AC Machines: Synchronous Machine

Parallel Operation

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Parallel Operation

- The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as synchronizing.
- Generally, alternators are used in a power system where they are in parallel with many other alternators.
- It means that the alternator is connected to a live system of constant voltage and constant frequency.
- Often the electrical system to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same.
- In that case, the alternator is said to be connected to infinite bus-bars.
- It is never advisable to connect a stationary alternator to live bus-bars, because, stator induced e.m.f. being zero, a short-circuit will result.
- Methods: dark lamp method, two bright and one dark lamp method, synchroscope method

Reasons of Parallel Operation of Alternators

- Continuity of service – When one alternator is taken out of service for its scheduled maintenance and inspection, the remaining alternators maintain the continuity of supply.
- Efficiency – During the periods of light load, one or more alternators may be shut down and those remaining operate at or near full-load and hence more efficiently.
- Several alternators operating in parallel can supply a bigger load than a single alternator.
- If there is a breakdown of an alternator, there is no interruption of the power supply.
- Load growth – In order to meet the increasing future demand of load more alternators can be added without disturbing the original installation of the power system.
- Economy – The operating cost and cost of energy generated are decreased when several alternators operate in parallel.

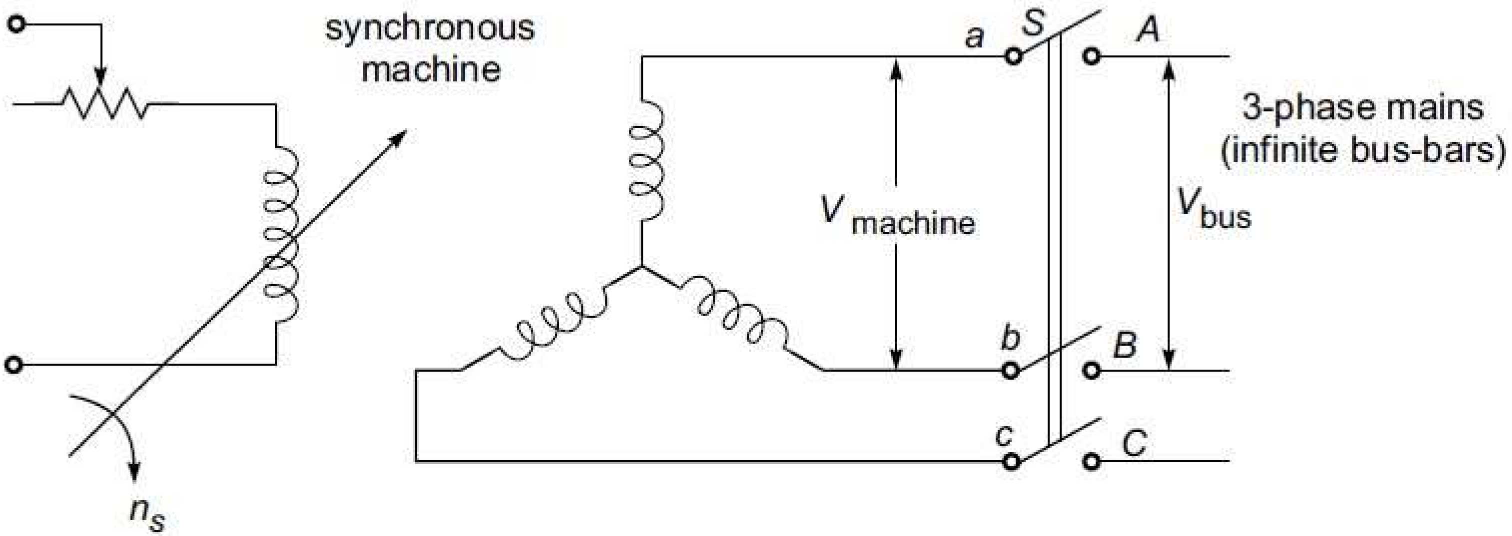
Parallel Operation: Conditions

- For proper synchronization of alternators, the following conditions must be satisfied :

1. The terminal voltage of the incoming alternator must be equal to the bus bar voltages.
2. The bus bar voltages and the terminal voltage of the incoming alternator must be in phase.
3. The phase sequence of the bus bar voltages and the incoming alternator voltage must be the same.
4. The frequency of the generated voltage of the incoming machine must be equal to the frequency of the voltages of the bus bar.

- In 3-φ alternators, it is necessary to synchronize one phase only, the other two phases will then be synchronized automatically.
- Condition (1) is indicated by a voltmeter, conditions (2), (3) and (4) are indicated by synchronizing lamps or a synchronoscope

Parallel Operation: Procedure



❖ The machine is run as a generator with its terminals so arranged that its phase sequence is the same as that of the bus-bars.

❖ The machine speed and field current are adjusted so as to satisfy the following conditions:

(i) The machine terminal voltage must be nearly equal to the bus-bars voltage.

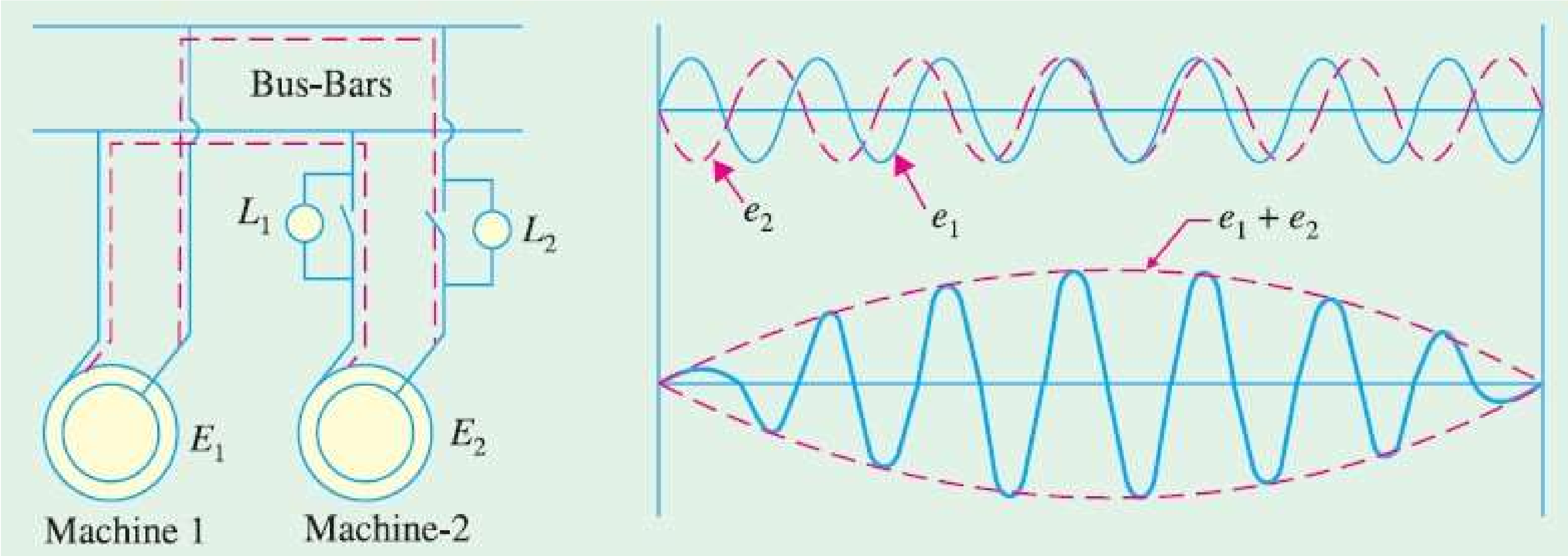
(ii) The machine frequency is nearly equal to the bus-bars frequency, i.e. the machine speed is close to synchronous speed.

Parallel Operation: Steps

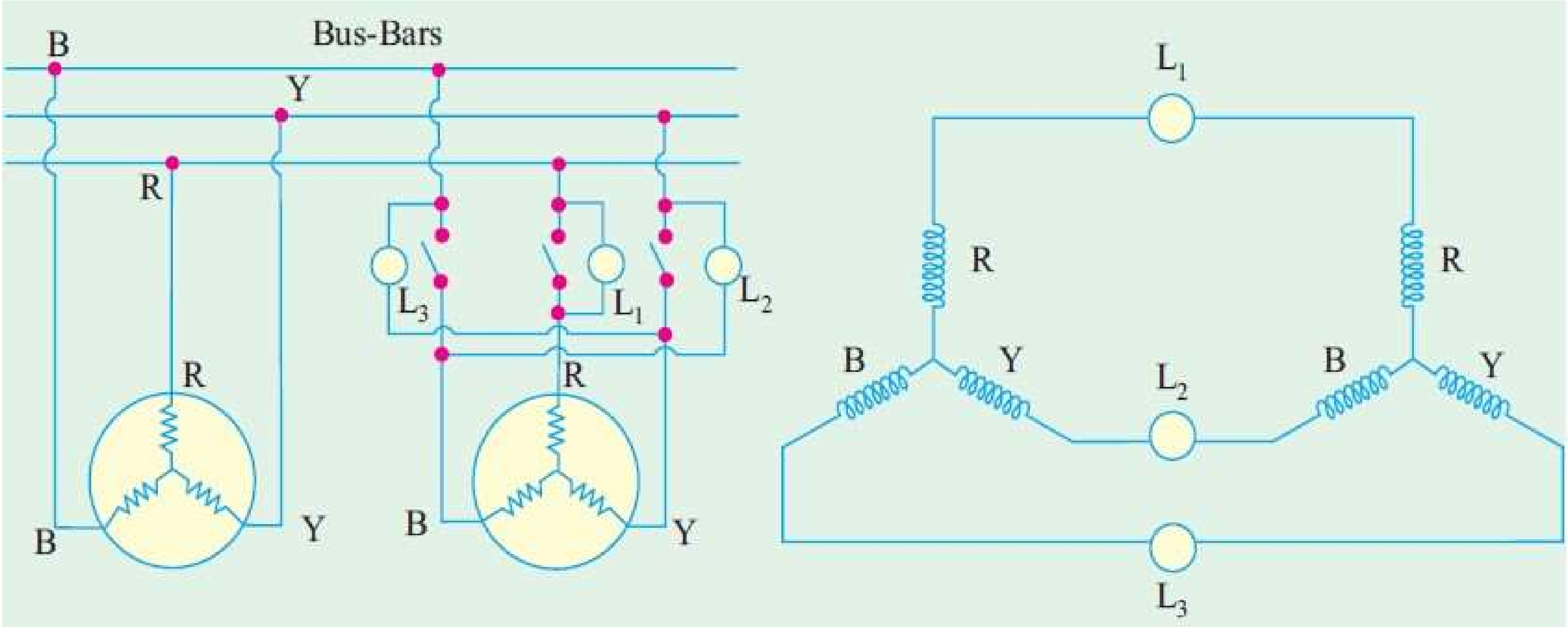
- Check the voltage of running and incoming alternators.
- Adjust the voltage (by changing the field excitation) and make the voltage of incoming and running alternators equal.
- The phase sequence of the alternators can be checked by three-lamp methods.
- In the three-lamp method, three light bulbs are connected to the terminals of the switch, S1.
- The voltage across each bulb is the difference in voltage between the incoming and running alternator.
- Bulbs become bright if the phase difference is large.
- Conversely, if the phase difference is small, bulbs will become dim.
- When the phase sequence is the same, the bulbs will show both dim and bright. On the other hand, if the phase sequence is opposite, the bulbs will get progressively brighter.
- To make the phase sequence equal, you can swap the connections on any two phases on one of the generators.

