated current per phase = 1000 x 103 / (√3 x 11000) = 52.48 A Draw OCC ZPF and the Potier triangle as shown

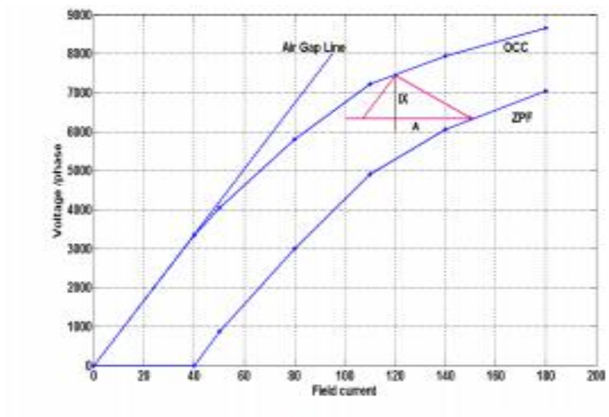
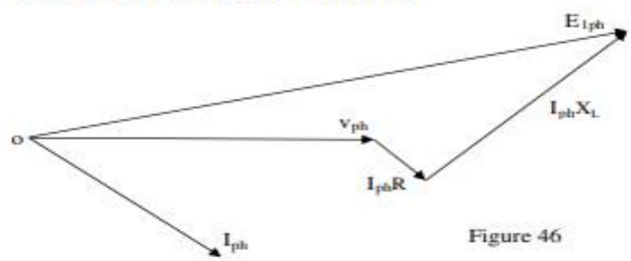


Figure.45

From the Potier triangle IX_L = 1000 volts



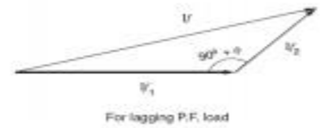


Figure 46

From the phasor diagram taking current as reference

$E_{1ph} = V\angle\varphi + I(R + jX_L)$

$= 6350\angle 36.86 + 105 + j1000$

$= 7072\angle 42.8$ volts.

Corresponding to this voltage of 7072 volts the field current (I_{f1}) required 111 amps

From potier triangle the filed current (I_{f2}) required to balance the armature reaction is 28 amps

Adding both the field currents I_{f1} and I_{f2} vectorially by cosine rule I_f = 130 amps.

Corresponding to this field current oc voltage from occ is 7650 volts

Hence % regulation = (7650 – 6350)/6350 x 100 = 20.5 %

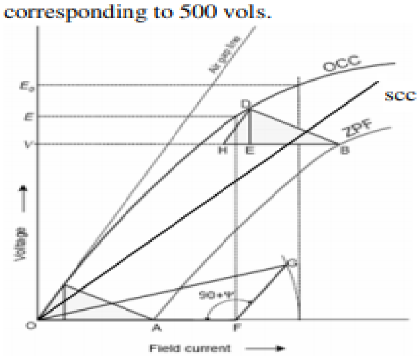
Q.. A 10 kVA, 440 volts, 50 Hz, 3 phase, star connected, alternator has the open circuit characteristics as below.

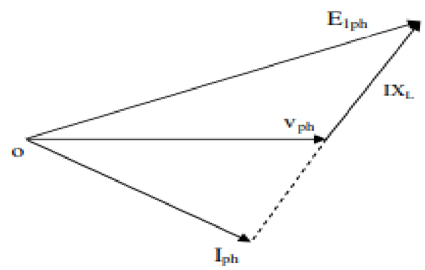
Field current (amps):	1.5	3	5	8	11	15
OC voltage (L-L):	150	300	440	550	600	635

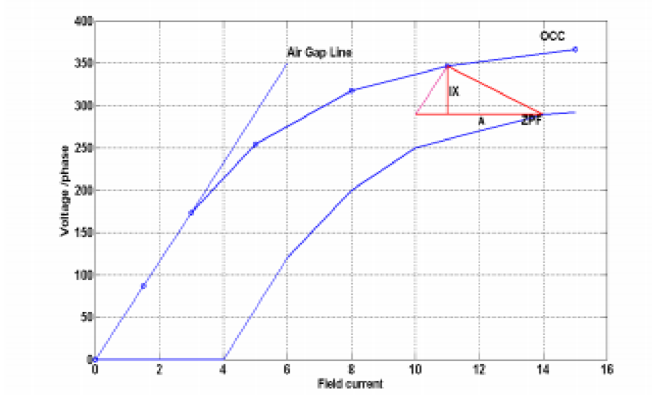
With full load zero power factor, the excitation required is 14 amps to produce 500 volts terminal voltage. On short circuit 4 amps excitation is required to produce full load current. Determine the full load voltage regulation at 0.8 pf lagging and leading.

Soln:

Draw OC, SC and ZPF characteristics to scale as shown. OC characteristics are drawn from the details given above. For sc characteristics 4 amps field current gives full load current. For ZPF characteristics two points are sufficient, one is 4 amps corresponding voltage of 0 volts, and the other is 14 amps corresponding to 500 vols.







From the potier triangle BDE, armature leakage reactance DE is 55 volts.
As armature resistance is negligible V_{ph} and IX_L drop are to be added.

(i) lagging PF

$V_{ph} = 440/\sqrt{3} = 254$ volts. Full load current $10000/(3 \times 254) = 13.123$ amps

Adding V_{ph} and IX_L drop vectorially, as shown in figure above.

$E_{1ph} = \sqrt{(V_{ph} \cos\Phi)^2 + (V_{ph} \sin\Phi + IX_L)^2}$

$= \sqrt{(254 \times 0.8)^2 + (254 \times 0.8 + 55)^2}$

$= 290.4$ volts

Corresponding to this voltage find the field current F1 from occ is 6.1 amps, (I_{f1})

From potier triangle the filed current required to balance the armature reaction is BE is 3.1 amps (I_{f2})

Figure 44

Adding the above two currents vectorially , $I_f = 8.337$ amps.

Corresponding to this field current the emf E_{ph} from OCC is 328 volts

Hence regulation = $(328 - 254)/254 \times 100 = 29.11$ %

(ii) leading PF

For the leading pf

Adding V_{ph} and IX_L drop vectorially,

$E_{1ph} = \sqrt{(V_{ph} \cos\Phi)^2 + (V_{ph} \sin\Phi - IX_L)^2}$

$= \sqrt{(254 \times 0.8)^2 + (254 \times 0.8 - 55)^2}$

$= 225.4$ volts

Corresponding to this voltage find the field current , I_{f1} from occ is 4.1 amps

From potier triangle the filed current (I_{f2}) required to balance the armature reaction BE is 3.1 amps

Adding the above two currents vectorially,(by cosine rule) $I_f = 3.34$ amps.

Corresponding to this field current the emf E_{ph} from OCC is 90 volts

Hence regulation = $(90 - 254)/254 \times 100 = -25.2$ %

PARALLEL OPERATION OF SYNCHRONOUS GENERATORS

Introduction

- In practice, a very large number of 3-phase alternators operate in parallel because the various power stations are interconnected through the national grid. Therefore, the output of any single alternator is small compared with the total interconnected capacity.
- The performance of a single alternator is unlikely to affect appreciably the voltage and frequency of the whole system. An alternator connected to such a system is said to be connected to infinite busbars. The outstanding electrical characteristics of such busbars are that they are constant-voltage, constant frequency busbars.
- If an alternator is connected to infinite busbars, no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same. The operation of connecting an alternator to the infinite busbars is known as paralleling with the infinite busbars.
- The operation of connecting two or more alternators in parallel is known as synchronizing.

Advantages of Parallel Operation of Alternators

The following are the advantages of operating alternators in parallel:

(i) Continuity of service. The continuity of service is one of the important requirements of any electrical apparatus. If one alternator fails, the continuity of supply can be maintained through the other healthy units. This will ensure uninterrupted supply to the consumers.

(ii) Efficiency. The load on the power system varies during the whole day; being minimum during die late night hours. Since alternators operate most efficiently when delivering full-load, units can be added or put off depending upon the load requirement. This permits the efficient operation of the power system.

