Module-4

Synchronous Generators (Salient Pole): *Effects of saliency, two-reaction theory, Parallel operation of generators and load sharing. Methods of Synchronization, Synchronizing power.* ***Performance of Synchronous Generators:*** *Power angle characteristic (salient and non-salient pole), power angle diagram, reluctance power, and Capability curve for large turbo generators. Hunting and damper windings. Numerical.*

Synchronous Generators (Salient Pole)

Effect of Saliency: Saliency in synchronous machines refers to the variation in the reluctance of the magnetic path for the rotor as it rotates. This variation can affect the performance of the machine, especially in terms of its ability to produce torque.

The reactance measured at the terminals of a salient-pole synchronous machine as opposed to a cylindrical rotor machine (with uniform air gap) varies as a function of the rotor position. The effects of saliency are taken into account by the two-reactance theory, in which the armature current ¯Ia is resolved into two components: Id in the direct or field axis, and Iq in the quadrature or interpolar axis. Iq will be in the time phase with the excitation speed voltage ¯Ef, whereas Id will be in the time quadrature with Ef . Direct- and quadrature-axis reactances (Xd and Xq) are then introduced to model the machine in two axes. While this involved method of analysis is not pursued here any further, the steady-state power-angle characteristic of a salient-pole synchronous machine (with negligible armature resistance) is shown in Figure. The resulting power has two terms: one due to field excitation and the other due to saliency. The maximum torque that can be developed is somewhat greater because of the contribution due to saliency.

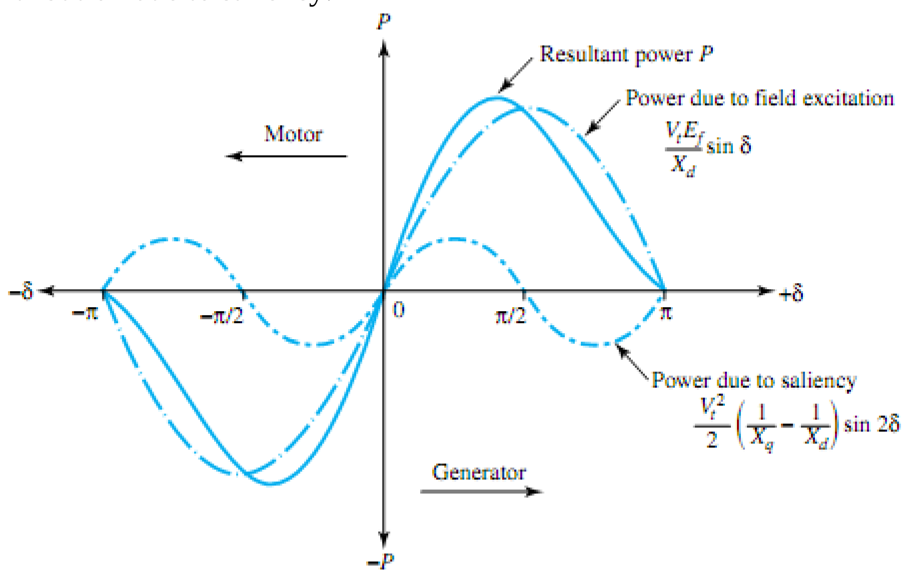


Figure Steady-state power-angle characteristic of a salient-pole synchronous machine (with negligible armature resistance).

Two Reaction Theory – Salient Pole Synchronous Machine

Two Reaction Theory was proposed by Andre Blondel. The theory proposes to resolve the given armature MMFs into two mutually perpendicular components, with one located along the axis of the rotor of the salient pole. It is known as the direct axis or d axis component. The other component is located perpendicular to the axis of the rotor salient pole. It is known as the quadrature axis or q axis component.

The d axis component of the armature MMF, Fa is denoted by Fd, and the q axis component by Fq. The component Fd is either magnetizing or demagnetizing. The component Fq results in a cross-magnetizing effect. If Ψ is the angle between the armature current Ia and the excitation voltage Ef and Fa is the amplitude

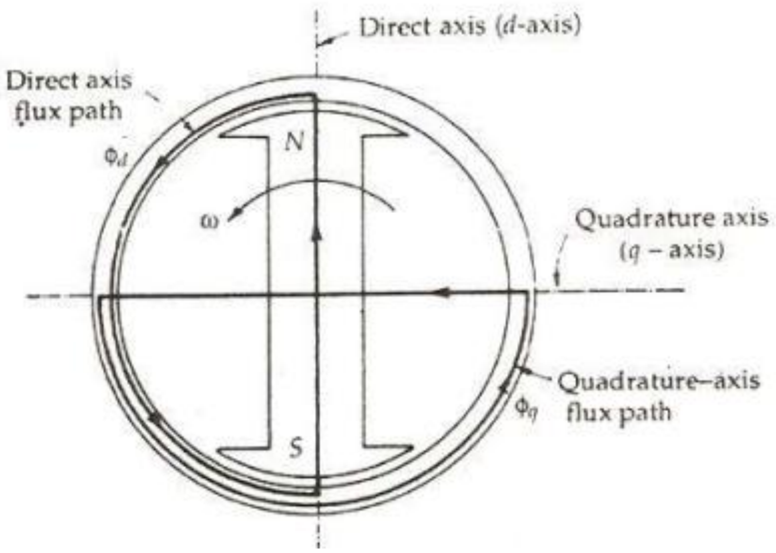
$$F_d = F_a \sin \Psi \qquad \text{and}$$

$$F_q = F_a \cos \Psi$$

of the armature MMF, then

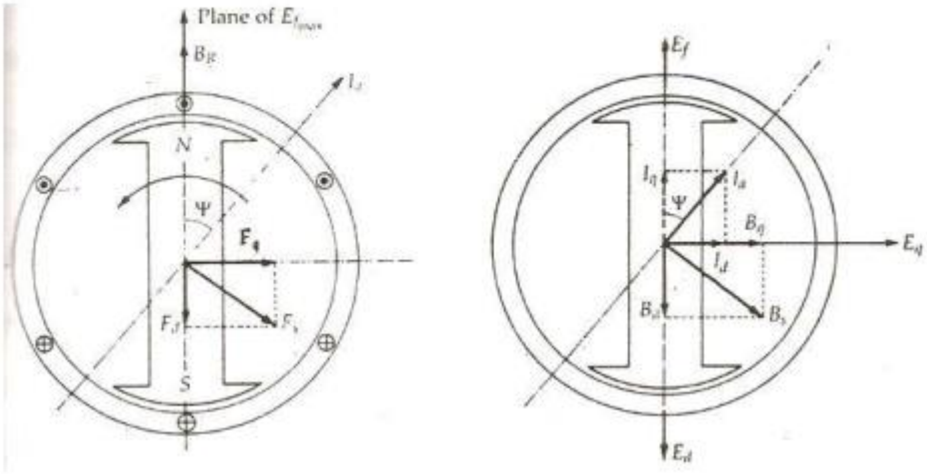
Salient Pole Synchronous Machine Two Rection Theory

In the cylindrical rotor synchronous machine, the air gap is uniform. The pole structure of the rotor of a salient pole machine makes the air gap highly non-uniform. Consider a 2 pole, salient pole rotor rotating in the anticlockwise direction within a 2 pole stator as shown in the figure below:



The axis along the axis of the rotor is called the direct or the d axis. The axis perpendicular to the d axis is known as the quadrature or q axis. The direct axis flux path involves two small air gaps and is the path of the minimum reluctance. The path shown in the above figure by ϕq has two large air gaps and is the path of the maximum reluctance.