Parallel Operation: Steps

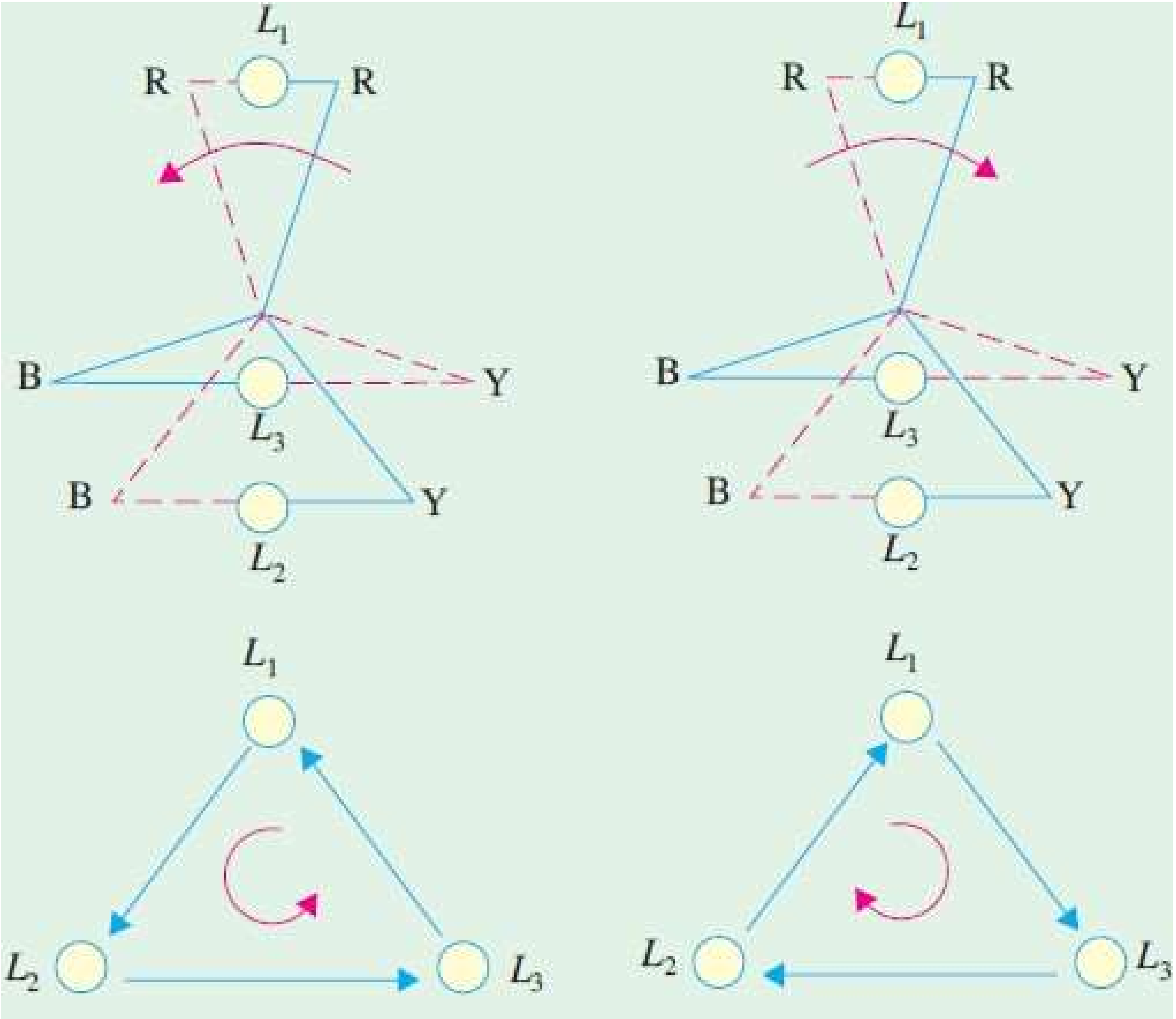
- Check and verify if the incoming and running system frequencies are nearly the same.
- One way to do this is by examining the frequency of dimming and brightening of lamps.
- When the frequencies of the incoming alternator and running system are almost the same, their voltages will gradually alter in phase.
- These changes can be observed, and S1 can be closed when the phase angles are equal.
- Synchronization by using incandescent lamps depends on the correct judgement of the operator.
- To use this method for high voltage alternators, extra step down transformers need to be added as ratings of lamps are normally low.
- Other method: Synchronization Of Alternator Using Synchroscope



- E1 and E2 are in-phase relative to the external circuit but are in direct phase opposition in the local circuit (shown dotted).
- If frequencies are different, there will be a phase-difference between their voltages (even when they are equal in magnitude)
- This phase-difference will be continuously changing with the changes in their frequencies.
- The result is that their resultant voltage will undergo changes.
- Sometimes the resultant voltage (voltage across the lamp) is maximum and some other times minimum.
- Lamps will flicker if there is a difference in frequency.



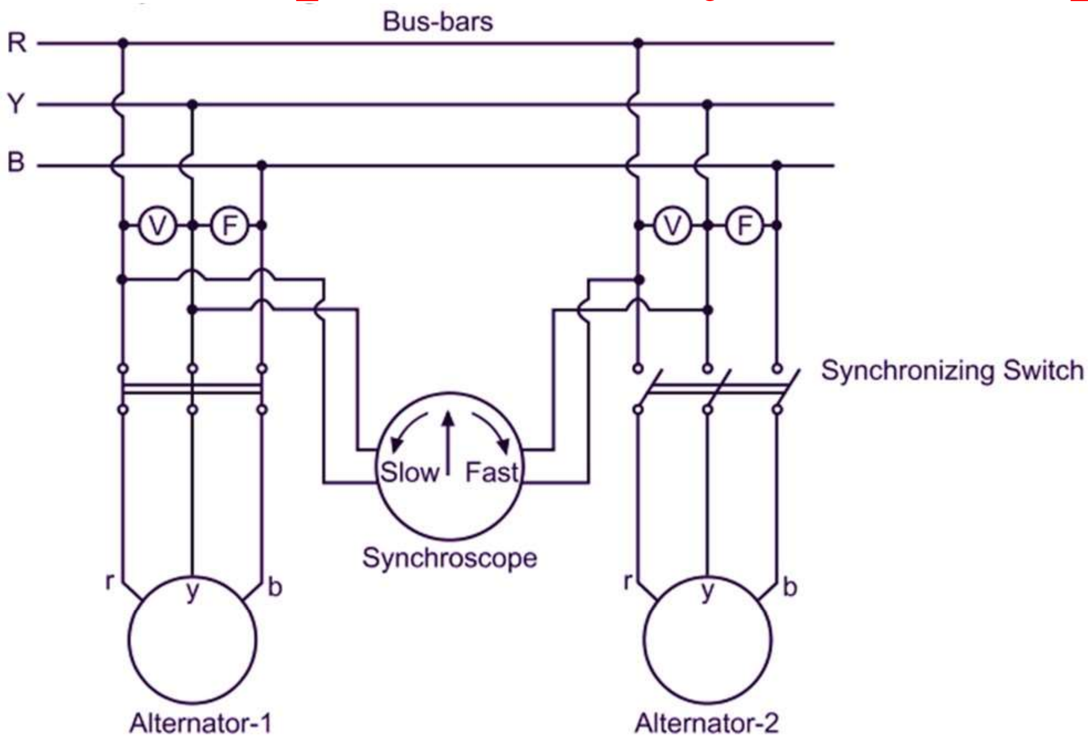
- The speed of the incoming machine must be such that its frequency (= PN/120) equals bus-bar frequency.
- Three lamps are used, but they are deliberately connected asymmetrically, as shown in Fig.
- This transposition of two lamps helps to indicate whether the incoming machine is running too slow or too fast.
- If lamps were connected symmetrically, they would dark out or glow up simultaneously


L_1
R
R
B
Y
L_3
B
Y
L_2
L_1
R
R
B
Y
L_3
B
Y
L_2
L_1
L_2
L_3
L_1
L_2
L_3

- Lamp L1 is connected between R and R′, L2 between Y and B′ (not Y and Y′) and L3 between B and Y′ (and not B and B′).
- Two sets of star vectors will rotate at unequal speeds if the frequencies of the two machines are different.
- If the incoming alternator is running faster, then voltage star R′Y′B′ will appear to rotate anticlockwise with respect to the bus-bar voltage star RYB at a speed corresponding to the difference between their frequencies.
- The voltage across L1 is RR′ and is seen to be increasing from zero, that across L2 is YB′ which is decreasing, having just passed through its maximum, that across L3 is BY′ which is increasing and approaching its maximum.
- Hence, the lamps will light up one after the other in the order 2, 3, 1 ; 2, 3, 1 or 1, 2, 3.

- Now, suppose that the incoming machine is slightly slower.
- Then the star R′Y′B′ will appear to be rotating clockwise relative to voltage star RYB.
- Here, the voltage across L3 i.e. Y′B is decreasing having just passed through its maximum, that across L2 i.e. YB′ is increasing and approaching its maximum, that across L1 is decreasing having passed through its maximum earlier.
- Hence, the lamps will light up one after the other in the order 3, 2, 1 ; 3, 2, 1, etc. which is just the reverse of the first order.
- Usually, the three lamps are mounted at the three corners of a triangle and the apparent direction of rotation of light indicates whether the incoming alternator is running too fast or too slow.
- Synchronization is done at the moment the uncrossed lamp L1 is in the middle of the dark period.
- It will be noted that when the uncrossed lamp L1 is dark, the other two ‘crossed’ lamps L2 and L3 are dimly but equally bright.
- Hence, this method of synchronizing is also sometimes known as ‘two bright and one dark’ method.

Parallel Operation: Synchroscope



- A synchroscope is a device which shows the correct instant of closing the synchronizing switch. (Split Phase Motor)
- Synchroscope has a pointer which rotates on the dial.
- The pointer rotates anticlockwise if the machine is running slower or it rotates clockwise if the machine is running fast.
- The correct instant of closing syncronizing switch is when the pointer is straight upwards.

Effect of Wrong Synchronization

- Wrong synchronization creates damage to the equipment and power system network.
- So it needs to be done with perfect matching of frequency, phase, phase sequence, and voltage magnitude

Effects of poor frequency matching

- When a generator has to be linked with a group of generators that are operating at the same frequency, it is known that the group of generator's rotating force will be huge in comparison to the one generator alone.
- After the generator is linked with the electrical power system – the frequency or speed of the generator is controlled by the group of generators.
- For instance, the electrical power system will push the new generator into its synchronised rotating condition.

Effect of Wrong Synchronization

- Hence, once the synchronizing switch is closed and if the frequency diverges from the electrical power system frequency, for example, improper matching – the high rotation force from the power system will pull the generator into it.
- As a result of the pulling, sudden deceleration or acceleration may potentially occur to the rotor and hence, the prime mover rotating torque.
- This may cause damage to the rotor and shaft body due to the momentary variation in rotating torque of the prime mover which raises the rotating mass forces on the generator's shaft.
- Moreover, the high torque can potentially lead to an increased current passing through the generator transformer winding and generator itself, which can result in severe damage to the winding.
- If improper generator synchronisation does occur – then, you may have to consider generator rewinding if you notice a drop in equipment performance or spot any faulty parts.

Effect of Wrong Synchronization

Incorrect voltage magnitude matching

- When the incoming voltage magnitude is significantly higher as compared to the running voltage, it will result in high reactive flow from the electrical generator – leading to high mechanical forces on stator winding and damage to the generator shaft.
- Meanwhile, if there's a lower reading of voltage magnitude – it means that there's a weak excitation field.
- But with high currents, the generator's windings are prone to suffering severe damage due to high reverse current.
- Moreover, protection operation may possibly occur during such conditions and disrupt the power generation.
- All in all, incorrect voltage magnitude does have a considerable negative effect on the generator.