(iii) Maintenance and repair. It is often desirable to carry out routine maintenance and repair of one or more units. For this purpose, the desired unit/units can be shut down and the continuity of supply is maintained through the other units.

(iv) Load growth. The load demand is increasing due to the increasing use of electrical energy. The load growth can be met by adding more units without disturbing the original installation.

Conditions for Paralleling Alternator with Infinite Busbars

In order to connect an alternator safely to the infinite busbars, the following conditions are met:

(i) The terminal voltage (r.m.s value) of the incoming alternator must be the same as busbars voltage.

(ii) The frequency of the generated voltage of the incoming alternator must be equal to the busbars frequency.

(iii) The phase of the incoming alternator voltage must be identical with the phase of the busbars voltage. In other words, the two voltages must be in phase with each other.

(iv) The phase sequence of the voltage of the incoming alternator should be the same as that of the busbars.

(v) The percentage impedance of both alternators should be same.

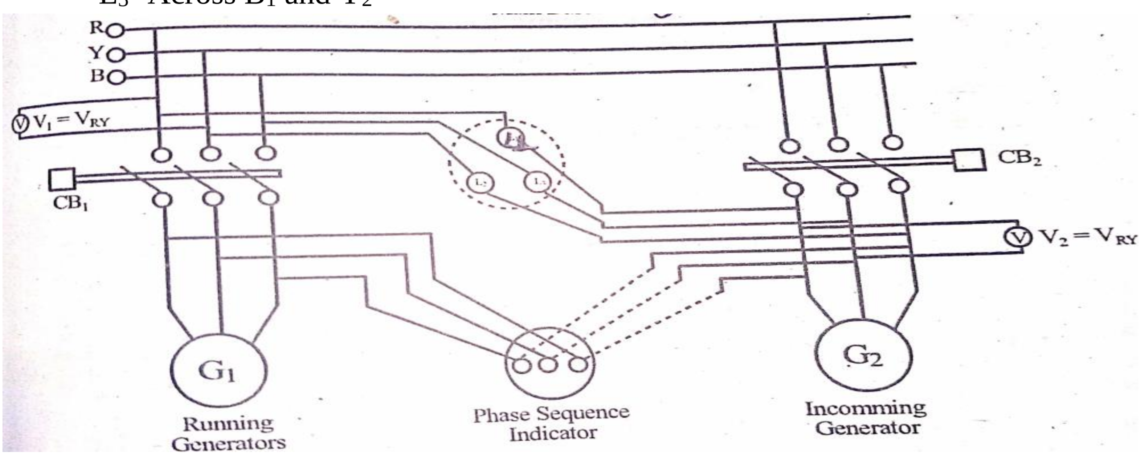
- The magnitude of the voltage of the incoming alternator can be adjusted by changing its field excitation.
- The frequency of the incoming alternator can be changed by adjusting the speed of the prime mover driving the alternator.
- Condition (i) is indicated by a voltmeter, conditions (ii) and (iii) are indicated by synchronizing lamps or a synchroscope. The condition (iv) is indicated by a phase sequence indicator.

Methods of Synchronization

- Method of connecting an incoming alternator safely to live busbars is called synchronizing. The equality of voltage between the incoming alternator and the busbars can be easily checked by a voltmeter. The phase sequence of the alternator and the busbars can be checked by a phase sequence indicator.
- Differences in frequency and phase of the voltages of the incoming alternator and busbars can be checked by one of the following two methods:
  (i) By Two Bright one dark Lamp method
  (ii) Three dark Lamp method
  (iii) By synchroscope

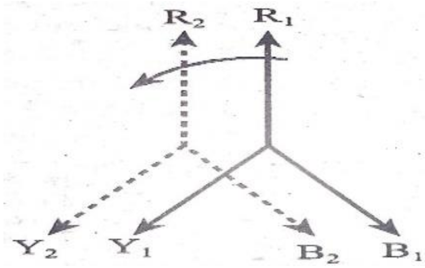
i. <u>By Two Bright one dark Lamp method</u>

- A set of synchronizing lamps can be used to check that the condition for paralleling the incoming machine with the infinite bus are satisfied. Figure below shows schematic setup for this purpose.
- In the figure three lamps are connected as
  L_1- Across R_1 and R_2
  L_2- Across Y_1 and B_2
  L_3- Across B_1 and Y_2



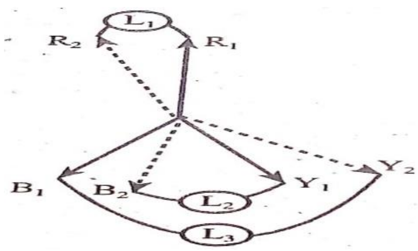
- Before synchronized, its phase sequence must be checked to determine that it has same phase sequence as that if the other alternators. The phase sequence can be checked by a phase sequence indicator. It is a small three phase induction motor that rotates in one direction for one phase sequence and in opposite direction for the other phase sequence. The incoming generator G_2 is rotated by prime mover approximately up to its synchronous speed keeping circuit breaker CB-2 open. If the motor rotates in the same direction with both voltages of G_1 and G_2 when connected separately, then it is clear that the both alternators have same phase sequence.
- The excitation of G_2 is adjusted so that the voltage generated by the incoming generator, as measured by V_2, is to match the main bus bar voltage, as measured by V_1.
- The synchronizing lamps are used to make sure that the voltage generated by G_2 is in phase with bus bar voltage and the frequency of incoming generator is same as that of the bus bar frequency. The frequency is made same by taking approximate position of lamp. The different condition is shown below.

  <u>Case I: if $f_1 = f_2$:</u> If the frequencies of the both voltages are equal, both vectors rotate with the same speed and the difference between R_1 and R_2, Y_1 and B_2, B_1 and Y_2 remains constant. Hence at this condition, L_1 remains dark and L_2 and L_3 will glow with equal brightness, then in such situation the CB-2 of the incoming generator can be closed so that both generators operate in parallel.

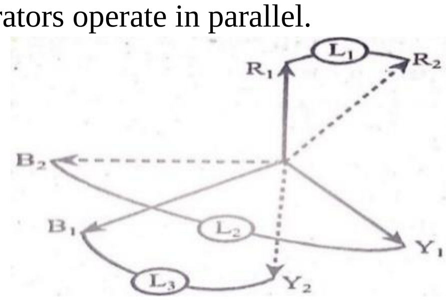


Case II: if $f_2>f_1$: If the frequency of the incoming generator G_2 is greater than that of the running generator G_1, then R_2-Y_2-B_2 vectors rotates faster than the R_1-Y_1-B_1 vectors as shown in Figure.

- In such a situation, voltage across the L_1 goes on increasing, voltage across the L_2 goes on decreasing and voltage across the L_3 goes on increasing. After sometime, the vectors B_2 and Y_1 will get coincide resulting in L_2 dark. Hence the light gets dark one after another in anti-clockwise direction. In such a situation the speed of the incoming generator G_2 has to be reduced until the situation f_1=f_2, then the CB-2 of the incoming generator can be closed so that both generators operate in parallel.