The rotor flux BR is shown vertically upwards as shown in the figure below:



The rotor flux induces a voltage Ef in the stator. The stator armature current Ia will flow through the synchronous motor when a lagging power factor load is connected to it. This stator armature current Ia lags behind the generated voltage Ef by an angle Ψ.

The armature current produces stator magnetomotive force Fs. This MMF lags behind Ia by angle 90 degrees. The MMF FS produces stator magnetic field BS long the direction of Fs. The stator MMF is resolved into two components, namely the direct axis component Fd and the quadrature axis component Fq.
If,

- ϕd is the direct axis flux
- Φq is the quadrature axis flux
- Rd is the reluctance of the direct axis flux path

$$\varphi_d = \frac{F_d}{R_d}$$

$$\varphi_q = \frac{F_q}{R_q}$$

Therefore

As, Rd < Rq, the direct axis component of MMF Fd produces more flux than the quadrature axis component of the MMF. The fluxes of the direct and quadrature axis produce a voltage in the windings of the stator by armature reaction.
Let,

- Ead be the direct axis component of the armature reaction voltage.
- Eaq be the quadrature axis component of the armature reaction voltage.

Since each armature reaction voltage is directly proportional to its stator current and lags behind by 90 degrees angles. Therefore, armature reaction voltages can be written as shown below:

$$E_{ad} = -j X_{ad} I_d \quad \dots\dots\dots (1)$$

$$E_{aq} = -j X_{aq} I_q \quad \dots\dots\dots (2)$$

Where,

• Xad is the armature reaction reactance in the direct axis per phase.
• Xaq is the armature reaction reactance in the quadrature axis per phase.
The value of Xad is always greater than Xaq. As the EMF induced by a given MMF acting on the direct axis is smaller than for the quadrature axis due to its higher reluctance.

The total voltage induced in the stator is the sum of EMF induced by the field excitation. The equations are

$$E' = E_f + E_{ad} + E_{aq} \quad \dots\dots\dots (3) \quad \text{or}$$

$$E' = E_f - j X_{ad} I_d - j X_{aq} I_q \quad \dots\dots . (4)$$

The voltage E' is equal to the sum of the terminal voltage V and the voltage drops in the resistance and leakage reactance of the armature. The equation is written as:

$$E' = V + R_a I_a + j X_l I_a \quad \dots\dots . (5)$$

The armature current is divided into two components; one is the phase with the excitation voltage Ef and the other is in phase quadrature to it.
If

• Iq is the axis component of Ia in phase with Ef.
• Id is the d axis Ia lagging Ef by 90 degrees.

Therefore, $$I_a = I_d + I_q \quad \dots\dots . (6)$$

Combining the equation (4) and (5) we get,

$$E_f = V + R_a I_a + jX_l I_a + jX_{ad} I_d + jX_{aq} I_q \dots\dots\dots (7)$$

Combining the equation (6) and (7) we get,

$$E_f = V + R_a(I_d + I_q) + j X_l(I_d + I_q) + jX_{ad}I_d + jX_{aq}I_q \dots\dots\dots (8)$$

$$E_f = V + R_a(I_d + I_q) + j(X_l + X_{ad})I_d + j(X_l + X_{aq}) I_q \dots\dots (9)$$

Let,

$$X_d \triangleq X_l + X_{ad} \dots\dots..(10)$$

$$X_q \triangleq X_l + X_{aq} \dots\dots..(11)$$

The reactance X_d is called the **direct axis synchronous reactance**, and the reactance X_q is called the **quadrature axis synchronous reactance.**

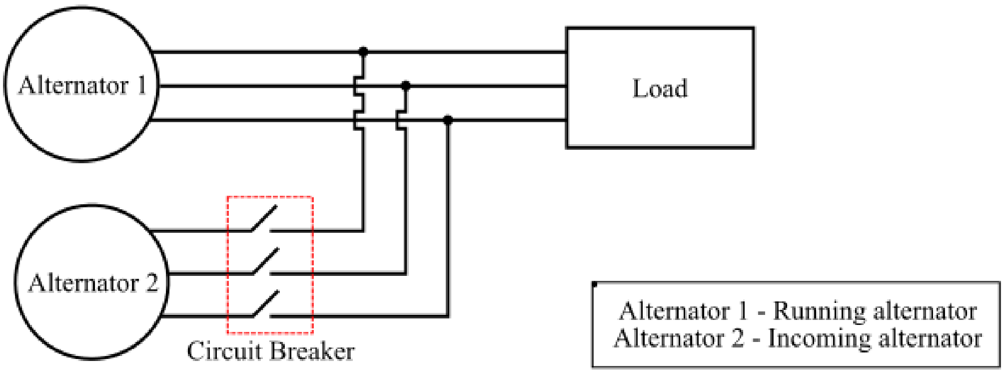
Combining the equations (9) (10) and (11), we get the equations shown below:

$$E_f = V + R_aI_d + R_aI_q + jX_dI_d + jX_qI_q \dots\dots\dots.(12) \text{ or}$$

$$E_f = V + R_aI_a + jX_dI_d + jX_qI_q \dots\dots\dots.(13)$$

The equation (12) shown above is the final voltage equation for a salient pole synchronous generator.

Parallel operation of generators:



In a generating station, two or more alternators are connected in parallel (as shown in Figure). Also, in an interconnected system forming a grid the alternators are located at different places and they are connected in parallel by means of transformers and transmission lines. Under normal operating conditions, all the alternators in an interconnected system operate in synchronism with each other. The parallel operation of alternators ensures greater security of supply and enables overall economic generation.

Advantages of Parallel operation of Synchronous Generators:

- Several alternators can supply a bigger load than a single alternator.

- One or more alternators may shut down during the period of light loads. Thus, the remaining alternator operates at near or full load with greater efficiency.
- When one machine is taken out of service for its scheduled maintenance and inspection, the remaining machines maintain the continuity of the supply.
- If there is a breakdown of the generator, there is no interruption of the power supply.
- A number of machines can be added without disturbing the initial installation according to the requirement to fulfill the increasing future demand of the load.
- Parallel operation of the alternator, reduces the operating cost and the cost of energy generation.
- It ensures the greater security of supply and enables overall economic generation.