Effect of Wrong Synchronization

Incorrect phase matching

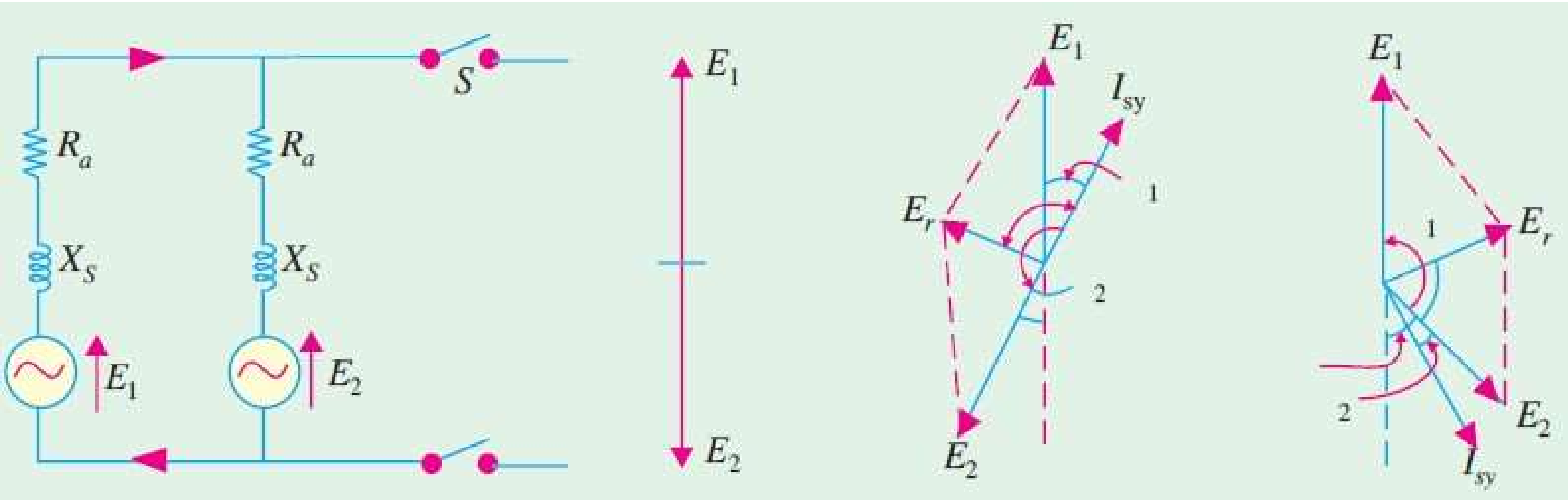
- Without a proper matching of the phase angles – a significant difference will be seen in the stator flux angle and rotor angle.
- The difference will lead to a high transient torque as it synchronises with the grid power supply as a result of a pull force from the huge power system.
- As such, it will lead to further deterioration of the generator windings and rotor mass.
- Adding on, when the equipment is synchronised with incorrect phase angle match with the electrical power system – it will result in a high resultant transient voltage that may cause damage to equipment's insulation.
- Without proper synchronisation – the healthy power system will be negatively affected, resulting in mechanical and electrical transients which may degrade the generator, prime mover, transformers, and other such power system parts.

Synchronizing Current

- Once synchronized properly, two alternators continue to run in synchronism.
- Any tendency on the part of one to drop out of synchronism is immediately counteracted by the production of a synchronizing torque, which brings it back to synchronism.
- When in exact synchronism, the two alternators have equal terminal p.d.'s and are in exact phase opposition, so far as the local circuit is concerned.
- The two e.m.f.s. are in opposition, so far as their local circuit is concerned but are in the same direction with respect to the external circuit.
- Hence, there is no resultant voltage (assuming $E_1 = E_2$ in magnitude) round the local circuit.
- Hence, there is no current circulating round the local circuit.

Synchronizing Current

- But now suppose that due to change in the speed of the governor of second machine, E_2 falls back by a phase angle of α electrical degrees.
- Now, they have a resultant voltage Er, which when acting on the local circuit, circulates a current known as synchronizing current $I_{SY} = Er / Z_S$ where Z_S is the synchronous impedance of the phase windings of both the machines.



Synchronizing Current

- The current I_{SY} lags behind Er by an angle θ given by $\tan\theta = X_S / Ra$ where X_S is the combined synchronous reactance of the two machines and Ra their armature resistance.
- Since Ra is negligibly small, θ is almost 90 degrees.
- So I_{SY} lags Er by 90° and is almost in phase with E_1.
- It is seen that I_{SY} is generating current with respect to machine No.1 and motoring current with respect to machine No. 2 (when the current flows in the same direction as e.m.f., then the alternator acts as a generator, and when it flows in the opposite direction, the machine acts as a motor).
- This current I_{SY} sets up a synchronising torque, which tends to retard the generating machine (i.e. No. 1) and accelerate the motoring machine (i.e. No. 2).
- The opposite will happen if E_2 tends to advance in phase then I_{SY}, being generating current for machine No. 2, tends to retard it and being motoring current for machine No. 1 tends to accelerate it.

- Hence, any departure from synchronism results in the production of a synchronizing current I_{SY} which sets up synchronizing torque.
- This re-establishes synchronism between the two machines by retarding the leading machine and by accelerating the lagging one.
- This current I_{SY},is superimposed on the load currents in case the machines are loaded.

Synchronizing Power

- When machine No. 1 is generating and supplying the synchronizing power = $E_1 I_{SY} \cos \varphi_1$ which is approximately equal to $E_1 I_{SY}$ (φ_1 is small).
- Since $\varphi_1 = (90° - \theta)$, synchronizing power = $E_1 I_{SY} \cos \varphi_1 = E_1 I_{SY} \cos (90° - \theta) = E_1 I_{SY}$, because $\theta \cong 90°$
- This power output from machine No. 1 goes to supply (a) power input to machine No. 2 (which is motoring) and (b) the Cu losses in the local armature circuit of the two machines.
- Power input to machine No. 2 is $E_2\ I_{SY} \cos \varphi_2$ which is approximately equal to $E_2\ I_{SY}$.

Synchronizing Power

- $E_1 I_{SY} = E_2 I_{SY}$ + Cu losses
- Now, let $E_1 = E_2 = E$ (say)
- Then, $Er = 2 E \cos [(180° - \alpha)/2] = 2E \cos [90° - (\alpha/2)]$
- $Er = 2 E \sin \alpha/2 = 2 E \times \alpha/2 = \alpha E$
- $I_{SY} = Er/2Xs$
- Synchronizing power (supplied by machine No. 1) is
- $P_{SY} = E_1 I_{SY} \cos \varphi 1 = E I_{SY} \cos (90° - \theta) = EI_{SY} \sin \theta \cong EI_{SY}$
- $P_{SY} = E.\alpha E/2 ZS = \alpha E^2/2Z_S \cong \alpha E^2/2X_S$
- More accurately, $P_{SY} = \alpha E^2 \sin \theta/2X_S)$
- Total synchronizing power for three phases =
- $3P_{SY} = 3 \alpha E^2/2X_S$ (or $3 \alpha E^2 \sin \theta/2X_S$)

Alternators Connected to Infinite Bus-bars

- If an alternator which is connected to infinite bus-bars, the expression for P_{SY} given earlier is still applicable but impedance (or reactance) of only that one alternator is considered
- $Er = \alpha E$
- $I_{SY} = Er/2Xs$
- $I_{SY} = Er/ZS \cong Er/XS = \alpha E/XS$
- Synchronizing power $P_{SY} = E\ I_{SY} = E.\alpha E/Z_S = \alpha E2/Z_S \cong \alpha E^2/X_S$ — per phase
- Now, $E/Z_S \cong E/X_S$ = S.C. current I_{SC}
- $\therefore P_{SY} = \alpha E^2/X_S = \alpha E.E/X_S = \alpha E.I_{SY}$ —per phase
- Total synchronizing power for three phases = 3 P_{SY}

Synchronizing Torque

- Let T_{SY} be the synchronizing torque per phase in N-m

(*a*) When there are two alternators in parallel

$$\therefore \qquad T_{SY} \times \frac{2\,\pi\,N_S}{60} = P_{SY} \;\; \therefore \;\; T_{SY} = \frac{P_{SY}}{2\,\pi\,N_S/60} = \frac{\alpha E^2/2X_S}{2\pi\,N_S/60} \text{ N-m}$$

$$\text{Total torque due to three phases.} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/2X_S}{2\pi N_S/60} \text{ N-m}$$

(*b*) Alternator connected to infinite bus-bars

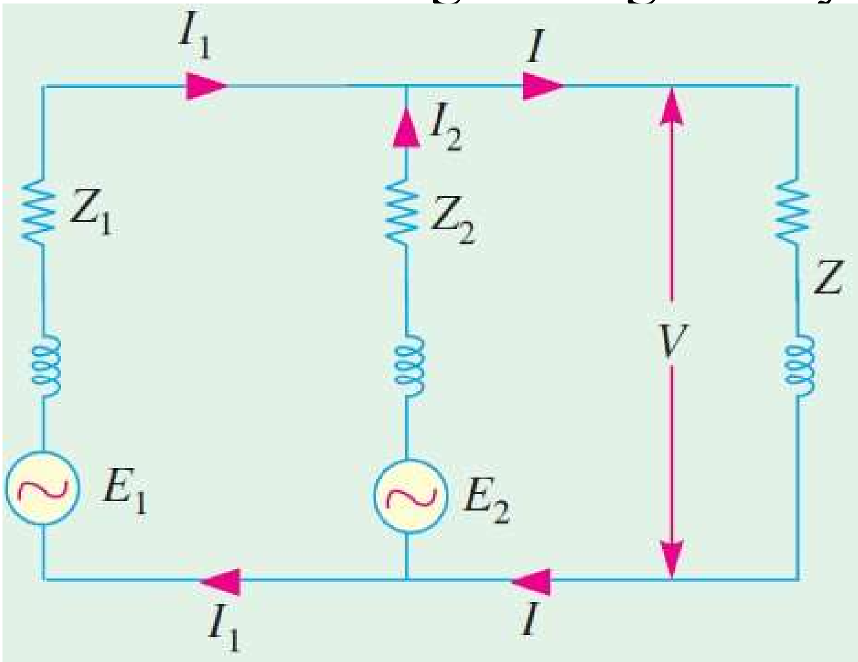
$$T_{SY} \times \frac{2\pi N_S}{60} = P_{SY} \;\; \text{or} \;\; T_{SY} = \frac{P_{SY}}{2\pi N_S/60} = \frac{\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

$$\text{Again, torque due to 3 phase} = \frac{3P_{SY}}{2\pi N_S/60} = \frac{3\alpha E^2/X_S}{2\pi N_S/60} \text{ N-m}$$

where N_S = synchronous speed in r.p.m. $= 120\,f/P$

Load sharing between alternators in parallel

- Consider two alternators with identical speed/load characteristics connected in parallel.
- The common terminal voltage V is given by



$$\mathbf{V} = \mathbf{E}_1 - \mathbf{I}_1\mathbf{Z}_1 = \mathbf{E}_2 - \mathbf{I}_2\mathbf{Z}_2$$

$$\therefore \quad \mathbf{E}_1 - \mathbf{E}_2 = \mathbf{I}_1\mathbf{Z}_1 - \mathbf{I}_2\mathbf{Z}_2$$

$$\text{Also} \quad \mathbf{I} = \mathbf{I}_1 + \mathbf{I}_2 \text{ and } \mathbf{V} = \mathbf{IZ}$$

$$\therefore \quad \mathbf{E}_1 = \mathbf{I}_1\mathbf{Z}_1 + \mathbf{IZ} = \mathbf{I}_1(\mathbf{Z} + \mathbf{Z}_1) + \mathbf{I}_2\mathbf{Z}$$

Load sharing between alternators in parallel

$$E_2 = I_2Z_2 + IZ = I_2(Z + Z_2) + I_1Z$$

$$I_1 = \frac{(E_1 - E_2)Z + E_1Z_2}{Z(Z_1 + Z_2) + Z_1Z_2}$$

$$I_2 = \frac{(E_2 - E_1)Z + E_2Z_1}{Z(Z_1 + Z_2) + Z_1Z_2};$$

$$I = \frac{E_1Z_2 + E_2Z_1}{Z(Z_1 + Z_2) + Z_1Z_2}$$

$$V = IZ = \frac{E_1Z_2 + E_2Z_1}{Z_1 + Z_2 + (Z_1Z_2/Z)}; I_1 = \frac{E_1 - V}{Z_1}; I_2 = \frac{E_2 - V}{Z_2}$$

Load sharing between alternators in parallel

Using Admittances

The terminal Voltage may also be expressed in terms of admittances as shown below:

$$V = IZ = (I_1 + I_2)Z \qquad \therefore\ I_1 + I_2 = V/Z = VY$$

Also $I_1 = (E_1 - V)/Z_1 = (E_1 - V)Y_1$; $\qquad I_2 = (E_2 - V)/Z_2 = (E_2 - V)Y_2$

$\therefore \qquad I_1 + I_2 = (E_1 - V)\,Y_1 + (E_2 - V)Y_2$

From Eq. (*i*) and (*ii*), we get

$$VY = (E_1 - V)Y_1 + (E_2 - V)Y_2 \quad \text{or} \quad V = \frac{E_1 Y_1 + E_2 Y_2}{Y_1 + Y_2 + Y}$$

P1: Two identical, three phase alternators operating in parallel share equally a load of 1000 kW at 6600 V and 0.8 p.f. lag. The field excitation of the first machine is adjusted so that the armature is 50 A at a lagging p.f. Determine (a) armature current od second alternator, and (b) the power factor at which each machine operates.

$$P_1 = \frac{1}{2} P_{Load} = \frac{1}{2} \times 1000 = 500 \text{ kW}$$

$$\sqrt{3}\, V_L I_{a_1} \cos\phi_1 = P_1$$

$$\sqrt{3} \times 6600\, I_{a_1} \cos\phi_1 = 500 \times 10^3$$

$$I_{a_1} \cos\phi_1 = \frac{500 \times 10^3}{\sqrt{3} \times 6600} = 43.74 \text{ A}$$

For an armature current of $I_{a_1} = 50$ A, the power factor of alternator 1 is

$$\cos\phi_1 = \frac{43.74}{I_{a_1}} = \frac{43.74}{50}$$

$$= 0.8748 \text{ (lagging)}$$

$$\phi_1 = -28.98^\circ$$

$$\mathbf{I}_{a_1} = I_{a_1} \angle -\phi_1 = 50 \angle -28.98^\circ$$

$$= 43.74 - j\,24.22 \text{ A}$$

Let 1 be the total load current at power factor 0.8 lagging.

$$\sqrt{3}\ V_L\ I \cos\phi = P_{load}$$

$$\sqrt{3} \times 6600\ I \times 0.8 = 1000 \times 10^3$$

$$I = \frac{1000 \times 10^3}{\sqrt{3} \times 6600 \times 0.8} = 109.35 \text{ A}$$

$$\mathbf{I} = 109.35 \angle -\cos^{-1} 0.8$$

$$= 109.35 \angle -36.87^\circ \text{ A}$$

$$= 87.48 - j\,65.61 \text{ A}$$

$$\mathbf{I}_{a_1} + \mathbf{I}_{a_2} = \mathbf{I}$$

$$\mathbf{I}_{a_2} = \mathbf{I} - \mathbf{I}_{a_1}$$

$$= (87.48 - j\,65.61) - (43.74 - j\,24.22)$$

$$= 43.74 - j\,41.39$$

$$= 60.22 \angle -43.42^\circ \text{ A}$$

Power factor of the second machine $\cos\phi_2 = \cos 43.42^\circ = 0.7263$ (lagging).