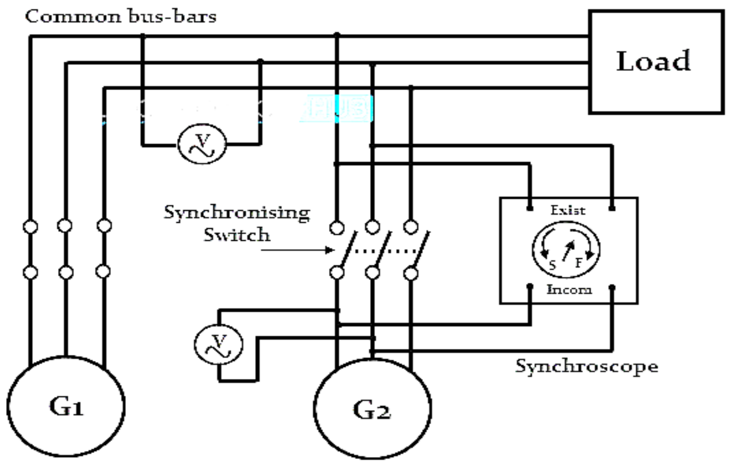
Case III: if $f_2< f_1$: If the frequency of the incoming generator G_2 is less than that of the running generator G_1, then R_2-Y_2-B_2 vectors rotates slower than the R_1-Y_1-B_1 vectors as shown in Figure. In such a situation, voltage across the L_1 goes on increasing, voltage across the L_3 goes on decreasing and voltage across the L_2 goes on increasing. After sometime, the vectors B_1 and Y_2 will get coincide resulting in L_3 dark. Hence the light gets dark one after another in anti-clockwise direction. In such a situation the speed of the incoming generator G_2 has to be increased until the situation f_1=f_2, then the CB-2 of the incoming generator can be closed so that both generators operate in parallel.



ii. Synchroscope Method

- it is similar to the two bright and one dark lamp method and indicates whether the alternator frequency is higher or lower than the bus bar frequency. A synchroscope is used for better accuracy of synchronization and it consists of two pairs of terminals.
- One pair of terminals marked as ‘existing’ has to be connected across the bus bar terminals or to the existing alternator and other pair of terminals marked as ‘incoming’ has to be connected across the terminals of incoming alternator.

- The synchroscope has circular dial over which a pointer is hinged that is capable of rotating in clockwise and anticlockwise directions.
- After the voltage condition is checked, operator has to check the synchroscope. The rate at which the pointer rotates indicates the difference of frequency between the incoming alternator and the bus bar.
- Also, direction to which the pointer rotates (to either fast or slow) gives the information, whether the incoming alternator frequency is higher or lower than the bus bar frequency and hence the pointer moves either fast or slow.
- When the frequencies are equal, the pointer is stationary. When the frequencies differ, the pointer rotates in one direction or the other. The direction of motion of the pointer shows whether the incoming machine is running too fast or too slow. This means that whether the frequency of the incoming machine is higher or lower in comparison to the infinite bus. The speed of rotation of the pointer is equal to the difference between the frequency of the incoming machine and the frequency of the infinite bus. The frequency and phase positions are controlled by adjusting the prime mover input of the incoming machine.

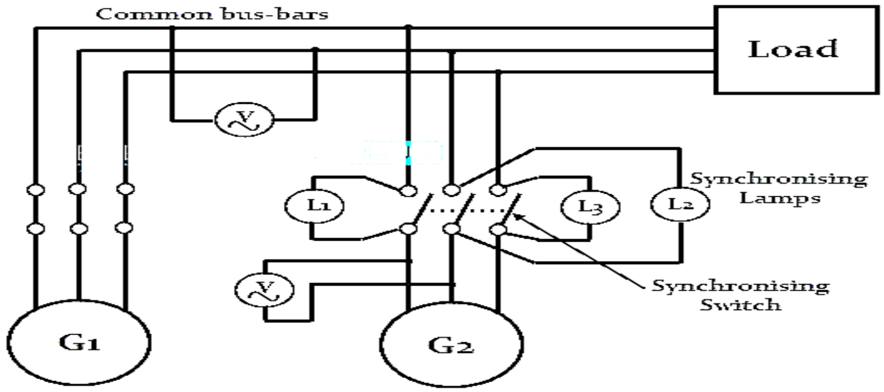


- The Synchroscope checks the relationships only on one phase and does not give any information about phase sequence.
- This process must be done carefully to prevent the disturbances in the power system as well as to avoid a serious damage to the machine.
- These processes need a skilled and experienced person to handle the equipment while synchronizing. Modern synchronization equipment's automate the whole synchronization process with the use of microprocessor-based systems that avoids manual lamps and synchroscope observations. These methods are easier to manage and more reliable.

iii. <u>Three Dark Lamps Method / synchronizing lamp</u>

- A set of three synchronizing lamps can be used to check the conditions for paralleling or synchronization of the incoming machine with the other machine.
- The prime mover of the incoming machine is started and brought nearer to its rated speed. A field current of the incoming machine is adjusted in such a way so that it becomes equal to the bus voltage. The flicker of the three lamps occurs at a rate which is equal to the difference in the frequencies of the incoming machine and the bus. All the lamps will glow and off at the same time if the phases are properly connected. If this condition does not satisfy, then the phase sequence is not connected correctly.

- Thus, in order to connect the machine in the correct phase sequence, two leads to the line of the incoming machine should be interchanged. The frequency of the incoming machine is adjusted until the lamp flicker at a slow rate. The flicker rate should be less than one dark period per second. After finally adjusting the incoming voltage, the synchronizing switch is closed in the middle of their dark period.
- The main disadvantage of this method is that rate of flickering only indicates the difference between the alternator-2 and the bus bar. But the information of alternator frequency in relation to bus bar frequency is not available in this method.



Synchronous Motor

Introduction

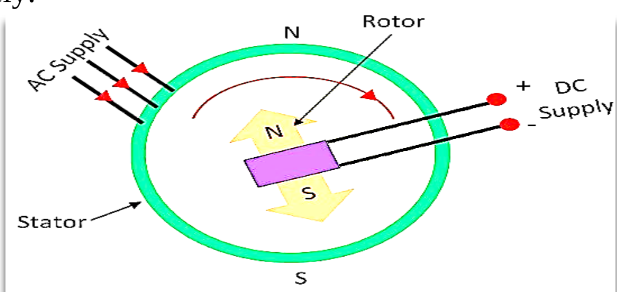
- The motor which runs at synchronous speed is known as the synchronous motor. The synchronous speed is the constant speed at which motor generates the electromotive force.

  $Ns = \frac{120\,f}{P}$ Where:

  N=Synchronous Speed (*in RPM)*   f =Supply Frequency (*in Hz*) P =Number of Poles
- Construction of a synchronous motor is similar to an alternator (AC generator). A same synchronous machine can be used as a synchronous motor or as an alternator. The stator and rotor are the two main parts of the synchronous motor. The stator is the stationary part, and the rotor is the rotating part of the machine. The three-phase AC supply is given to the stator of the motor. The stator and rotor both are excited separately. The excitation is the process of inducing the magnetic field on the parts of the motor with the help of an electric current.
- The speed of the synchronous motor is independent of the load, i.e., the variation of the load does not affect the speed of the motor.
- The synchronous motor is not self-starting. The prime mover is used for rotating the motor at their synchronous speed. Some auxiliary methods are used for starting.
- The synchronous motor operates both for leading and lagging power factor.

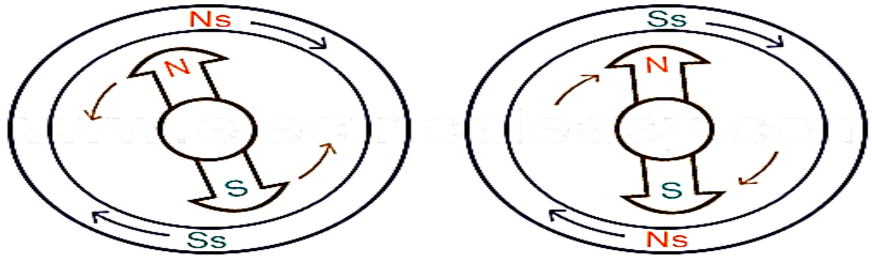
Principle of Operation Synchronous Motor

- Synchronous motors are a doubly excited machine, i.e., two electrical inputs are provided to it. Its stator winding is provided three-phase supply to three-phase stator winding, and DC to the rotor winding.
- When the three-phase supply is given to the stator, the rotating magnetic field developed between the stator and rotor gap. The field having moving polarities is known as the rotating magnetic field. The rotating magnetic field develops only in the polyphase system. Because of the rotating magnetic field, the north and south poles develop on the stator.
- The rotor is excited by the DC supply. The DC supply induces the north and south poles on the rotor. As the DC supply remains constant, the flux induces on the rotor remains same. Thus, the flux has fixed polarity. The north pole develops on one end of the rotor, and the south pole develops on another end.
- The AC is sinusoidal. The polarity of the wave changes in every half cycle, i.e., the wave remains positive in the first half cycle and becomes negative in the second half cycle. The positive and negative half cycle of the wave develops the north and south pole on the stator respectively.