Necessary Conditions for Parallel Operation of the Alternator:

Most synchronous machines will operate in parallel with other synchronous machines. The process of connecting one machine in parallel with another machine or with an Infinite Busbar system is known as Synchronizing. The machine carrying the load is known as Running Machines while the alternator which is to be connected in parallel with the system is known as the Incoming machine.

- The phase sequence of the Busbar voltages and the incoming machine voltage must be the same.
- The Busbar voltages and the incoming machine terminal voltage must be in phase.
- The terminal voltage of the incoming machine and the alternator which is to be connected in parallel or with the busbar voltage should be equal.
- The frequency of the generated voltage of the incoming machine and the frequency of the voltage of the busbar should be equal.

Methods of Synchronization:

Different techniques are available for the synchronization of alternators. The primary purpose of these techniques is to check all four conditions discussed above. The common methods used for synchronizing the alternators are given below:

- Three Dark Lamps Method
- Two Bright, One Dark Method
- Synchroscope Method

Three Dark Lamps Method:

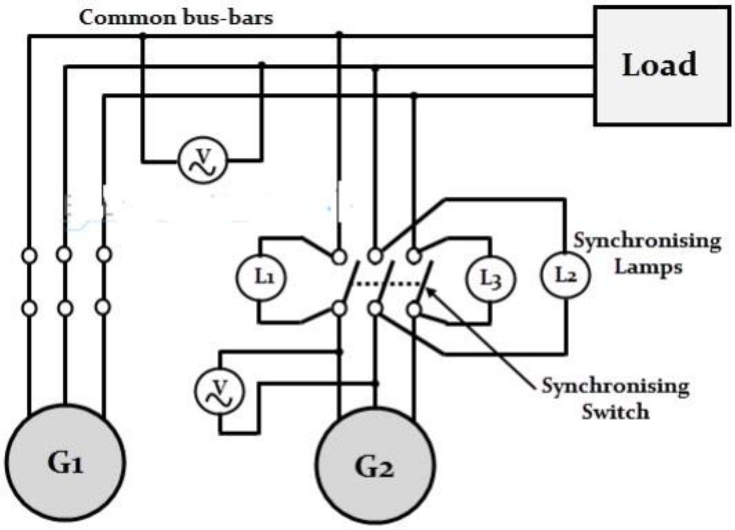
The figure shows the circuit for the bright lamp method used to synchronize the alternators. Assume that the alternator is connected to the load supplying rated voltage and frequency to it. Now the alternator-2 is to be connected in parallel with alternator-1.
Three lamps (each of which is rated for alternator terminal voltage) are connected across the switches of the alternator-2. From the figure, it is clear that the moment when all the conditions of parallel operation are satisfied, the lamps should be more or less dark.

To synchronize the alternator-2 with bus bar, the prime mover of the alternator-2 is driven at speed close to the synchronous speed decided by the bus bar frequency and number of poles of the alternator.

Now the field current of the generator-2 is increased till voltage across the machine terminals is equal to the bus bar voltage (by observing the readings on voltmeters).

If lamps go ON and OFF concurrently, indicating that the phase sequence of alternator-2 matches with bus bar. On the other hand, if they ON and OFF one after another, it resembles the incorrect phase sequence.

By changing the connections of any two leads of alternator-2 after shutting down the machine, the phase sequence can be changed.



Depending on the frequency difference between alternator-2 voltage and bus bar voltage, ON and OFF rate of these lamps is decided. Hence, the rate of flickering has to be reduced to match the frequency. This is possible by adjusting the speed of alternator by its prime mover control.

When all these parameters are set, the lamps become dark and then the synchronizing switch can be closed to synchronize alternator-2 with alternator-1.

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.

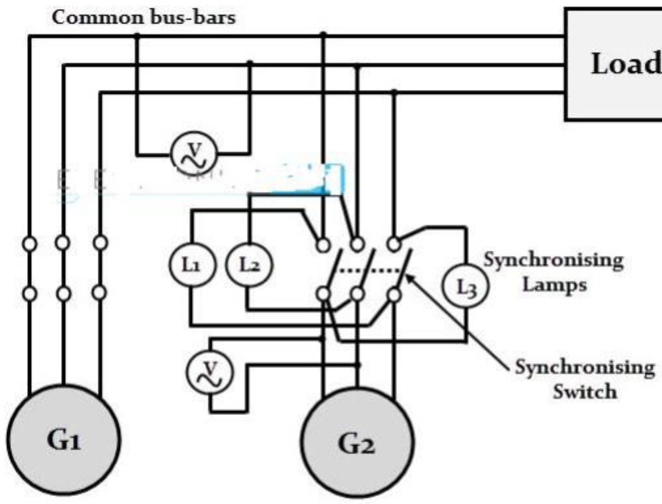
Suppose, if the bus bar frequency is 50Hz, the rate of flickering of lamps is same when the frequency of the alternator is either 51 or 49 Hz, as the difference in these two cases is 1Hz.

Two Bright and One Dark Lamp Method:

The connections for this method are shown in figure and it is useful in finding whether the alternator frequency is lower or higher than the bus bar frequency.

To synchronize the alternator-2 with bus bar, the prime mover of the alternator-2 is driven at speed close to the synchronous speed decided by the bus bar frequency and number of poles of the alternator.

Now the field current of the generator-2 is increased till voltage across the machine terminals is equal to the bus bar voltage (by observing the readings on voltmeters).
Here, the lamp L2 is connected across the pole in the middle line of synchronizing switch as similar to the dark lamp method, whereas the lamps L1 and L3 are connected in a transposed manner.
The voltage condition checking is similar to the previous method and after it, the lamps glow bright and dark one after another. The lower or higher value of alternator frequency in comparison with bus bar frequency is determined by the sequence in which the lamps become dark and bright.