P2: Two 3-phase 6.6 kV, star connected alternators supply a load of 3000 kW at 0.8 p.f. lag. The synchronous impedance per phase of machine A is 0.5 + j 10 Ω and of machine B is 0.4 + j 12 Ω. The excitation of machine A is adjusted so that it delivers 150 A at a lagging p.f. load, and the governors are so adjusted that the load is equally shared between the machines. Determine the current, powe factor, induced emf and load angle of each machine.

SOLUTION. For machine 1, $I_{a_A} = 150$ A

$$\sqrt{3} \times 6.6 \times 10^3 \, I_{a_1} \cos \phi_A = \frac{1}{2} \times 3000 \times 10^3$$

$$\cos \phi_A = \frac{1500 \times 10^3}{\sqrt{3} \times 6.6 \times 10^3 \times 150} = 0.8748 \text{ (lagging)}$$

$$\phi_A = 28.98°$$

$$\mathbf{I}_{a_A} = I_{a_A} \angle -\phi_1 = 150 \angle -28.98°$$

$$= 131.2 - j\,72.68 \text{ A}$$

Total current

$$I = \frac{P_{3\phi}}{\sqrt{3}\ V_L \cos\phi} = \frac{3000 \times 10^3}{\sqrt{3} \times 6.6 \times 10^3 \times 0.8} = 328\ \text{A}$$

$$\mathbf{I} = I \angle{-\phi} = 328 \angle{-\cos^{-1} 0.8} = 328 \angle{-36.87°}\ \text{A}$$

$$= 262.4 - j\,196.8\ \text{A}$$

$$\mathbf{I}_{a_A} + \mathbf{I}_{a_B} = \mathbf{I}$$

$$\mathbf{I}_{a_B} = \mathbf{I} - \mathbf{I}_{a_A}$$

$$= (262.4 - j\,196.8) - (131.2 - j\,72.68)$$

$$= 131.2 - j\,124.12 = 180.6 \angle{-43.14°}\ \text{A}$$

Power factor of the second machine

$$\cos\phi_B = \cos(-43.14°) = 0.7264\ \text{lagging}$$

$$\mathbf{Z}_A = 0.5 + j\,10 = 10.01 \angle{87.14°}\ \Omega$$

$$\mathbf{E}_{a_{A}p} = \mathbf{V}_p + \mathbf{I}_{a_A} \mathbf{Z}_A$$

$$= \frac{6600}{\sqrt{3}} + (150 \angle -28.98^\circ)(10.01 \angle 87.14^\circ)$$

$$= 3810.5 + 1501.5 \angle 58.16^\circ$$

$$= 3810.5 + 792 + j\,1275.6$$

$$= 4602 + j\,1275.6 = 4776 \angle 15.49^\circ \text{ V}$$

Line value of e.m.f of machine A

$$E_{a_A L} = \sqrt{3}\, E_{a_A p} = \sqrt{3} \times 4776 = 8272 \text{ V}$$

$$\mathbf{Z}_B = 0.4 + j\,12 = 12.007 \angle 88.1^\circ\ \Omega$$

$$\mathbf{E}_{a_B p} = \mathbf{V}_p + \mathbf{I}_{a_B} \mathbf{Z}_B$$

$$= 3810.5 + (180.6 \angle -43.14^\circ)(12.007 \angle 88.1^\circ)$$

$$= 3810.5 + 2168.5 \angle 44.96^\circ$$

$$= 3810.5 + 1534.4 + j\,1532.3$$

$$= 5344.9 + j\,1532.3 = 5560.2 \angle 16^\circ \text{ V}$$

Line value of e.m.f. of machine $B = \sqrt{3}\, E_{a_B p} = \sqrt{3} \times 5560.2 = 9631$ V

P3: A 3,000-kVA, 6-pole alternator runs at 1000 r.p.m. in parallel with other machines on 3,300-V bus-bars. The synchronous reactance is 25%. Calculate the synchronizing power for one mechanical degree of displacement and the corresponding synchronizing torque.

P4: Two single-phase alternator operating in parallel have induced e.m.fs on open circuit of 230 ∠0° and 230 ∠10° volts and respective reactances of j2 Ω and j3 Ω. Calculate (i) terminal voltage (ii) currents and (iii) power delivered by each of the alternators to a load of impedance 6 Ω (resistive).

P5: A 3-phase 400 kVA, 6.6 kV, 1500 rpm., 50 Hz alternator is running in parallel with infinite bus bars. Its synchronous reactance is 25%. Calculate (i) for no load (ii) full load 0.8 p.f. lagging the synchronizing power and torque per unit mechanical angle of displacement.

Hint: Find I, Vph, IXs= 25% of Vph, Find Xs.

α (mech) = 1: α (elect) = 1 × (P/2), α (elect) × π/180 elect. Radian

No Load: $P_{SY} = \alpha Vph^2/X_S$, **F.L. 0.8 p.f.:** $P_{SY} = \alpha EV/X_S$.

AC Machines: Synchronous Machine

Synchronous Motor

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Synchronous Motor

❖ A given synchronous machine may be used, as an alternator, when driven mechanically or as a motor, when driven electrically.

❖ Some characteristic features of synchronous motor are";

1. It runs either at synchronous speed or not at all i.e. while running it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because $Ns = 120f / P$).

2. It is not inherently self-starting. It has to be run upto synchronous (or near synchronous) speed by some means, before it can be synchronized to the supply.

3. It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.

Operating Principle of Synchronous Motor

- Suppose the stator poles are at a particular instant situated at points A and B.
- The two similar poles, N (of rotor) and N_S (of stator) as well as S and S_S will repel each other, with the result that the rotor tends to rotate in the anticlockwise direction.

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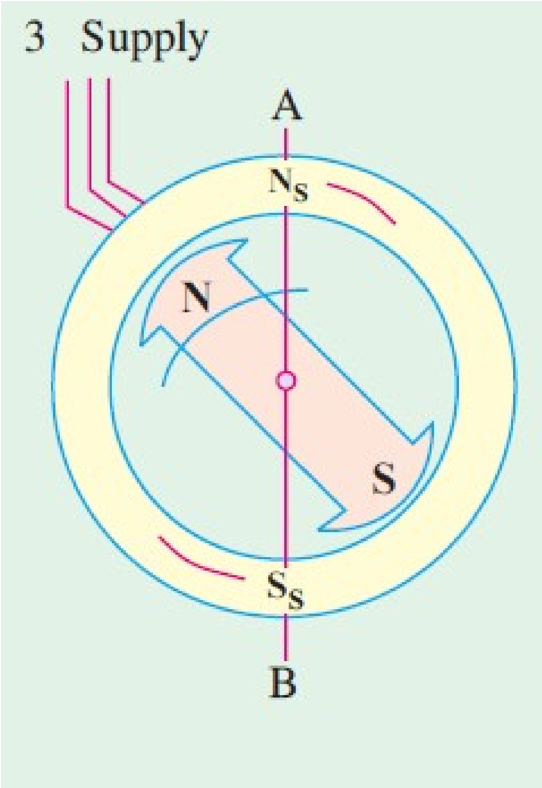
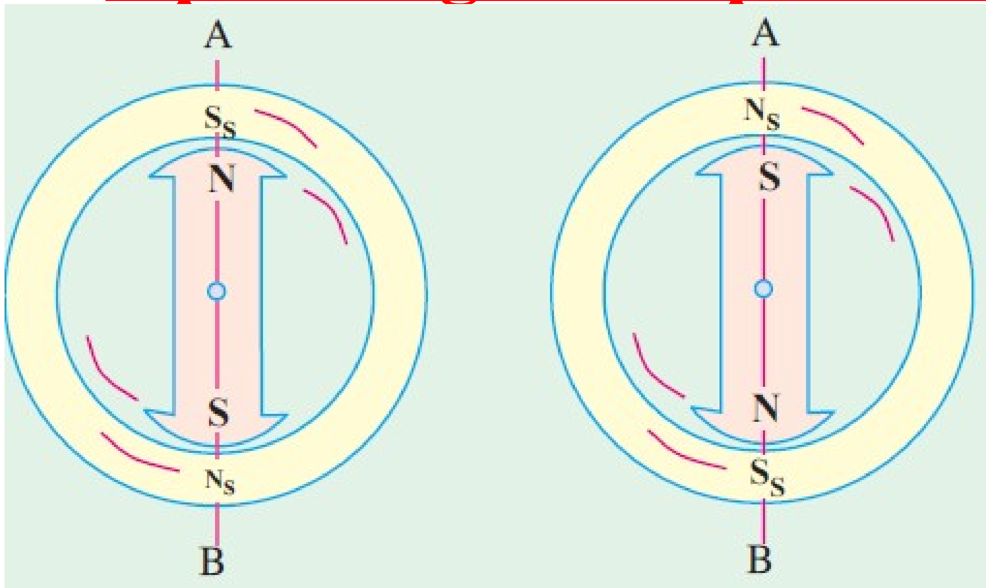
- But half a period later, stator poles, having rotated around, interchange their positions i.e. N_S is at point B and S_S at point A.
- Under these conditions, N_S attracts S and S_S attracts N. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction).

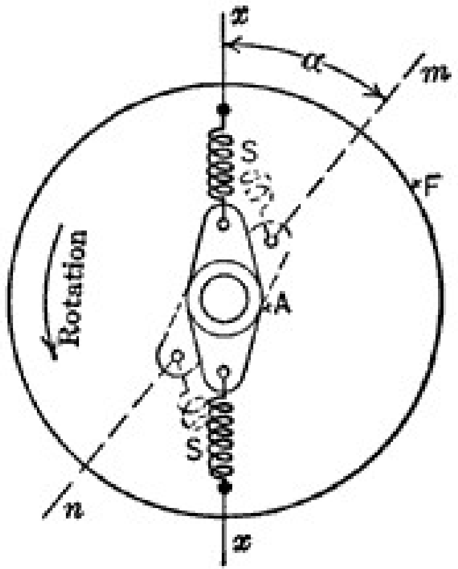


Operating Principle of Synchronous Motor

- Due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing i.e., in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction.
- Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.
- Synchronous motor is not self starting.
- Assume that the stator and rotor poles are attracting each other.
- Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions.
- Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque i.e., clockwise torque.

Operating Principle of Synchronous Motor





Mechanical analogies:

✓the rotor and stator are connected by a magnetic spring.