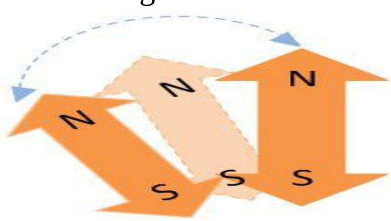


Synchronous Motor

- Consider a two-pole synchronous machine as shown in figure below.



- Now, the stator poles are revolving with synchronous speed (let's say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then poles of stator & rotor will repel each other, and torque produced will be anticlockwise.
- The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor cannot rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and *the torque produced will be clockwise.*
- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start. Thus, the rotor becomes pulsated only at one place. This is the reason because of which the synchronous motor is not self-starting.



Pulsating of Rotor

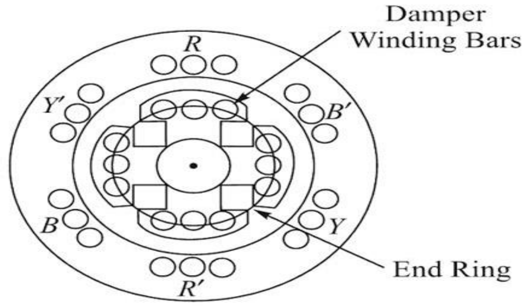
- But, if the rotor is rotated up to the synchronous speed of the stator by means of an external force (in direction of revolving field of the stator), and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. On achieving synchronous speed, magnetic locking occurs (opposite poles of the stator and rotor will get locked with each other), and the synchronous motor continues to rotate even after removal of external mechanical means. Now, the rotor will rotate at the synchronous speed.

Methods of Starting of Synchronous Motor

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 methods in practice. The various methods to start the synchronous motor are,

a) Using damper winding: It is an additional winding in the synchronous machine which is provided in the pole face slots in addition to the normal field winding. Bars of aluminum, copper, bronze, or similar alloys are inserted in slots of pole shoes as shown in Fig. These bars are short-circuited by end-rings on each side of the poles. Thus, these short-circuited bars form a squirrel-cage winding.

When a three-phase supply is given to the stator, the synchronous motor with damper winding will start as a three-phase induction motor with the speed of rotation near to synchronous speed. Then DC 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 cannot be any induced EMF 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.

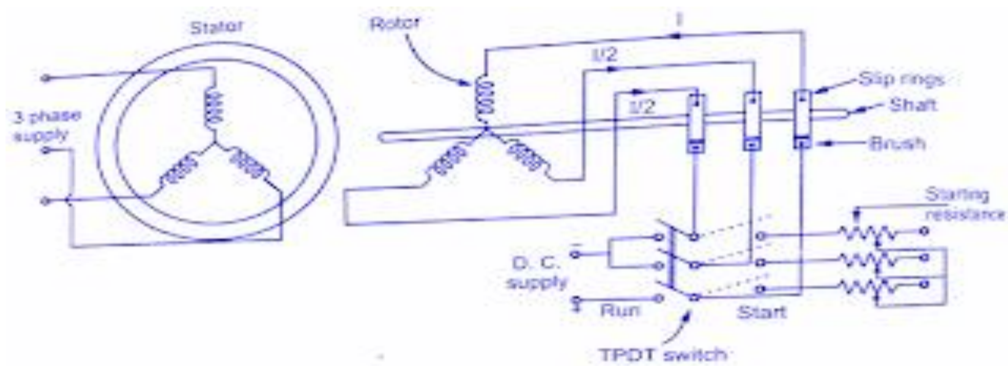


Damper winding made on pole faces of a synchronous machine

b) **Using a D.C Motor Coupled to the Synchronous Motor:** A DC machine is coupled to the synchronous motor. The DC machine works like a DC motor initially and brings the synchronous motor to synchronous speed. Once it achieves the synchronous speed, the DC machine works like a DC generator and supplies DC to the rotor of the synchronous motor. This method offers easy starting and better efficiency than the earlier method.

c) **As a Slip Ring Induction Motor:** Here, an external rheostat is connected to the rotor through slip-rings. Here, ends of the damper winding are brought of the motor and connected either in star or delta. The rheostat is connected in series with the rotor. At starting high resistance is connected with the rotor to limited the current drawn by the motor. As the motor starts as a slip ring induction motor at starting, it draws large currents.

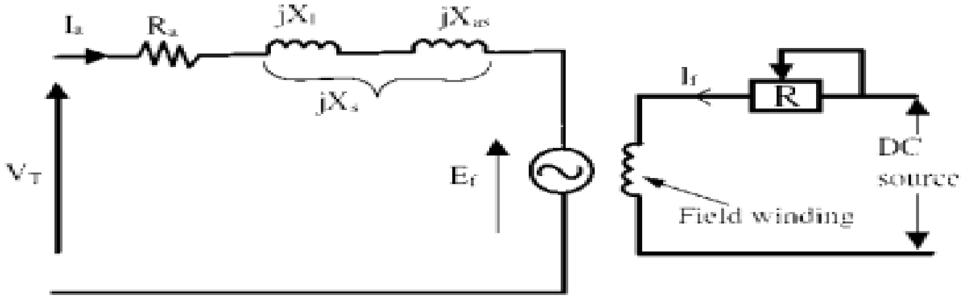
When the motor picks up its speed, resistance is gradually cut off from the rotor circuit. As the speed reaches near to synchronous speed, d.c. excitation is given to the rotor and it is pulled into synchronism.



d) **Pony motor start**: Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or DC shunt motor. DC excitation is not fed initially. It is rotated at speed very close to its synchronous speed and after that DC excitation is given. After some time when magnetic locking takes place supply to the external motor is cut off

e) with the Help of a Separate Small Induction Motor of at least one pair less than synchronous motor: in this method, a separate induction motor is used to bring the speed of the synchronous motor to synchronous speed. The number of poles of the synchronous motor needs to be more than that of poles of the induction motor to enable the induction motor to rotate at the synchronous speed of the synchronous motor. As the set attains synchronous speed, dc excitation is applied and as the rotor and stator of the synchronous motor are pulled in synchronism, the induction motor is switched off.

Equivalent circuit model and phasor diagram of synchronous motor



Equivalent-circuit model for one phase of a synchronous motor armature

$V_T = I_a R_a + jI_a X_l + jI_a X_{as} + E_f$

Combining reactance's, $X_s = X_l + X_{as}$

$V_T = E_f + I_a (R_a + jX_s)$

or $V_T = E_f + I_a\ Z_s$

where: R_a = armature resistance (/phase) X_l = armature leakage reactance (/phase) X_s = synchronous reactance (/phase) Z_s = synchronous impedance (/phase)

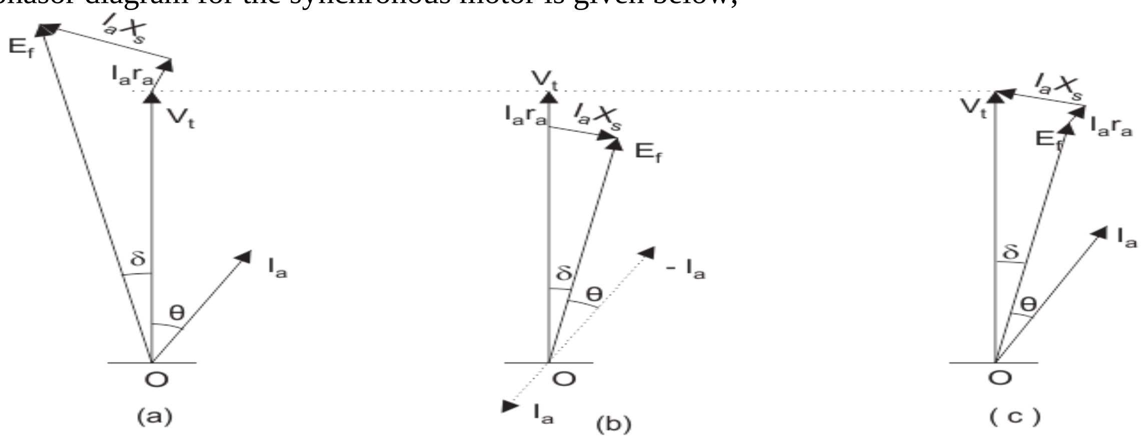
V_T = applied voltage/phase (V) I_a = armature current/phase(A)