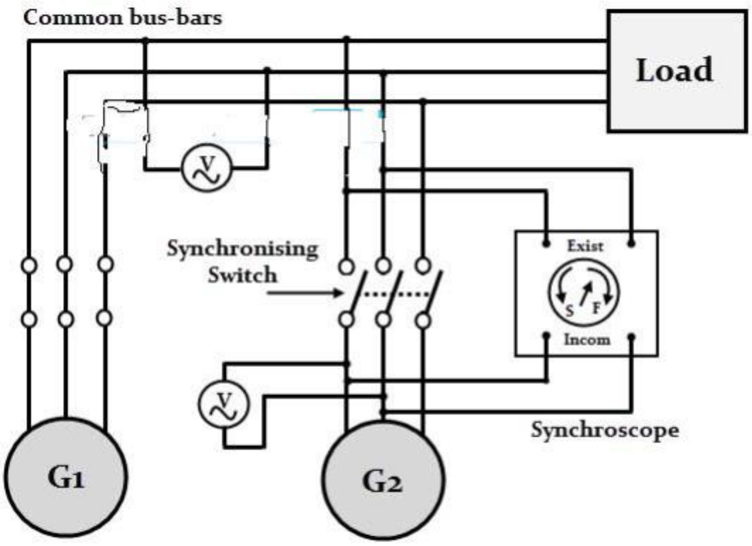


The sequence of becoming bright and dark L1- L2 – L3 indicates that the incoming generator frequency is higher than the bus bar frequency. Hence, the alternator speed has to be reduced by prime mover control till the flickering rate is brought down to a small.
On the other hand, the sequence flickering L1- L3 – L2 indicates that incoming alternator frequency is less than that of bus bar.
Hence, the speed of the alternator is increased by the prime mover till the rate of flickering is brought down to as small as possible. The synchronizing switch is then closed at the instant when lamps L1 and L3 are equally bright and lamp L2 is dark.
The disadvantage of this method is that the correctness of phase sequence cannot be checked. However, this requirement is unnecessary for permanently connected alternators where checking of phase sequence is enough to be carried out for the first time of operation alone.

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.
To synchronize the alternator-2 with bus bar, the prime mover of the alternator-2 is driven at speed close to the synchronous speed decided by the bus bar frequency and number of poles of the alternator.

Now the field current of the generator-2 is increased till voltage across the machine terminals is equal to the bus bar voltage (by observing the readings on voltmeters).
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.



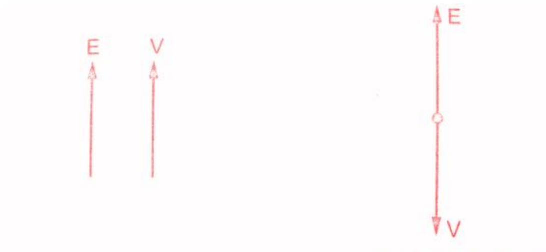
After the voltage condition is checked, the operator has to check the synchroscope. The rate at which the pointer rotates indicates the difference of frequency between the incoming alternator and the bus bar.
Also, the direction to which the pointer rotates (to either fast or slow) gives the information, whether the incoming alternator frequency is higher or lower than the bus bar frequency and hence the pointer moves either fast or slow.
The appropriate correction has to be made to control the speed of the alternator so as to bring the rate of rotation of the pointer as small as possible. Therefore, a synchroscope along with voltmeters are enough for synchronization process. However, in most of the cases a set of lights along with synchroscope is used as a double-check system.

These are the methods of synchronizing the generators. 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. Only three lamps methods are not preferred today due to less accuracy and manual operation.
These processes need a skilled and experienced person to handle the equipment while synchronizing. In most cases synchroscope method with set of lamps is used as mentioned above.

Synchronizing Power(P_{SY}):

Synchronizing Power is defined as the difference between input power to alternator at power angle δ and input power to alternator at power angle $\delta + \delta'$.Synchronizing Power is denoted by P_{SY}.

Consider an alternator connected to the infinite bus bar. Let V be the bus bar voltage and E be the EMF induced in the alternator. The excitation of the alternator is adjusted in such a way that E and V are equal in magnitude. In the local circuit, the two voltages E and V are in phase opposition while in the external circuit they are in the same phase. This is represented in the below figure.



(a) In external circuit (b) In local circuit

Consider the alternator to be at no load. If by some means power input to the machine is decreased and it's induced EMF E will then lag behind V by say angle 2δ.Due to this difference, E and V will not remain in exact phase opposition but will give rise to resultant EMF Er. This Er will act in the local circuit and a synchronizing current will start flowing in the local circuit. The synchronizing current is given by,

$$I_{SY} = E_r/Z_s$$

Isy is lagging behind Er by an angle θ given by

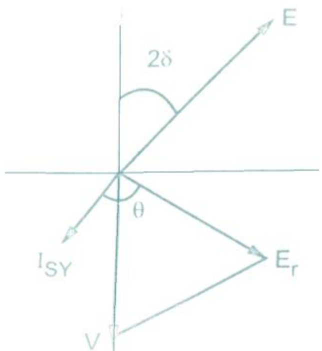
$$\theta = \tan^{-1}(X_s/R)$$

R is very very small it can be neglected.

$$\theta \approx 90°$$

The angle 2δ is very very small and θ is approximately equal to 90° so the synchronizing current Isy is almost in phase with V and in phase opposition with E. So infinite bus bar will deliver some power to the alternator. As the current in the local circuit is always opposed to induced EMF E, the alternator will act as a synchronous motor.

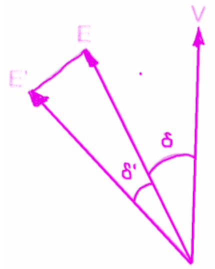
Thus synchronizing torque will be developed which will try to accelerate the machine. Thus the angle 2δ will go on decreasing and the resultant EMF Er also goes on decreasing. Finally, the two EMF E and V will again be in phase opposition and the machine will now act as an alternator in synchronism with the bus bar.



Thus the power which automatically comes into play and accelerates the machine which was retarding and decelerates the machine which tries to accelerate is called synchronizing power. This power will keep the machine in step with the infinite bus bar.

Expression for Synchronizing Power(P_{SY}):

Consider an alternator that is operating at a power angle δ i.e. E leads V by an angle δ.



Let power input of this alternator be increased suddenly so that it will now operate at a new power angle given by $\delta + \delta$'.So the synchronizing emf ESY will come into play and sends a circulating current given by $I_{SY} = E_{SY}/Zs$. This current produces synchronizing power. Now we will derive the expression for synchronizing power per phase.