✓The rotor has a magnetic field (like a simple bar magnet)

✓the stator has a magnetic field from the currents flowing in the windings

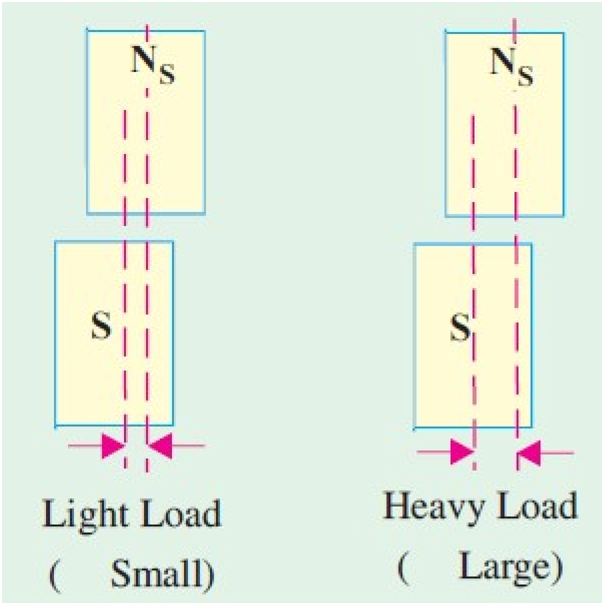
✓If the machine is operating as a motor, the spring is stretched, and the stator magnet is pulling to rotor magnet toward it and around

Starting of Synchronous Motor

- Three-phase supply is fed to stator.
- The rotor (which is as yet unexcited) is speeded up to synchronous
- / near synchronous speed by some arrangement and then excited by the d.c. source.
- The moment this (near) synchronously rotating rotor is excited, it is magnetically locked into position with the stator i.e., the rotor poles are engaged with the stator poles and both run synchronously in the same direction.
- It is because of this interlocking of stator and rotor poles that the motor has either to run synchronously or not at all.
- The synchronous speed is given by the usual relation N_S=120 f / P.
- However, it is important to understand that the arrangement between the stator and rotor poles is not an absolutely rigid one.
- As the load on the motor is increased, the rotor progressively tends to fall back in phase (but not in speed) by some angle but it still continues to run synchronously.

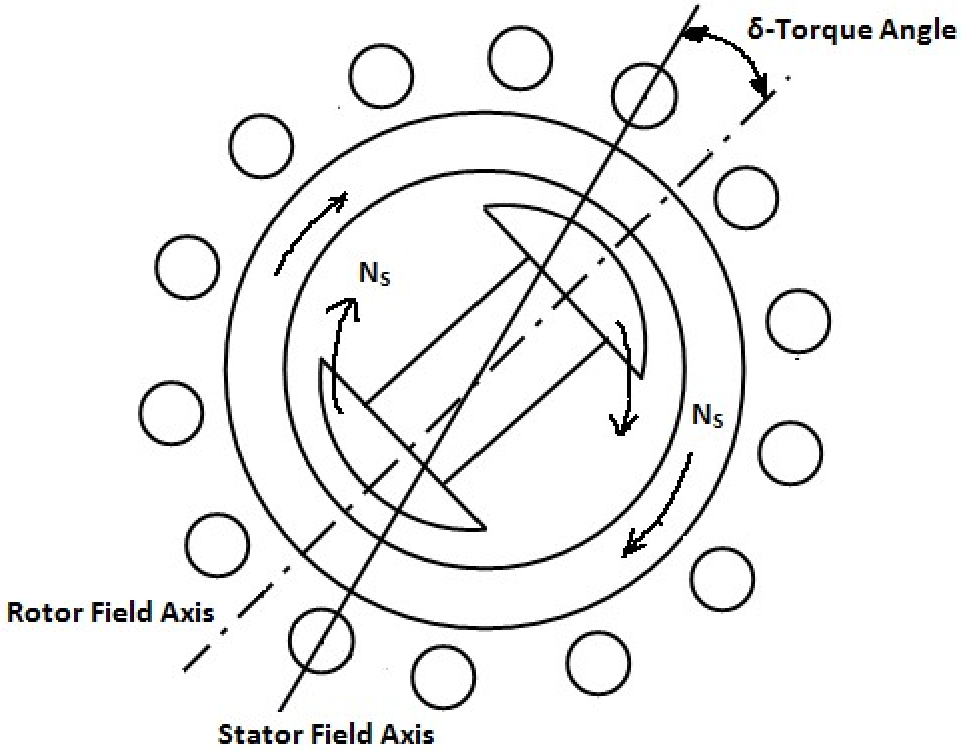
Starting of Synchronous Motor

- The value of this load angle or coupling angle depends on the amount of load to be met by the motor.
- In other words, the torque developed by the motor depends on this angle.
- When motor is loaded, it's rotor slightly falls behind, the load angle being a measure of the torque transmitted.
- It is clear that unless motor is so heavily loaded as to break the
- coupling, both stator poles and rotor must run at exactly the same speed.



Torque Angle of Synchronous Motor

- Torque angle δ is the angle between Rotor flux and Stator fluxes, both are rotating at synchronous speed.
- It is noted that for synchronous motors the rotor flux axis lags the stator flux axis by the angle δ



Phasor Diagram of Synchronous Motor

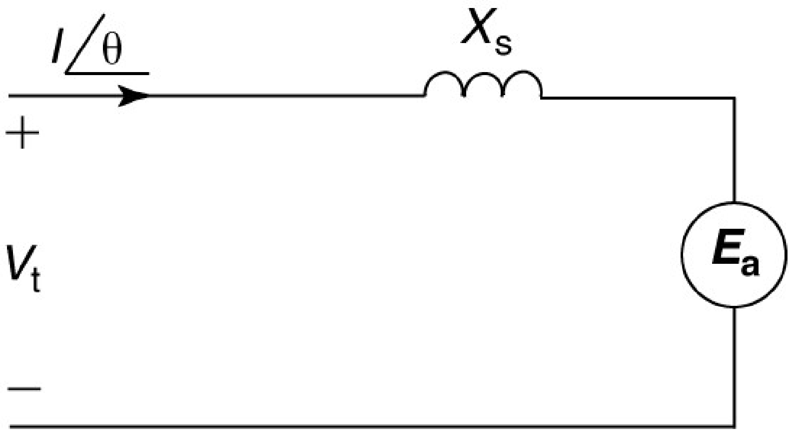


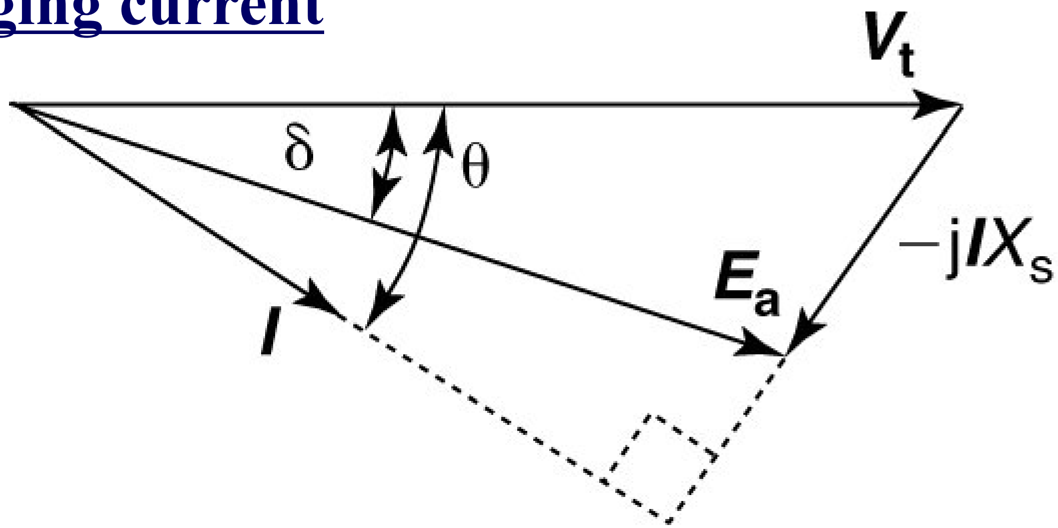
Figure 1: Per-phase equivalent circuit for a synchronous motor.

Vt=Ea+jIXs => Ea=Vt−jIXs

Phasor Diagram for Lagging current

$E_a \cos\delta < V_t$

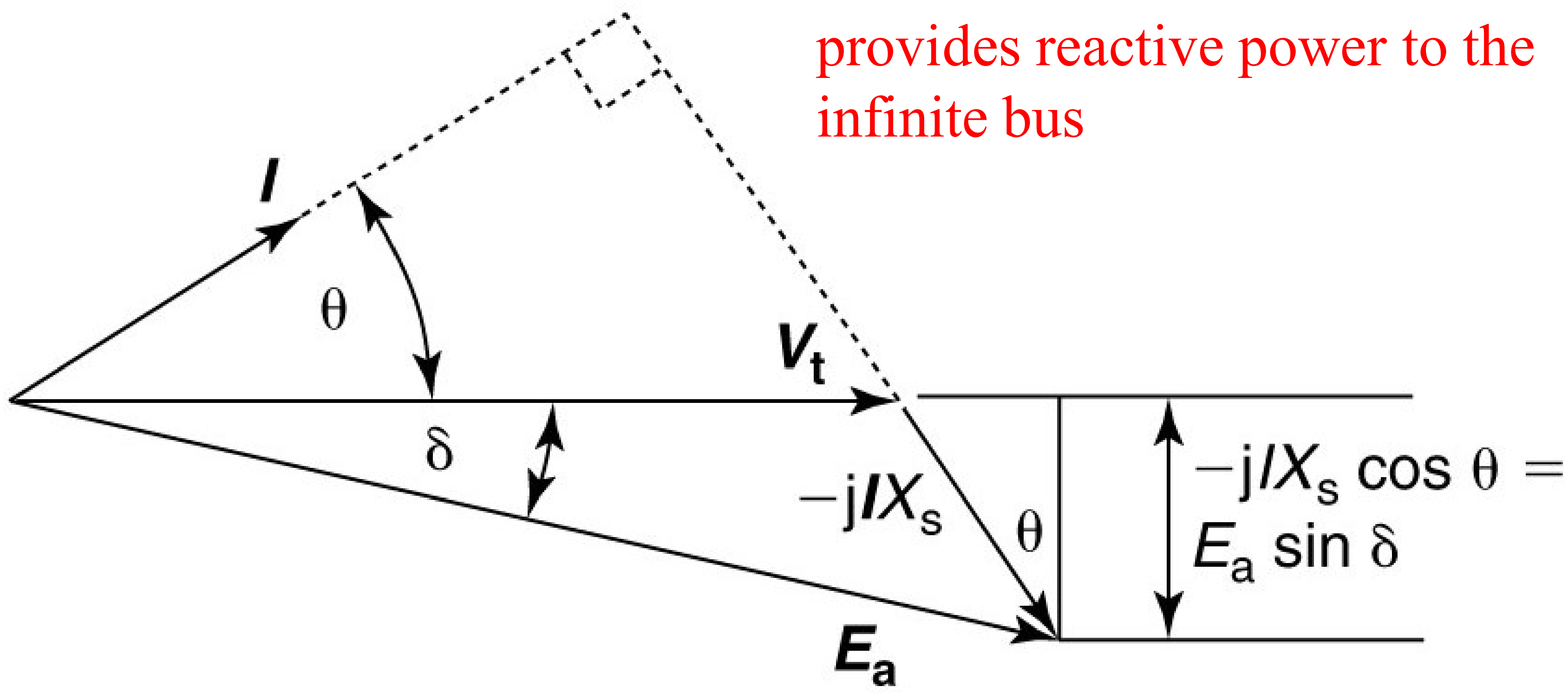
The motor is operating in an under-excited condition, drawing reactive power from the infinite bus



Phasor Diagram for Leading current

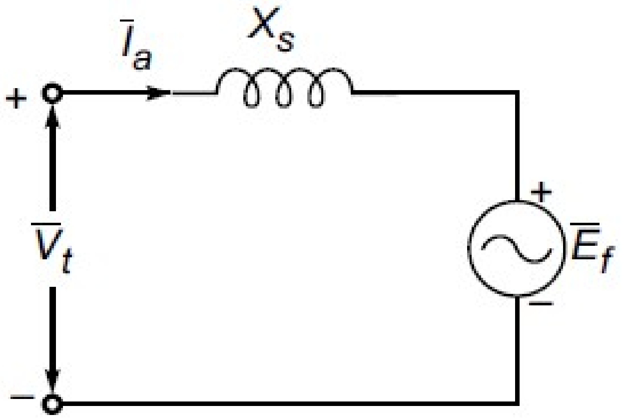
The motor is accepting leading current, it is acting like a capacitive load
The generated voltage still lags the terminal voltage by the power angle, but the magnitude of the generated voltage is now greater than the terminal voltage: $E_a \cos \delta > V_t$

The motor is overexcited and provides reactive power to the infinite bus

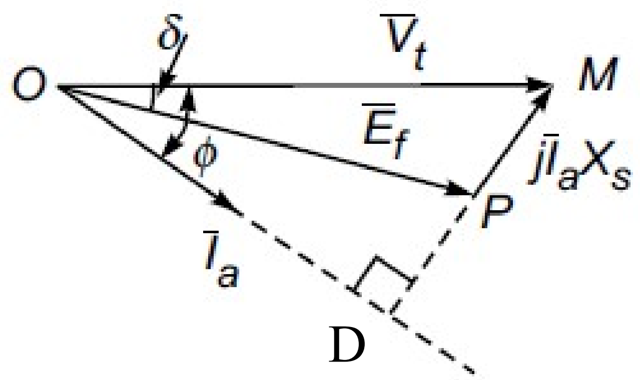


- When the synchronous motor operates at lagging current, it is in an under excited state.
- This means that the field excitation is lower than the required value, resulting in a lagging power factor.
- The motor absorbs reactive power from the system, which can decrease the overall power factor.
- At leading current, the synchronous motor operates in an overexcited state.
- Motor’s field excitation is higher than the required value, resulting in a leading power factor.
- The motor can supply reactive power to the system and improve the overall power factor.
- A leading power factor signifies good power factor correction and the ability to supply reactive power to the system.
- On the other hand, a lagging power factor indicates a need for reactive power compensation.
- The power factor influences the motor’s efficiency, voltage regulation, and overall system stability.