Let, V_t as the reference phasor. In order to draw the phasor diagram, one should know these two important points

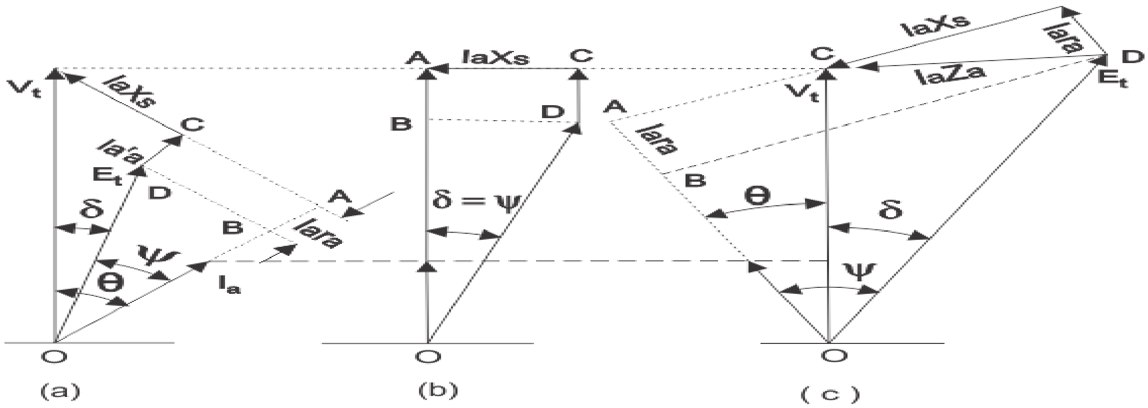
(1) We know that if a machine is made to work as a asynchronous motor then direction of armature current will in phase opposition to that of the excitation emf.

(2) Phasor excitation emf is always behind the phasor terminal voltage.

- Above two points are sufficient for drawing the phasor diagram for synchronous motor. The phasor diagram for the synchronous motor is given below,



- In the phasor one the direction of the armature current is opposite in phase to that of the excitation emf
- It is usually customary to omit the negative sign of the armature current in the phasor of the synchronous motor so in the phasor two we have omitted the negative sign of the armature current. Now we will draw complete phasor diagram for the synchronous motor.



(a) Motoring operation at lagging power factor.
(b) Motoring operation at unity power factor.
(c) Motoring operation at leading power factor.

No-load and loaded operation

- Synchronous motor is not self- starting. It had to be speeded up to synchronous speed by some auxiliary means, the supply to the DC winding of the rotor had to be switched on, then the rotor poles will get magnetically locked up with stator poles.
- However, the engagement between stator and rotor poles is not absolutely rigid one. As the load on the motor increases, the rotor progressively tends to fall but the motor still continues to run with the synchronous speed.
- At no load, if there is no power loss in the motor, the stator poles and rotor poles will be along the same axis and phase difference between the applied voltage 'V' and the back emf 'Eb', developed in the armature winding will be exactly 180° (see fig a).
- But this is not possible in practice, because some power loss takes place due to iron loss and friction loss. Hence, the rotor pole lags by some angle '' with the stator pole and the phasor diagram will be as shown in figure b.
- The current drawn by armature at no load is given by,

$Ia = \frac{V-Eb}{Zs} = \frac{ER}{Zs}$ Where, E_R = Net voltage across the armature Z_S = Synchronous impedance per phase

- In case of DC motor, the speed of the armature decreases with increase in load, due to which the back emf will decrease and then the armature current will increase to overcome the increased load. But in case of synchronous motor, the speed does not change with load.
- When the load on a synchronous motor increases, the rotor poles lags the stator poles by larger angle ' and the phase angle between V and Eb will increase (note that magnitude of Eb will remain constant) so that the net voltage ER will increase and the armature current will increase.

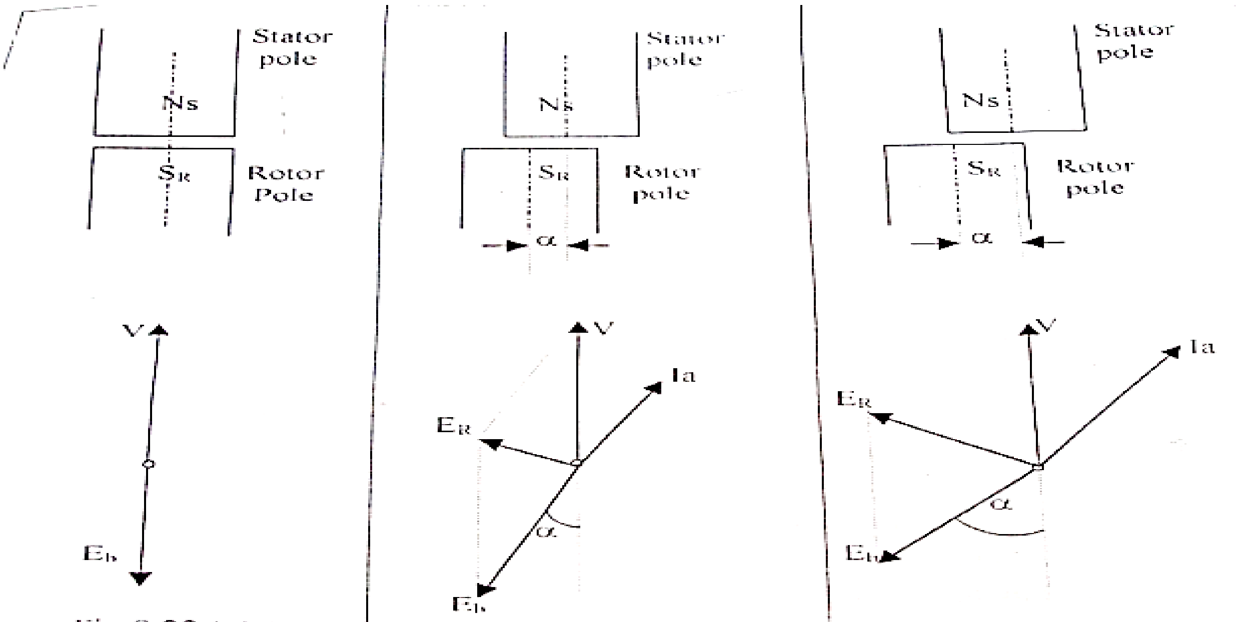
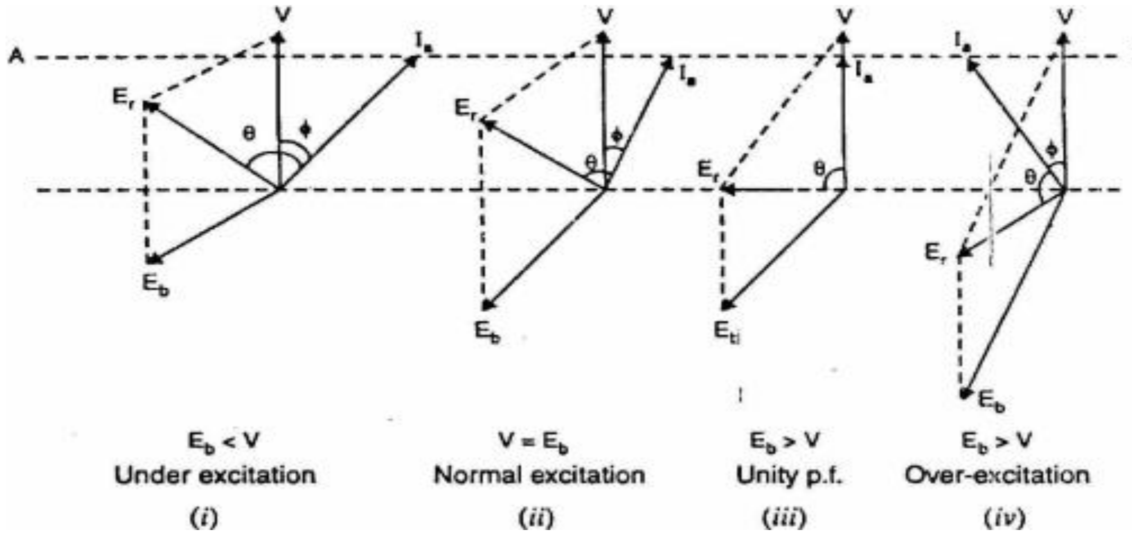