Before increasing the input of the alternator, the power input P_{i1} is given by,

$$P_{i1} = \frac{E}{Z_s}[E\cos\theta - V\cos(\theta + \delta)]$$

When power angle δ has changed to $\delta \pm \delta'$ (+ sign indicates acceleration and – sign indicates deceleration) the power input P_{i2} is given by

$$P_{i2} = \frac{E}{Z_s}[E\cos\theta - V\cos(\theta + \delta \pm \delta')]$$

The difference between these two powers is nothing but synchronizing power P_{SY}.

$$P_{SY} = P_{i2} - P_{i1}$$

$$= \left\{\frac{E}{Z_s}[E\cos\theta - V\cos(\theta+\delta\pm\delta')]\right\} - \left\{\frac{E}{Z_s}[E\cos\theta - V\cos(\theta+\delta)]\right\}$$

$$= \frac{E}{Z_s}[V\cos(\theta+\delta) - V\cos[(\theta+\delta)+\delta']] \ldots \text{(considering + ve sign for } \delta')$$

$$= \frac{EV}{Z_s}\{\cos(\theta+\delta) - [\cos(\theta+\delta)\cos\delta' - \sin(\theta+\delta)\sin\delta']\}$$

$$= \frac{EV}{Z_s}\{\sin(\theta+\delta)\sin\delta' + [\cos(\theta+\delta)(1-\cos\delta']\}$$

$$= \frac{EV}{Z_s}\left\{\sin(\theta+\delta)\sin\delta' + \cos(\theta+\delta)\left[2\sin^2\frac{\delta'}{2}\right]\right\}$$

If δ' is small then $\delta'/2$ is very very small. Therefore $\sin^2(\delta'/2)$ can be neglected as it is tending towards zero.

$$P_{SY} = \frac{VE}{Z_s}\sin(\theta + \delta)\sin\delta'$$

For large synchronous machines θ = 90° and Zs = Xs as Ra is neglected

$$P_{SY} \approx \frac{V\,E}{X_s}\cos\delta \,.\ \sin\delta'$$

For synchronous generator which is synchronized with bus bar V = E, $\delta = 0$ and δ' is very very small.

$$\text{Sin } \delta' = \delta' \quad \text{and} \quad \text{Cos } \delta = 1$$

$$P_{SY} = \frac{V^2}{X_s}\delta' = \frac{E^2}{X_s}\,.\ \delta' = E\left(\frac{E}{X_s}\right).\ \delta' = E.I_s\ \delta'$$

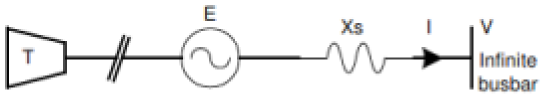
The above expression is per phase power. Therefore for the machine having 'm' phases the **synchronizing power** is given by,

$$P_{SY} = m\ E\ I\ \delta'$$

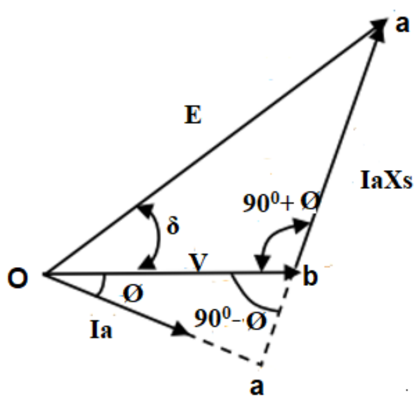
Power angle characteristics:

Non-Salient and Cylindrical Rotor Synchronous Machine:

When the synchronous generator feeds power to the infinite bus bar at constant terminal voltage V_t and single line diagram of the phasor diagram for lagging power factor is shown in the below figure. For the large size of generators, armature resistance Ra is negligible.



Cylindrical-rotor alternator connected to infinite bus-bar single line diagram



Power delivered to the infinite bus per phase is given by,

Pi = V Ia cosØ

From the above phasor diagram it can be seen that

∠OBA = 90-Ø

∠OBC = 180-(90-Ø) = 90 +Ø

From Δ OBC,

$$\frac{BC}{sin\angle BOC} = \frac{OC}{sin\angle OBC}$$

$$\frac{Ia\,Xs}{sin\delta} = \frac{E}{\sin(90+\emptyset)}$$

$$Ia\ Xs\ \sin(90+\emptyset)\ E\ \sin\delta$$

$$IaXs\ \cos\emptyset = E\ \sin\delta$$

$$Ia\ \cos\emptyset = \frac{E\ sin\delta}{Xs}$$

Substituting the above value of Ia cosØ in the expression for power we get,

$$P_i = V\ \frac{E\ sin\delta}{Xs}$$

$$P_i = \frac{E\ V}{Xs}\ sin\delta$$

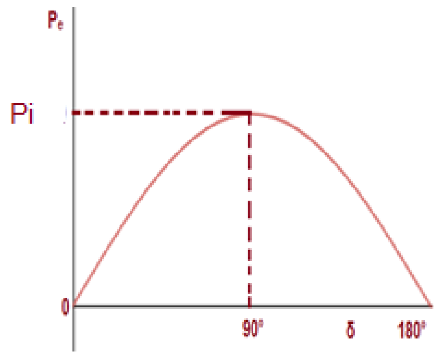
The above power is the electrical power exchanged with bus bars. Angle δ, between E and V is known as power angle.

Power angle characteristics of non-salient pole synchronous machine:

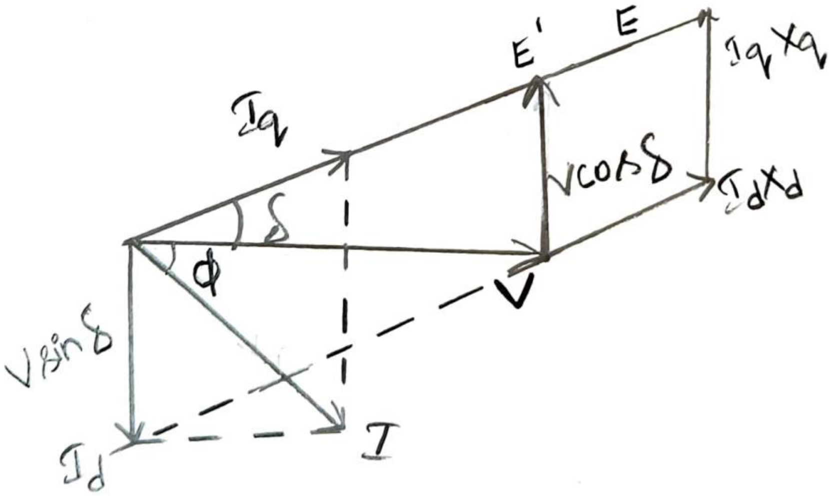
$$P_i = \frac{E\ V}{Xs}\ sin\delta$$

The relation between Pi and δ is known as power angle characteristics of the machine.

The maximum power occurs at $\delta = 90^0$. Beyond this point the machine falls out of step and loses synchronism. The machine can be taken up to P_{imax} only by gradually increasing the load. This is known as steady state steability limit of the machine. The machine is normally operated at δ much less than 90^0.