Power Angle Characteristics (P vs δ): Non-salient Pole



(b) Motoring mode $\bar{E}_f = \bar{V}_t - j\bar{I}_a X_s$



(d) Motoring mode

∠MOD =φ
∠MOP =δ
∠ODM =90^0

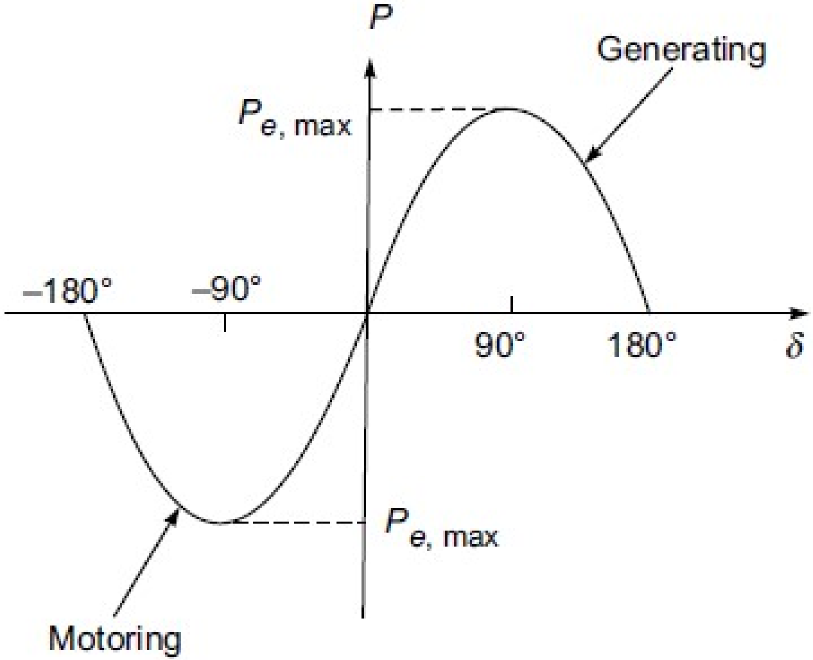
- Fig. above shows the circuit diagrams and phasor diagrams of a synchronous machine in motoring mode
- The machine is connected to infinite bus-bars of voltage V_t.
- It is easily observed from the phasor diagrams that in motoring mode, the excitation emf E_f lags V_t by angle δ.
- ∠OMP=180-(90+φ)= 90- φ
- From the phasor triangle OMP: OP/(sin ∠OMP)= MP/(sin ∠MOP)

$$\frac{E_f}{\sin(90 \pm \phi)} = \frac{I_a X_s}{\sin \delta}\ ; \begin{array}{l}(90^\circ + \phi), \text{generating} \\ (90^\circ - \phi), \text{motoring}\end{array}$$

$$I_a \cos \phi = \frac{E_f}{X_s} \sin \delta$$

Power Angle Characteristics (P vs δ): Non-salient Pole

❖ Multiplying both sides by V_t :



Power-angle characteristic

$$I_a \cos\phi = \frac{E_f}{X_s} \sin\delta$$

$$V_t I_a \cos\phi = \frac{V_t E_f}{X_s} \sin\delta$$

$$P_e = \frac{V_t E_f}{X_s} \sin\delta$$

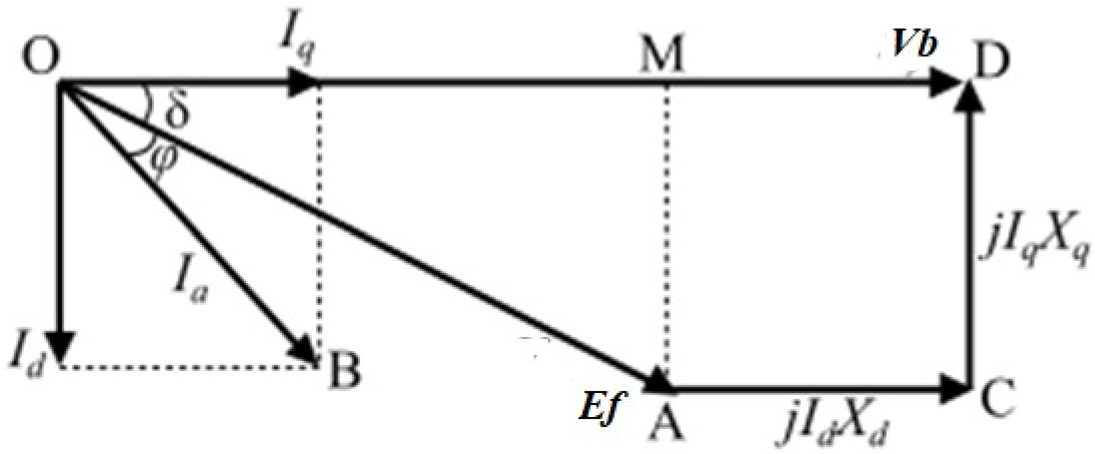
$$P_{e,\max} = \frac{V_t E_f}{X_s}$$

❖ $P_e = V_t I_a \cos\varphi$ = electrical power exchanged with the bus-bars

❖ δ = Angle between E_f and V_t and is called the power angle

❖ The relationship of P_e vs δ is known as the power-angle characteristic of the machine and is plotted for given V_t and E_f.

Power Angle Characteristics (P vs δ): Salient Pole



OD = V_b
MD = OD-OM = AC
AC = I_dX_d
OM = E_f cos δ
MA = E_f sin δ = DC
DC = I_qX_q

- The resistance R_a of the armature can be neglected since it has 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 R_a is shown above.
- Power = VI cos φ= IVcos φ= Current x Component of voltage in phase with current
- $Pe = I_d MA + I_q OM = I_d E_f \sin\delta + I_q E_f \cos\delta$
- $I_d X_d = AC = MD = OD\text{-}OM = V_b - E_f \cos\delta \quad \Rightarrow \quad I_d = \dfrac{V_b - E_f\cos\delta}{X_d}$
- $I_q X_q = DC = MA = E_f \sin\delta \quad \Rightarrow \quad I_q = \dfrac{E_f\sin\delta}{X_q}$

Power Angle Characteristics (P vs δ): Salient Pole

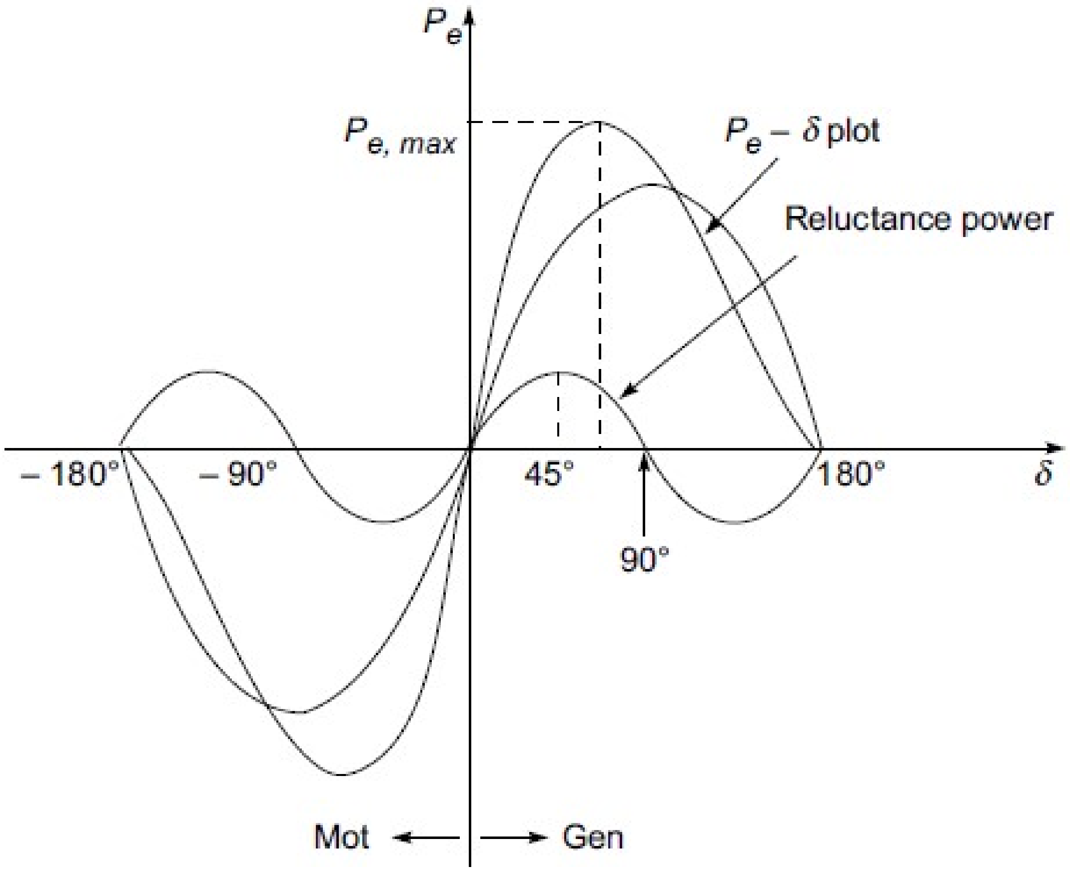
$$P_e = \frac{V_b E_f}{X_d}\sin\delta + \frac{V_b^{\,2}}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

P3φ=3P1φ

✓The second term in above Eq. is known as the reluctance power.

✓The reluctance power varies as sin 2 δ with a maximum value at δ = 45° .