Fig.9.22 (a) (No-load , No-loss) Fig.9.22(b) No-load Fig.9.22(c) With -load

Effect of Excitation

- The DC current supplied to the rotor field winding is known as excitation in synchronous motor. As the speed of the synchronous motor is constant, the magnitude of back emf remains constant provided the flux per pole produced by the rotor does not change. So, the magnitude of back emf can be changed by field excitation.
- One of the most important features of a synchronous motor is that by changing the field excitation, it can be made to operate from lagging to leading power factor. If the excitation is changed at a constant load, the magnitude of armature current and power factor will change.
- Consider a synchronous motor having a fixed supply voltage and driving a constant mechanical load. Since the mechanical load as well as the speed is constant, the power input to the motor (=3 VIa cos φ) is also constant. This means that the in-phase component Ia cos φ drawn from the supply will remain constant. If the field excitation is changed, back e.m.f. Eb also changes. This results in the change of phase position of Ia w.r.t. V and hence the power factor cos φ of the motor changes.
- Fig. below shows the phasor diagram of the synchronous motor for different values of field excitation.



- The value of excitation for which the magnitude of back emf, Eb is equal to the applied voltage, V is known as 100% excitation.
- If the excitation is more than 100%, then the motor is said to be over excited and if the excitation is less than 100%, then the motor is said to be under excited.

  (i) **Under excitation**: The motor is said to be under-excited if the field excitation is such that Eb < V. Under such conditions, the current Ia lags behind V so that motor power factor is lagging as shown in Fig. (i)). This can be easily explained. Since Eb < V, the net voltage Er is decreased and turns clockwise. As angle θ (= 90°) between Er and Ia is constant, therefore, phasor Ia also turns clockwise i.e., current Ia lags behind the supply voltage. Consequently, the motor has a lagging power factor.

  (ii) **Normal excitation**: The motor is said to be normally excited if the field excitation is such that Eb = V. This is shown in Fig. (ii)). Note that the effect of increasing excitation (i.e., increasing Eb) is to turn the phasor Er and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor V. Therefore, p.f. increases though still lagging. Since input power (=3 V Ia cos φ) is unchanged, the stator current Ia must decrease with increase in p.f. Suppose the field excitation is increased until the current Ia is in phase with the applied voltage V, making the p.f. of the synchronous motor unity [See Fig. (iii)]. For a given load, at unity p.f. the resultant Er and, therefore, Ia are minimum.

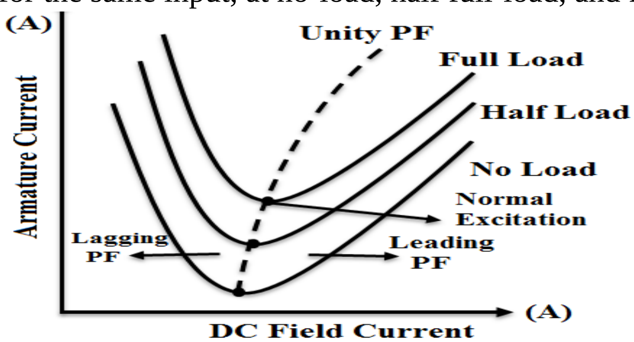
  (iii) **Over excitation:** The motor is said to be overexcited if the field excitation is such that Eb > V. Under-such conditions, current Ia leads V and the motor power factor is leading as shown in Fig. (iv). Note that Er and hence Ia further turn anti-clockwise from the normal excitation position. Consequently, Ia leads V. From the above discussion, it is concluded that if the synchronous motor is under-excited, it has a lagging power factor. As the excitation is increased, the power factor improves till it becomes unity at normal excitation. Under such conditions, the current drawn from the supply is minimum. If the excitation is further increased (i.e., over excitation), the motor power factor becomes leading.
- Note. The armature current (Ia) is minimum at unity p.f and increases as the power factor becomes poor, either leading or lagging.

Effect of excitation on armature current and power factor- V and inverted V curves

V Curves

- *The graphs plotted between armature current (I_a) and field current (I_f) for different constant*

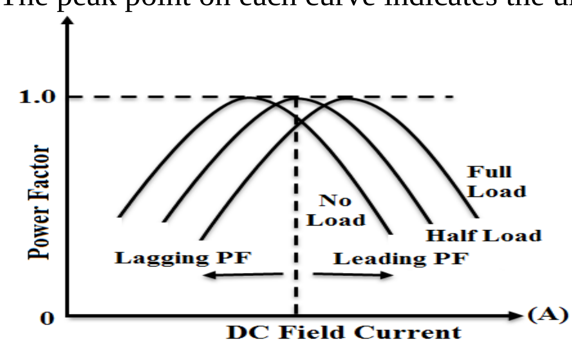
- If the armature current I_a is plotted against excitation (field current) for various load conditions, we obtain a set of curves known as 'V-Curves' clue to their shape similar to English letter V.
- In the below figure V-Curve of a synchronous motor shows how armature current I_a changes with excitation 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).

<u>Inverted V curve</u>

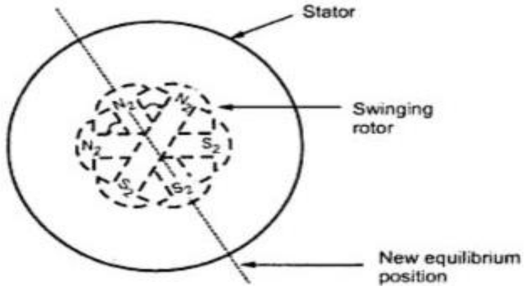
- If the variation of power factor is plotted against the variation in field current for a different constant load, the curves obtained are known as the Inverted V curves of a synchronous motor.
- The over-excited motor runs with a leading power factor and the under-excited motor runs with a lagging power factor. Under the normal excitation, the motor operates at the unity power factor. The peak point on each curve indicates the unity power factor.



Hunting in a Synchronous Motor

The phenomenon of oscillation of the rotor about its final equilibrium position is called **Hunting.** On the sudden application of load, the rotor search for its new equilibrium position and this process is known as **Hunting**.

If the load connected to the motor is suddenly changed by a large amount, then rotor tries to retard to take its new equilibrium position. But due to inertia of the rotor, it cannot achieve its final position instantaneously. While achieving its new position due to inertia it passes beyond its final position corresponding to new load. This will produce more torque than what is demanded. This will try reduce the load angle and rotor swings in other direction. So, there is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load. such oscillations of the rotor about its new equilibrium position, due to sudden application or removal of load is called swinging or hunting in synchronous motor.