Salient Pole Synchronous Machine:



The resistance Ra of the armature can be neglected since it has a negligible effect on the relationship between the power output of a synchronous machine and its torque angle δ. The phasor diagram at lagging power factor for a salient pole synchronous machine, neglecting Ra is shown in Figure. The power-angle characteristics of a salient-pole machine may be derived from the phasor diagram.

$$E = V\cos\delta + I_d X_d$$

$$I_d = \frac{E - V\cos\delta}{X_d} \quad \ldots\ldots\ldots\ldots(1)$$

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

$$I_q = \frac{V\sin\delta}{X_q} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Power = I_d (component of voltage along d axis) + I_q (component of voltage along q axis)

$$P_i = \left(\frac{E - V\cos\delta}{X_d}\right) V\sin\delta + \left(\frac{V\sin\delta}{X_q}\right) V\cos\delta$$

$$= \frac{EV\sin\delta}{X_d} - \frac{V^2\cos\delta\sin\delta}{X_d} + \frac{V^2\cos\delta\sin\delta}{X_q}$$

$$= \frac{EV\sin\delta}{X_d} + V^2\cos\delta\sin\delta\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$$

$$= \frac{EV\sin\delta}{X_d} + \frac{2V^2\cos\delta\sin\delta}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$$

Sin2ϴ = 2 sinϴ cosϴ

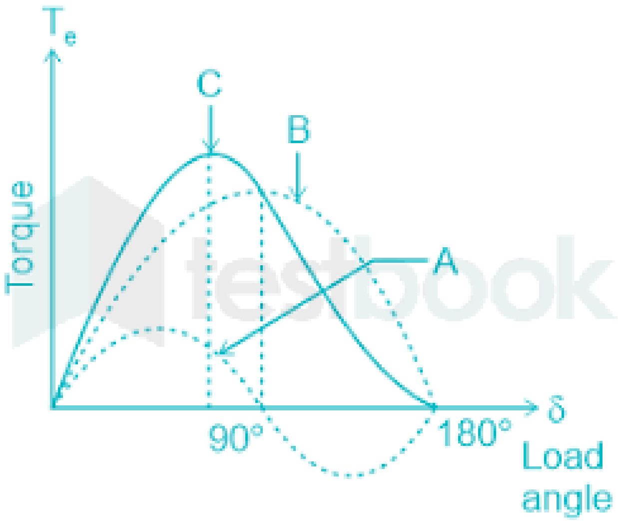
$$P_i = \frac{EV\sin\delta}{X_d} + \frac{2V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

Per phase power output from salient pole alternator

From the output power equation, the power against load angle characteristics can be obtained.

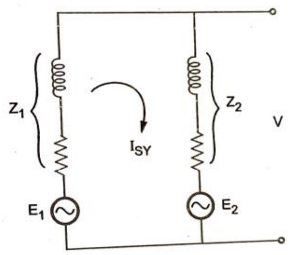
Excitation power or Electromagnetic power

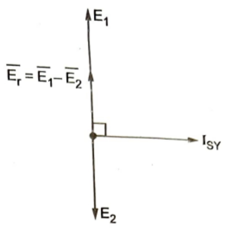
Reluctance power or power due to saliency



Effect of Change in Excitation: In case of alternators a field rheostat may be used to change the excitation or its field current. If alternators are running in parallel, a change in the field current will not change the active power shared significantly but will change the operating power factor with change in the excitation the armature current will change which will change active power by a small amount.

Alternator on No Load:

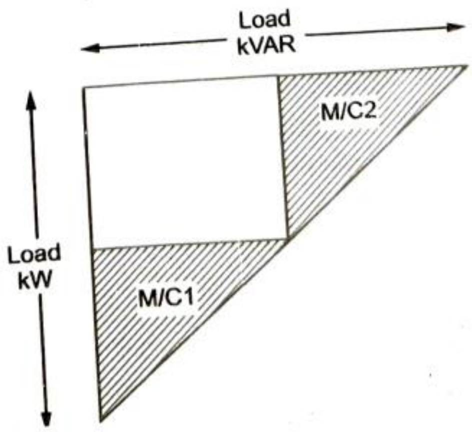




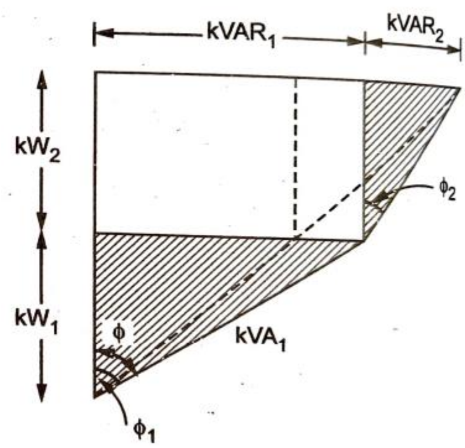
- Consider two alternators on no load and working in parallel. If their excitation is adjusted properly then the e.m.f.s E_1 and E_2 will be equal. Thus, there will not be any current in circuit.
- Excitation of alternator 1 is increased magnitude of E_1 will be more than that of E_2 will cause resultant voltage $Er = E_1 – E_2$ will appear in the local circuit.
- This resulting voltage will set up a synchronizing current Isy in the local circuit and since the synchronizing impedances are mainly reactive, current lags Er by approximately 90^0.
- For alternator 1, Isy lags behind El by 90^0 lagging current will produce demagnetizing effect and will try to reduce the generated e.m.f.
- Alternately for another alternator, Isy leads E_2 by 90^0. There will be leading current which will produce magnetizing effect and the field will be strengthened which will try to increase the generated e.m.f.

- Thus E_l will be reduced whereas E_2 will be increased. Hence the circulating current will try to make the two generated e.m.f.s equal at no load whereas the power angle will remain at zero degrees.

Alternator on Load:



- Two alternators running in parallel with each alternator supplying one half Of active power and one half of reactive power. Each alternator supplies a load of I such that total load current is 2I.
- El = E2 while the operating power factor is cosØ and terminal voltage V. The power triangles for both the alternators can be represented as shown below.
- If now excitation on alternator no.1 ia increased then its induced emf E_1 will increase which will raise the terminal voltage $\left(V = \frac{E_1 + E_2}{2}\right)$. Now the difference in induced emf will set up a circulating current $\left(I_{sy} = \frac{E_1 - E_2}{2\,Z}\right)$ that flows in local circuit. This current is superimposed on original current distribution.



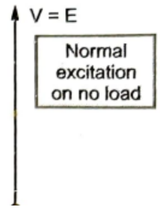
- Current Isy is vectorially added to the load current of alternator no. 1 and subtracted from the load current of alternator no. 2. Now the load currents will be changed to I_1 and I_2 with change in power factors. The new power factors are cos $Ø_1$ and cos $Ø_2$.
- It can be seen from the figure cos $Ø_1$ is reduced whereas cos $Ø_2$ is increased. The armature currents for the two machines are changed but their active components are not changed. Thus changes in kW loading of the two alternators is negligible but reactive power $kVAR_1$ from first alternator is increased whereas $kVAR_2$ supplied by second alternator is decreased which can be seen from power triangles.