✓This term is independent of field excitation and would be present even if the field is unexcited



A synchronous motor is drawing 50 A from 400 V, three-phase supply at unity pf with a field current of 0.9 A. The synchronous reactance of the motor is 1.3 Ω. (a) Find the power angle. (b) With the mechanical load remaining constant, find the value of the field current which would result in 0.8 leading power factor. Assume linear magnetization.

$$V_t = \frac{400}{\sqrt{3}} = 231\angle 0 \text{ A}$$

$$\text{pf} = \text{unity, pf angle, } \theta = 0°,\ \overline{I_a} = 50\angle 0°$$

$$\overline{E}_f = \overline{V_t} - j\,\overline{I_a}\,X_s = 231 - j\,50 \times 1.3 = 231 - j\,65 = 240\angle{-15.7°} \text{ V}$$

$$\delta = 15.7°,\ E_f \text{ lags } V_t \text{ (motor)}$$

As there is no ohmic loss

$$P_e = P_m = V_t I_a \cos\theta$$

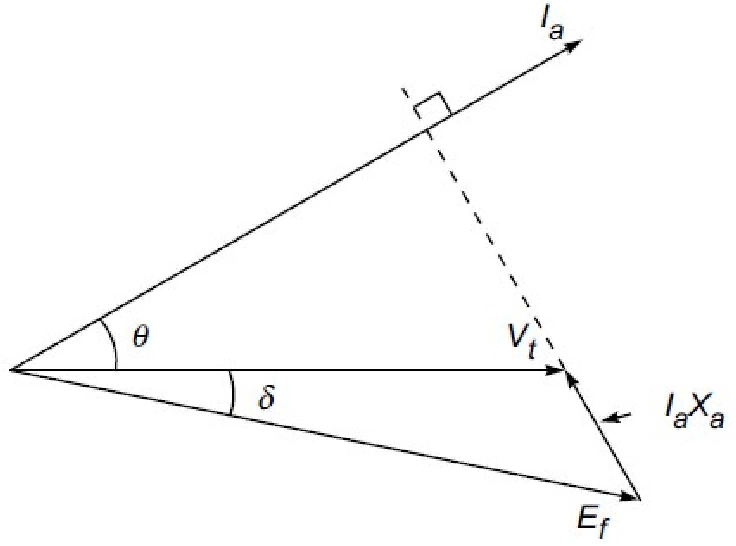
$$P_m = V_t I_a \cos\theta = 231 \times 50 \times 1 = 11550 \text{ W}$$

$$11550 = 231 \times I_a \times 0.8$$

$$I_a = 62.5\text{ A}$$

$$I_a X_s = 62.5 \times 1.3 = 81.25\text{ V}$$

$$\theta = \cos^{-1} 0.8 = 36.9° \text{ leading}$$



$$E_f^2 = (V_t \cos\theta)^2 + (V_t \sin\theta + I_a X_s)^2$$

$$= (184.8)^2 + (219.85)^2$$

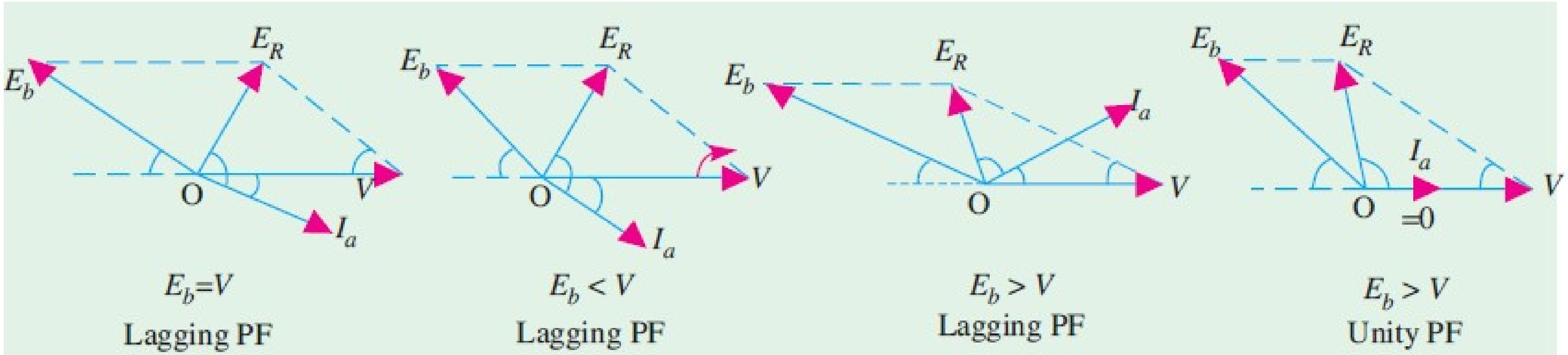
$$E_f = 287.2\text{ V}$$

On linear magnetization basis

$$I_f = 0.9 \times \frac{287.2}{240} = 1.077\text{ A}$$

Effect of Change in Excitation

- A synchronous motor is said to have normal excitation if $E_f = V$.
- If field excitation is such that $E_f < V$, the motor is said to be under-excited.
- In both these conditions, it has a lagging power factor i.e I lags V
- If d.c. field excitation is such that $E_f > V$, then motor is said to be over-excited and draws a leading current
- There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity.



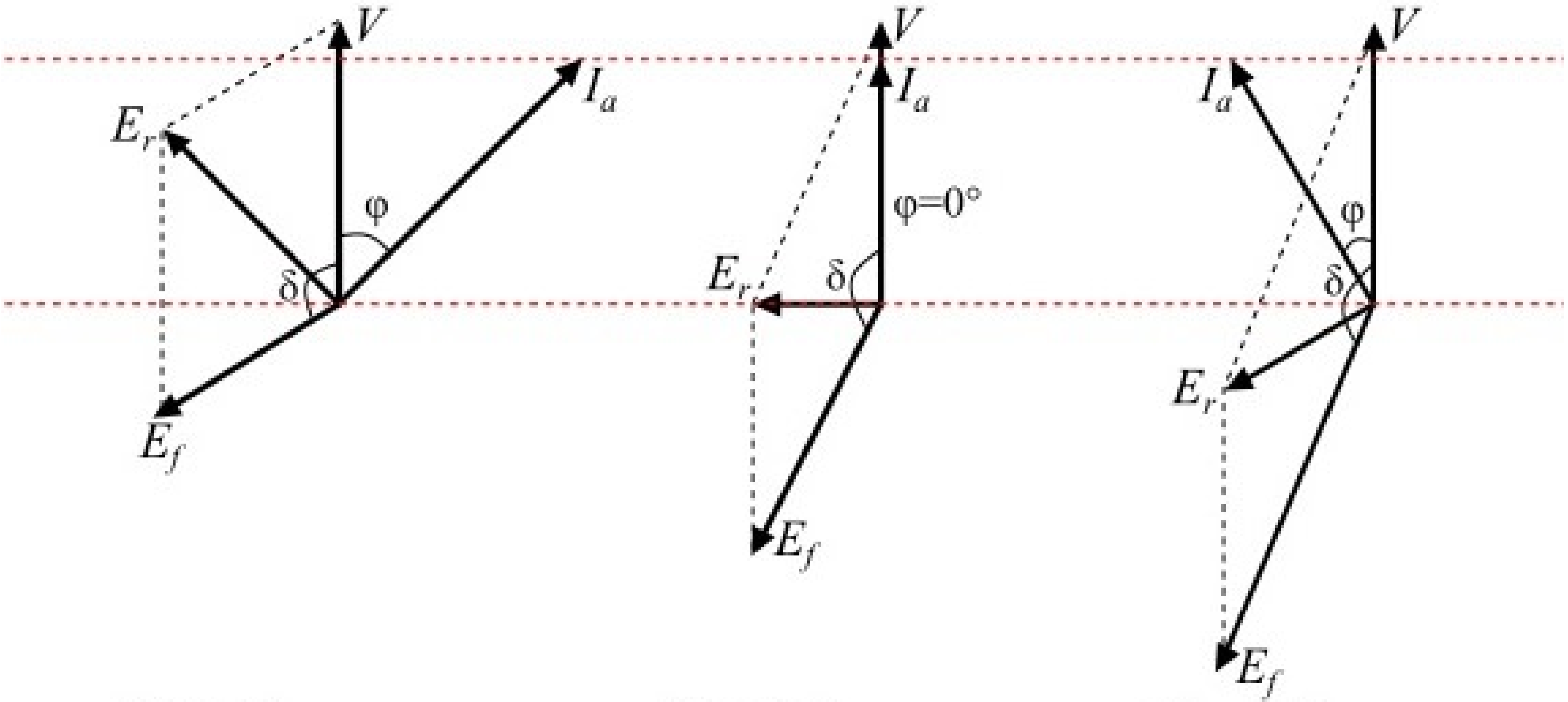


Figure-1 Under-Excitation	Figure-2 Normal-Excitation	Figure-3 Over-Excitation
$E_f < V$	**$E_f = V$**	**$E_f > V$**
I_a lags V	**I_a & V In phase**	**I_a leadss V**
p.f. is lagging	**p.f. is unity (max)**	**p.f. is leading**
Consumes Q	**Q = 0**	**Supplies Q**
I_a is more	**I_a is minimum**	**I_a is more**

V Curve of Synchronous Motor

- *The graphs plotted between armature current (I_a) and field current (I_f) for different constant loads are known as the V curves of the synchronous motor.*
- The power factor of a synchronous motor can be controlled by changing the field excitation, i.e., by variation of field current (I_f).
- Also, the armature current (I_a) changes with the change in the excitation or field current (I_f).
- Now, let us assume that the synchronous motor is operating at no-load.
- If the field current (I_f) is increased from a small value, the armature current (I_a) decreases until I_a becomes minimum.
- The power factor of the motor corresponding to this minimum armature current is unity.
- Up to the point of minimum armature current, the motor was operating at lagging power factor.

V Curve of Synchronous Motor

- If a graph is plotted between armature current (I_a) and field current (I_f) at noload, the lowest curve in Figure-1 is obtained.
- In order to obtain a family of curves as shown in Figure-1, the above procedure is to be repeated for various increased loads.

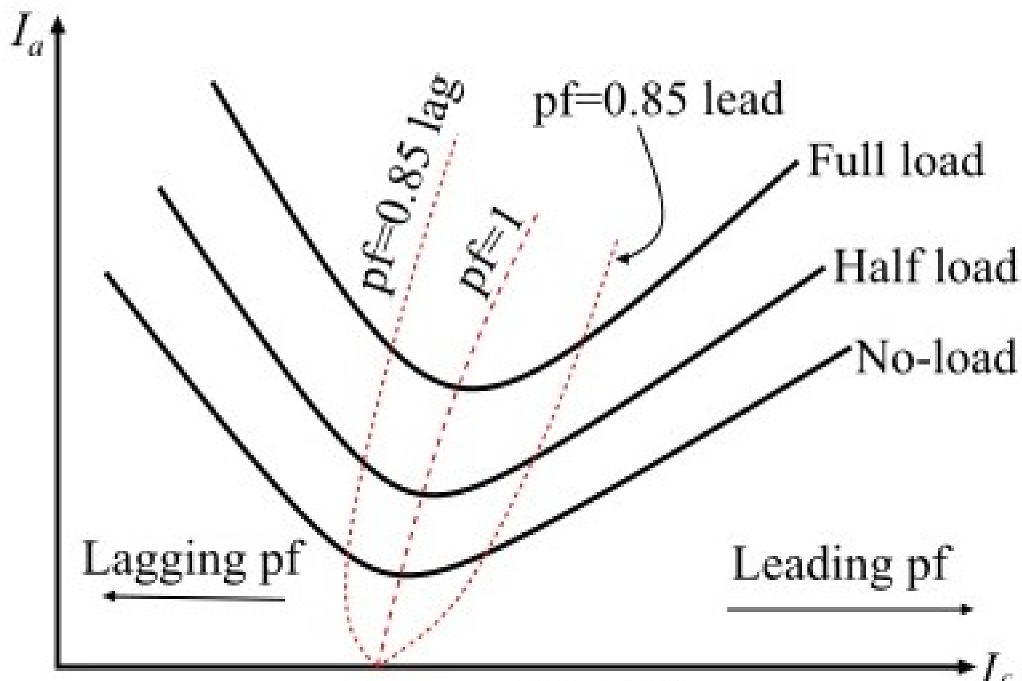


Figure-1

Inverted V Curve of Synchronous Motor

- *Inverted V curves of a synchronous motor are defined as the graphs plotted between power factor and field current (If) of the motor.*
- The peak point on each of these curves indicates unity power factor.
- From the curves, it can be seen that the field current (I_f) for unity power factor at full-load is greater than the field current (I_f) for unity power factor at no-load.