Causes of Hunting

The various causes of hunting are as follows: -

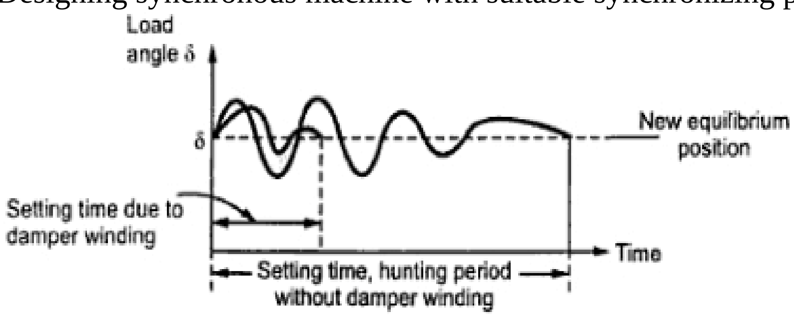
- Sudden changes of load.
- Faults were occurring in the system which the generator supplies.
- Sudden change in the field current.
- Cyclic variations of the load torque.
- Suddenly change in excitation.

Effects of Hunting in Synchronous Motor

- It may lead to loss of synchronism.
- Produces mechanical stresses in the rotor shaft so, Increases machine losses and cause temperature rise.
- Cause greater surges in current and power flow.
- It can cause variations of the supply voltage producing undesirable lamp flicker.
- The possibility of Resonance condition increases. If the frequency of the torque component becomes equal to that of the transient oscillations of the synchronous machine, resonance may take place.

Reduction of Hunting in Synchronous Motor

- Use of Damper Winding: It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. Damper winding damps out hunting by producing torque opposite to slip of rotor. The magnitude of damping torque is proportional to the slip speed.
- Use of Flywheels: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.
- Designing synchronous machine with suitable synchronizing power coefficients.



Applications of Synchronous Motors

(i) 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.

(ii) Overexcited synchronous motors can be used to improve the power factor of a plant while carrying their rated loads. Thus, are also used to improve the voltage regulation of transmission lines.
(iv) High-power electronic converters generating very low frequencies enable us to run synchronous motors at ultra-low speeds. Thus, huge motors in the 10 MW range drive crushers, rotary kilns & variable-speed ball mills.

Power in synchronous machine

Power developed in cylindrical rotor

The armature resistance of a synchronous motor is negligible as compared to its synchronous reactance.

Hence the equivalent circuit for the motor becomes as shown in **Fig. 36.10** (a).

Fig. 36.10 (a)

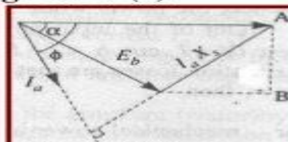


Fig. 36.10 (b)

From the phasor diagram of **Fig. 36.10(b)**, it is seen that $\boxed{AB = E_b \sin\alpha = I_a X_S \cos\phi}$

$\boxed{\text{Or, } VI_a X_S \cos\phi = E_b V \sin\alpha}$

Now, $VI_a\cos\phi$ = motor power input/phase

$$\boxed{\therefore P_{in} = \frac{E_b V}{X_S}\sin\alpha \quad \text{– per phase}} \qquad \boxed{\therefore P_{in} = \frac{3E_b V}{X_S}\sin\alpha \quad \text{– for three phase}}$$

Since Stator Cu losses have been neglected, P_{in} also represents the gross mechanical power (P_m) developed by the motor.

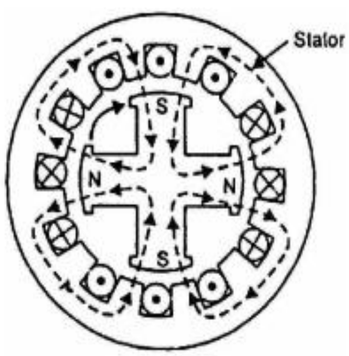
$$\boxed{\therefore P_m = P_{in} = \frac{3E_b V}{X_S}\sin\alpha}$$

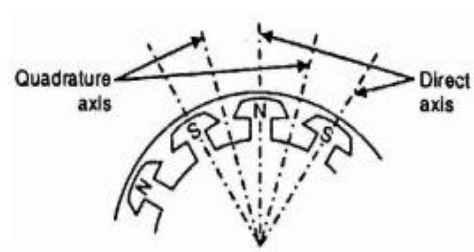
The gross torque developed by the motor is $T_g = 9.55 P_m/N_S$ N-m -N_S in rpm.

$$\boxed{\therefore T_g = 9.55\frac{P_m}{N_S} = \frac{9.55\times 3E_b V}{N_S X_S}\sin\alpha = 28.65\frac{E_b V\sin\alpha}{N_S X_S} \quad \text{N} - \text{m}}$$

Effect of Salient Poles

- The details of synchronous generators developed so far is applicable to only round rotor or non-salient pole alternators. In such machines the air gap is uniform throughout and hence the effect of mmf will be same whether it acts along the pole axis or the inter polar axis. Hence reactance of the stator is same throughout all directions of armature flux relative to the rotor and hence it is called synchronous reactance X_s and the value of X_s is constant.
- However, in a salient-pole machine, the radial length of the air-gap varies so that reluctance of the magnetic circuit along the polar axis (called direct axis or d-axis) is much less than the reluctance along the interpolar axis (called quadrature axis or q-axis). This is illustrated in Fig. b





- Because of the lower reluctance along the polar axis (i.e., d-axis), more flux is produced along d-axis than along the q-axis. Therefore, reactance due to armature reaction will be different along d-axis and q-axis. These are:

  X_{ad} = direct axis reactance due to armature reaction
  X_{aq} = quadrature axis reactance due to armature reaction

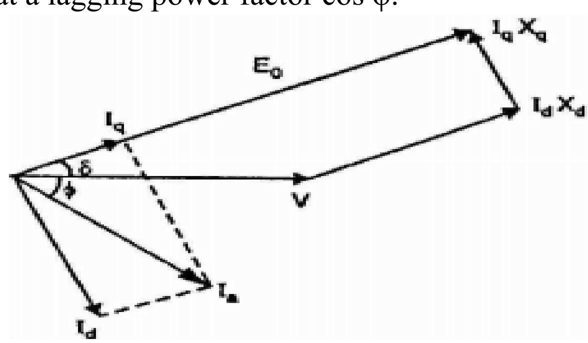
- Such the mmf components of armature-reaction in a salient-pole machine cannot be considered as acting on the same magnetic circuit. Hence the effect of the armature reaction cannot be taken into account by considering only the synchronous reactance, in the case of a salient pole synchronous machine.
- In fact, the direct-axis component Fad acts over a magnetic circuit identical with that of the main field system and produces a comparable effect while the quadrature-axis component F_{aq} acts along the interpolar axis, resulting in an altogether smaller effect and, in addition, a flux distribution totally different from that of F_{ad} or the main field m.m.f.

Two-Reactance Concept for Salient-Pole Machines / Blondel's two-reaction theory

- Blondel's two-reaction theory considers the effects of the quadrature and direct-axis components of the armature reaction separately. Neglecting saturation, their different effects are considered by assigning to each an appropriate value of armature-reaction "reactance," respectively x_{ad} and x_{aq} .
- The effects of armature resistance and true leakage reactance (X_L) may be treated separately, or may be added to the armature reaction coefficients on the assumption that they are the same, for either the direct-axis or quadrature-axis components of the armature current (which is almost true).
- Thus the combined reactance values can be expressed as:

  $X_d = x_{ad} + x_l$ and

  $X_q = x_{aq} + x_l$ for the direct- and cross-reaction axes respectively.
- The effects of salient poles can be taken into account by resolving the armature current into two components; I_d perpendicular to excitation voltage E_0 and I_a along E_0 as shown in phasor diagram in Fig. Note that this diagram is drawn for an unsaturated salient-pole generator operating at a lagging power factor cos φ.



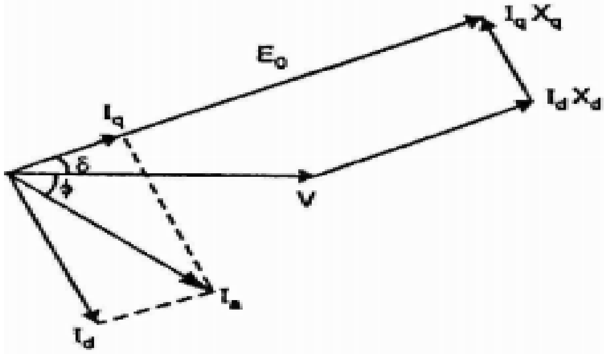
- Note that in drawing the phasor diagram, the armature resistance R_a is neglected since it is quite small. Further, all values arc phase values. Here V is the terminal voltage phase and E_0 is the e.m.f. per phase to which the generator is excited.
- Referring to Fig.