Synchronous Generator on Infinite Busbar:

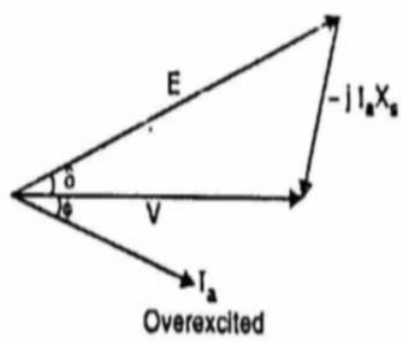
A network in which a generating plant maintaining a constant voltage at constant frequency is called infinite busbar. A generator connected to such a network is called synchronous generator on infinite busbar.

Consider synchronous generator connected to infinite busbar having constant phase voltage V. Let the generator is on no load so it is not supplying any power to the load. Let the excitation of this generator is varied.

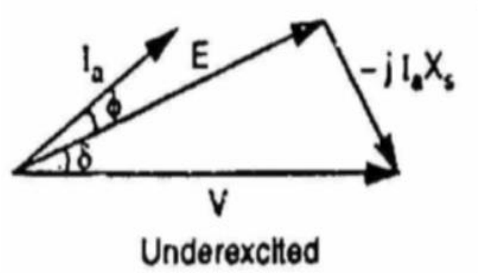
1. **Normal excitation :** The normal excitation means the excitation is adjusted such internal e.m.f. E is exactly equal to the voltage V. Thus no current will flow into or out of the armature as E = V.



2. **Over Excitation:** When the alternator is overexcited, it must deliver lagging current since lagging current produces an opposing m.m.f. to reduce the over-excitation. Thus an overexcited alternator supplies lagging current in addition to the constant active component of current. Therefore, an overexcited alternator will operate at lagging power factor. Note that excitation does not control the active power but it controls power factor of the current supplied by the alternator to the infinite busbars.



3. **Under Excitation:** Excitation of the alternator is decreased below normal excitation (under-excitation) while the power input to the prime mover is unchanged. Therefore, the active power output (W or kW) of the alternator will remain unchanged L e., active component of current is unaltered. The under-excited alternator supplies leading current (and hence leading reactive power) to the infinite busbars. It is because when an alternator is under-excited, it must deliver leading current since leading current produces an aiding m.m.f. to increase the under-excitation. Thus an under-excited alternator supplies leading current in addition to the constant active component of current. Therefore, an under-excited alternator will operate at leading power factor.



Capability Curve for large turbo generator:

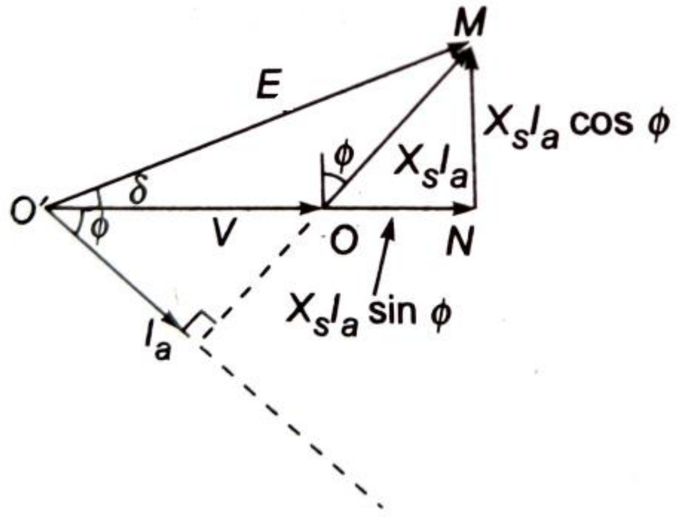
The Capability Curve of a Synchronous Generator defines a boundary within which the machine can operate safely.

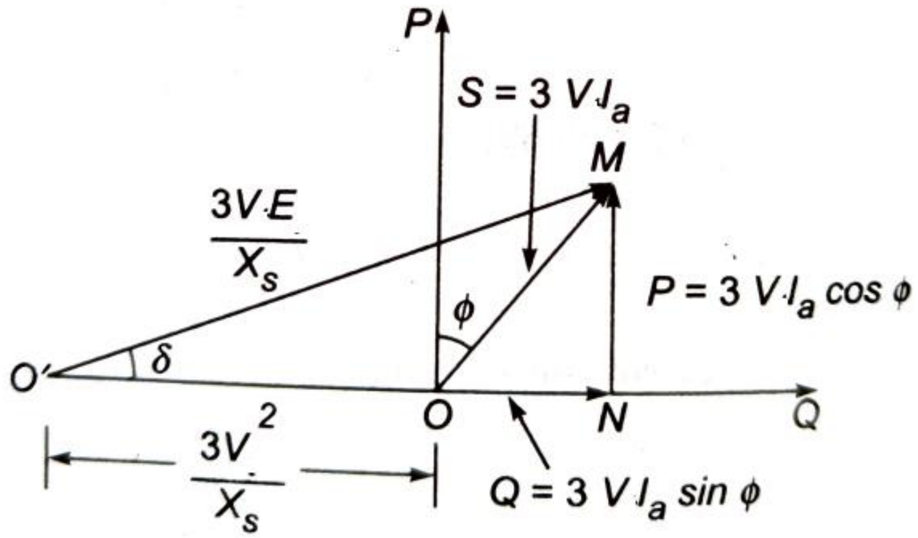
- The MVA loading should not exceed the generator rating. This limit is determined by the armature of the stator heating by the armature current.
- The MW loading should not exceed the rating of the prime mover.
- The field current should not be allowed to exceed a specified value determined by the heating of the field.
- For steady-state or stable operation, the load angle δ must be less than 90 degrees. The theoretical stability limit of the stable condition occurs when $\delta = 90^{o}$.

The capability curve is based upon the phasor diagram of the synchronous machine. The phasor diagram of a cylindrical rotor alternator at lagging power factor is shown in figure 1. After multiplying voltage magnitude of each voltage phasor by $\left(3\,V_t/X_s\right)$, the phasor diagram is redrawn in figure 2. It is recognize that OMN is the complex power triangle .