  $I_q = I_a \cos(\delta + \varphi)$ and $I_d = I_a \sin(\delta + \varphi)$

  And, Ia $=\sqrt{Iq^2 + Id^2}$

  The angle δ between E_0 and V is called the power angle.

Power Developed in Salient-Pole Synchronous Generator



Neglecting the armature winding resistance, the power output of the generator is given by:

$P = V * I_a \cos\varphi$ ……………………1)

This can be expressed in terms of δ, by

$I_a \cos\varphi = I_q \cos\delta + I_d \sin\delta$ ………2)

Also, $E_o = V\cos\delta + I_d X_d$

or, $I_d = \frac{Eo - V\cos\delta}{Xd}$ ....3)

And, $V\sin\delta = I_q X_q$

or, $I_q = \frac{V\sin\delta}{Xq}$ …………………………………4)

Substituting value of 3) and 4) in 2)

$I_a \cos\varphi = \frac{V\sin\delta}{Xq} \cos\delta + \frac{Eo - V\cos\delta}{Xd} \sin\delta$ …………5)

- From equation 1) and 5)

$P = V * \left(\frac{V\sin\delta}{Xq} \cos\delta + \frac{Eo - V\cos\delta}{Xd} \sin\delta \right)$

$P = \frac{Eo\, V}{Xd} \sin\delta + V^2 \left[\frac{\sin\delta \cos\delta}{Xq} - \frac{\sin\delta \cos\delta}{Xd} \right]$

$P = \frac{Eo\, V}{Xd} \sin\delta + \frac{V^2}{2} \left[\frac{1}{Xq} - \frac{1}{Xd} \right] \sin 2\delta$ per phase

The above expression for power consists of two terms first is called electromagnetic power and the second is called reluctance power. It is clear from the above expression that the power is a little more than that for a cylindrical rotor synchronous machine, as the first term alone represents the power for a cylindrical rotor synchronous machine. A term in (sin 2δ) is added into the power – angle characteristic of a non-salient pole synchronous machine. This also shows that it is possible to generate an MMF even if the excitation E0 is zero. Likewise, it can be shown that the machine develops a torque - called the reluctance torque - as this torque is developed due to the variation of the reluctance in the magnetic circuit even if the excitation E_0 is zero.

Summary, the following points may be noted:

i) If there is no saliency, $X_d = X_q$

$\therefore P = \frac{EoV}{Xd} \sin\delta$ per phase This is the power developed by cylindrical rotor machine.

(ii) The second term in eq. (ii) above introduces the effect of salient poles. It represents the reluctance power i.e., power due to saliency.

(iii) If $E_0 = 0$, $P = \frac{V^2}{2} \left[\frac{1}{Xq} - \frac{1}{Xd} \right] \sin 2\delta$ per phase

The power obtained with zero excitation is called reluctance power. It should be noted that reluctance power is independent of the excitation.

- It is clear that reluctance power varies with δ at twice the rate of the excitation power. The peak power is seen to be displaced towards δ = 0, the amount of displacement depends upon the excitation. In Fig, the excitation is such that the excitation term has a peak value about 2.5 times that of the reluctance term. Under steady-state conditions, the reluctance term is positive because $X_d > X_q$.

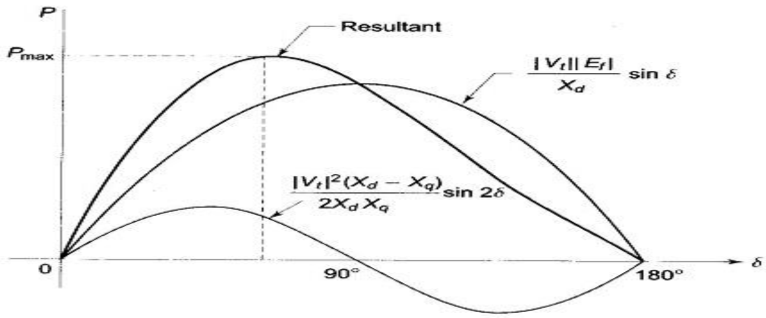
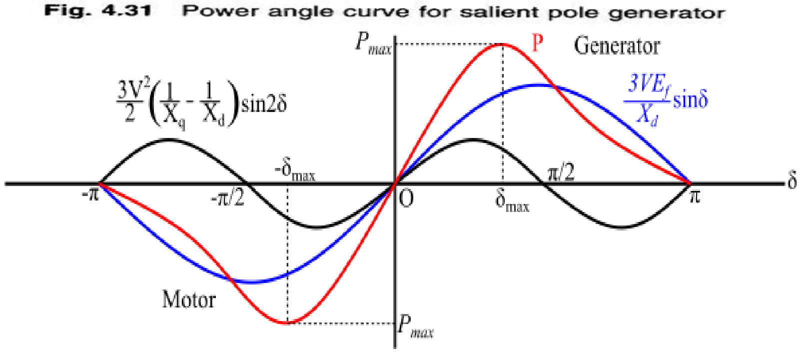


Fig. 4.31 Power angle curve for salient pole generator



Very short question answer

1. **Why are Alternators rated in kVA and not in kW?**

The continuous power rating of any machine is generally defined as the power the machine or apparatus can deliver for a continuous period so that the losses incurred in the machine gives rise to a steady temperature rise not exceeding the limit prescribed by the insulation class. Apart from the constant loss incurred in Alternators is the copper loss, occurring in the 3 –phase winding which depends on I2R, the square of the current delivered by the generator. As the current is directly related to apparent – power delivered by the generator, the Alternators have only their apparent power in VA/kVA/MVA as their power rating.

The KVA rating of ac machine depends on the power factor of the load. The power factor in turn depends on the operating conditions. The operating conditions differ from place to place. Therefore, the KVA rating is specified for all ac machines.

2. **What are the causes of changes in voltage in Alternators when loaded?**

When alternator is loaded the armature carries load current. Due to this load current the voltage drops occur in alternator. Hence terminal voltage decreases due to following voltage drops:

1. Voltage drop due to the resistance of the winding, R
2. Voltage drop due to the leakage reactance of the winding, Xl
3. Voltage drops due to the armature reactance, Xa

3. **Why a synchronous motor is a constant speed motor?**

When load increase in synchronous motor the load angle δ also increases but speed remains constant. The further increase in load cause further increase in load angle. When load angle reaches 90 degrees electrical then the motor comes out of synchronism. Hence the motor rotates at synchronous speed otherwise it comes out of synchronism.

4. **What is pull in torque and pull-out torque?**

The torque which is required to pull the motor into synchronism when it is running as induction motor is called pull in torque.
The maximum torque developed by the motor without pulling out of synchronism is called pull out torque. Its value varies from 1.5 to 3.5 times full load torque.

5. **What is an exciter and how does it work?**

There are two types of exciters, static exciter and rotary exciter. Purpose of excitor is to supply the excitation dc voltage to the fixed poles of generator. Rotary excitor is an additional small generator mounted on the shaft of main generator. if it is dc generator, it will supply dc to the rotary poles through slip ring and brushes (conventional alternator). if it is an ac excitor, output of ac excitor is rectified by rotating diodes and supply dc to main fixed poles.ac excitor is the ac generator whose field winding are stationery and armature rotates. initial voltage is built up by residual magnetism. It gives the starting torque to the generator.

6. **What happens when the field current of asynchronous motor is increased beyond the normal value at constant input?**

Increase in emf causes the motor to have reactive current in the leading direction. The additional leading reactive current causes the magnitude of line current, accompanied by the decrease in power factor.