OM= S(MW); ***NM = P(W);*** ***ON = Q(VAR)***

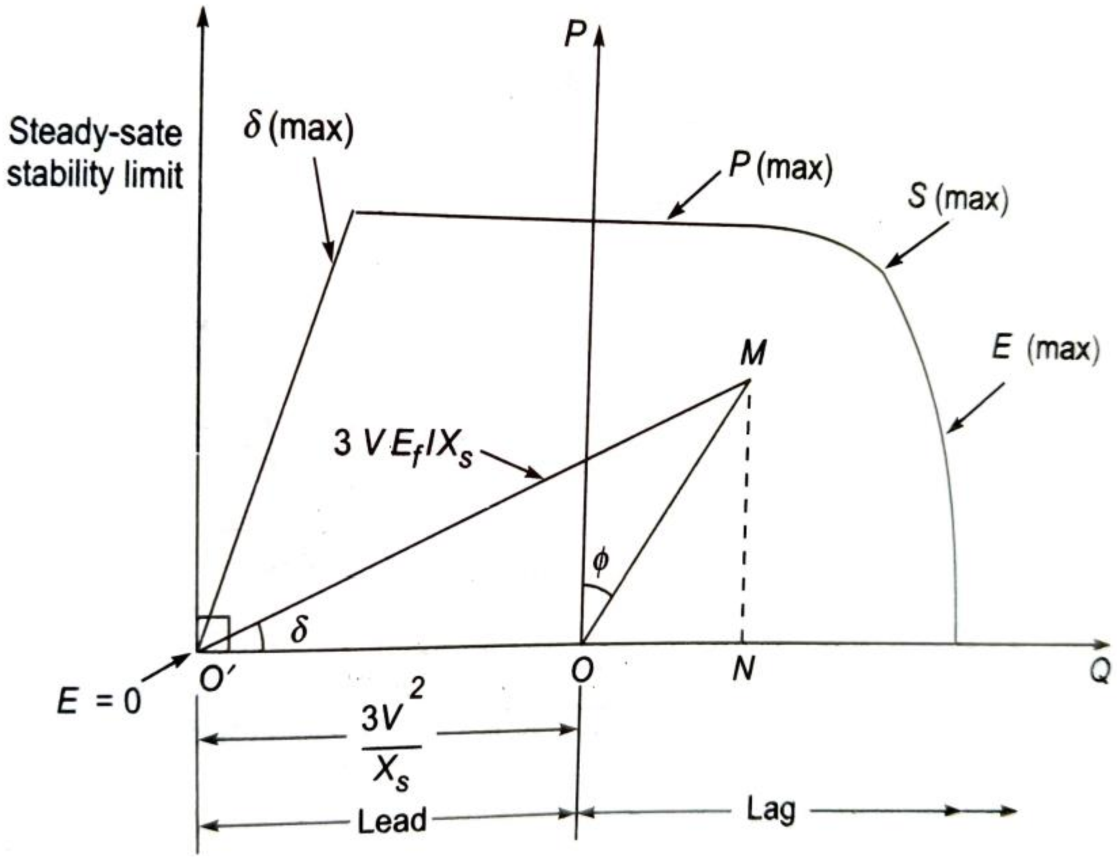
Q is positive for lagging power factor, Ø being an angle of OM from P-axis. A mere scale change will convert these values to the units of MVA, MW and MVAR.



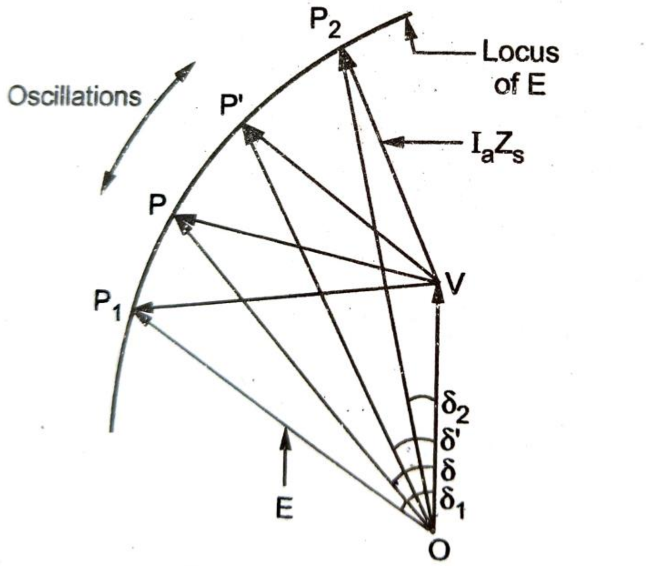


Constant S operation will lie on a circle centered at O and radius OM. Constant P operation will lie on a line parallel to O` Q-axis. Constant excitation operation will lie on a circle centered O` of radius OM. Constant pf operation will lie on a radial line through O.

Now with specified upper limits of S,P and E the boundaries of the capability curve can be drawn.



Hunting: The phenomenon of oscillation of the rotor about its final equilibrium position is called Hunting. On the sudden application of load, the rotor searches for its new equilibrium position, and this process is known as Hunting. The Hunting process occurs in a synchronous motor as well as in synchronous generators if an abrupt change in load occurs.



Consider a synchronous generator working with a constant load with a power angle and operating point is P . Let the load is suddenly changed so that the expected new operating point is P' with power angle δ'. But before achieving new position P', the alternator oscillates about V and the load angle oscillates about δ' as shown in that such oscillations about P' cause variations in current and power which is called hunting or phase swinging. Such oscillations are undesirable.

In synchronous motors, hunting produces severe mechanical stresses and large variations in current and power. If such oscillations achieve resonance, the machine may get damaged.

various causes of hunting in synchronous machines

1. Sudden change in load.
2. Sudden change in field current i.e. excitation.
3. A fault in the supply system.
4. Change in supply frequency load consists of harmonic torques.

The various undesirable effects of hunting are,

l) Large surges in current and power

2) Produces mechanical stress on the rotating

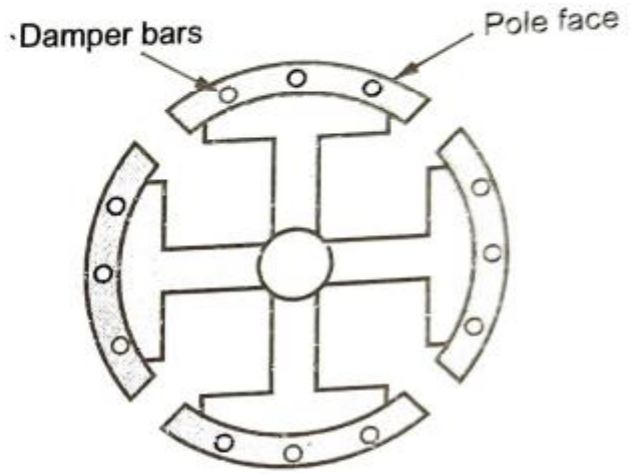
3) Produces more losses in the machine.

4) Increase the temperature rise of the machine.

5) The machine may become unstable and fall out of step.

Hence it is necessary to reduce hunting in synchronous machines.

Damper Winding: The effective practical way of reducing hunting is the use of damper windings. The damper windings are short-circuited copper or aluminum bars. These are placed in the faces of the field poles of salient pole machines as shown in Fig.



When there are oscillations in the rotor, there is relative motion between the magnetic field and damper winding. This induces e.m.f. in the damper winding to set up eddy currents. The direction of these currents is to oppose the cause producing them, as per Lenz's law. The cause is the rotor oscillations. Thus damper winding tries to dampen the oscillations. Hence the hunting gets reduced in the synchronous machines.