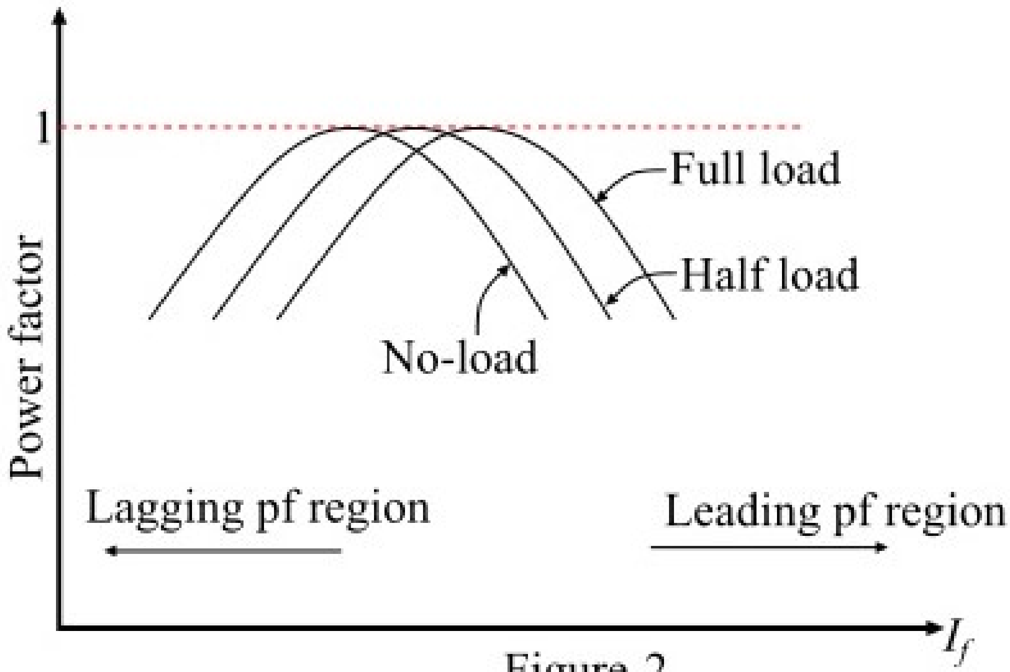


Figure-2

Power Factor Correction Applications

- Most of the industrial loads such as induction motors are inductive in nature and hence have low lagging power factor.
- Around 60% of the utility load consists of motors and hence the overall power factor of the power system is low.
- The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilization devices.
- The power factor can be improved by connecting the synchronous motor operated in an overexcited mode in parallel with the industrial loads operating at lagging power factor.
- Synchronous motors takes a leading current which partly neutralizes the lagging reactive component of the load.

❖ Application of synchronous motor as compensation equipment in a system has the following effects:

(1) Improvement in power factor of the system
(2) Reduction in reactive component of line current.
(3) Maintenance of voltage profile within limit.
(4) Reduction of I^2R losses in the line and other equipment due to reduction in current.
(5) Reduction in investment in the system per kW of load supplied.
(6) Decrease in kVA loading of generators, transformers and other equipments. This decrease in kVA loading may relieve an over load conditions or release capacity of load growth.
(7) Reduction in kVA demand charges for large consumers.

AC Machines: Synchronous Machine

Hunting & Sudden Short Circuit

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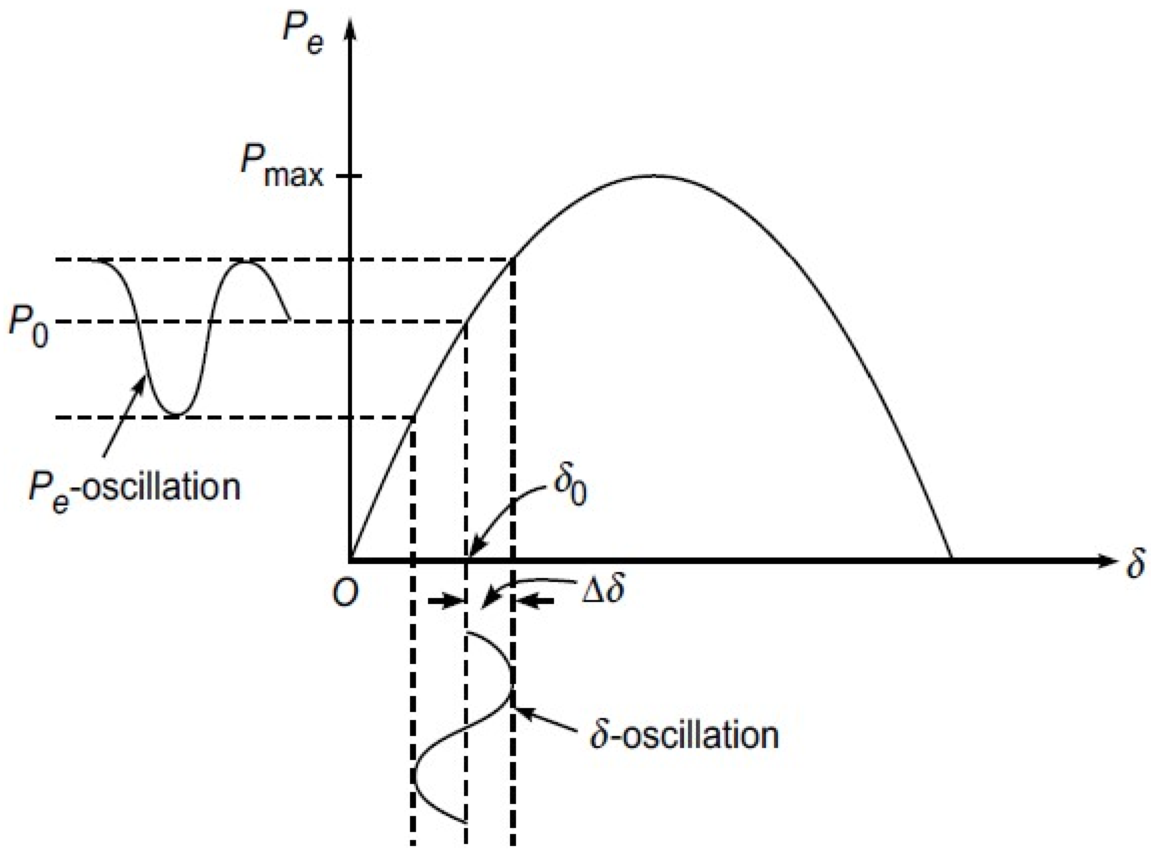
VSSUT, Burla

Hunting in Synchronous Machines

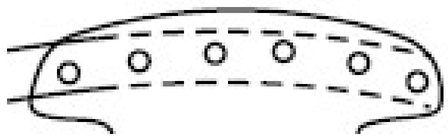
- When a synchronous machine is operating at steady load indicated by point (P_0, δ_0) on the P – δ characteristic.
- Certain disturbances are bound to occur on electrical and mechanical parts of the machine.

- These disturbances are:
  - ✓ Sudden Change in Load (electrical and mechanical)
  - ✓ Sudden Change in Field Current
  - ✓ Presence of Harmonic variations in load and prime mover torque



- A change in rotor angle $\Delta\delta$ caused by a disturbance produces synchronizing power (and associated synchronizing torque) which is proportional to $\Delta\delta$
- The synchronizing torque acts on the drive machine or machine-mechanical load inertia to counter the change $\Delta\delta$
- The system is set into oscillations of δ and Pe about (P_0, δ_0)
- The δ-variations are reflected in the speed variations i.e. the rotor oscillates following a disturbance
- As the system friction is quite small these oscillations are slow to decay out.
- This Oscillatory behaviour of the synchronous machine about the operating point known as hunting which is highly undesirable as it causes shaft fatigue.
- These oscillations must be damped out fast.
- A small amount of damping, contributed by system losses (both mechanical and electrical), is always present in the machine but this is insufficient to kill hunting.
- Additional damping must therefore be introduced in the machine.

Damper Winding



- Additional damping is provided in the salient pole synchronous machine by means of damper bars located in the main poles of the machine and short-circuited through round rings at both ends.
- As the rotor oscillates, the damper bars have a relative movement with respect to the air-gap flux which causes induction of emfs and flow of currents in these damper bars.
- The torque created by the damper bar currents as per Lenz's law always opposes the relative motion.
- Oscillatory motion of the rotor about the operating point is considerably reduced in amplitude and the rotor quickly returns to the steady position.
- These short-circuited bars are known as damper winding or ammortisseur winding.
- They also provide a starting torque for the synchronous motors which is not self-starting.
- Therefore, the damper winding serves the dual purpose

Sudden Short Circuit in Synchronous Machines

- Majority of faults/disturbences occurring in practice on synchronous machines are unsymmetrical between phases.
- Symmetrical faults are although rarer, it is more severe but easy to analyse.
- Short-circuit test: (all three terminals of an unloaded synchronous generator are short-circuited simultaneously) is a well established method of checking its transient characteristics.
- If speed is not constant during the transient: A step by step method is required to solve the non-linear equations.
- If speed is assumed constant during the transient: The non-linear equations are linearized and solved by means of superposition and Laplace transform
- Superposition: The voltages and currents after the short-circuit are equal to the sum of the original values and the changes resulting from the short-circuit.

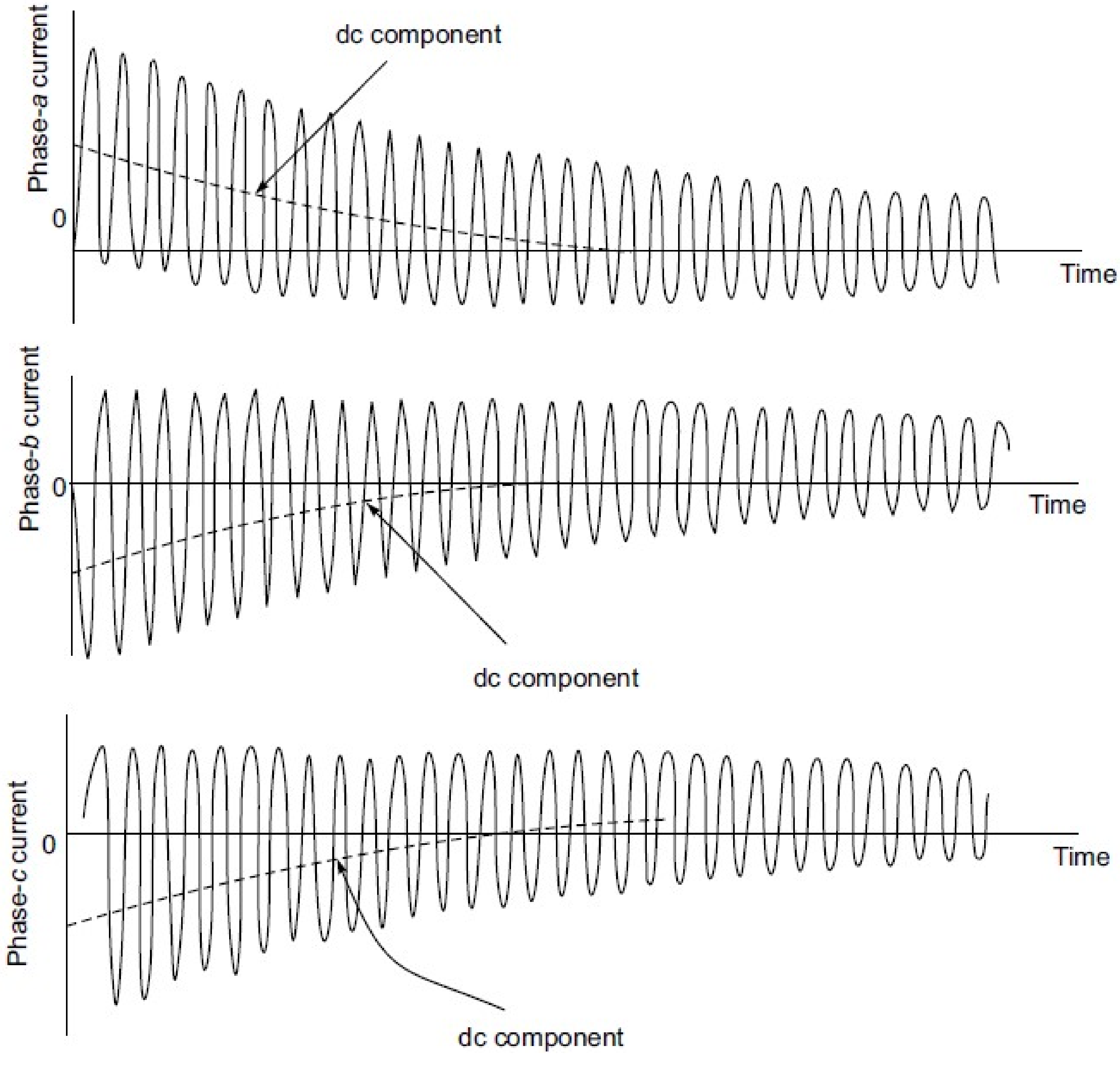
Sudden Short Circuit in Synchronous Machines

- ❖ Unloaded synchronous generator:
- ✓ Original Voltages are no load (open circuit) voltages and changes to zero in short-circuit.
- ✓ Original Currents are zero (no load) and changes short-circuit current.
- ❖ During normal steady a.c. operation, speed of the machine is constant at synchronous speed.
- ❖ The field voltages and currents are constant.
- ❖ The damper currents are zero.
- ❖ The armature phase voltages and currents are balanced three phase quantities.

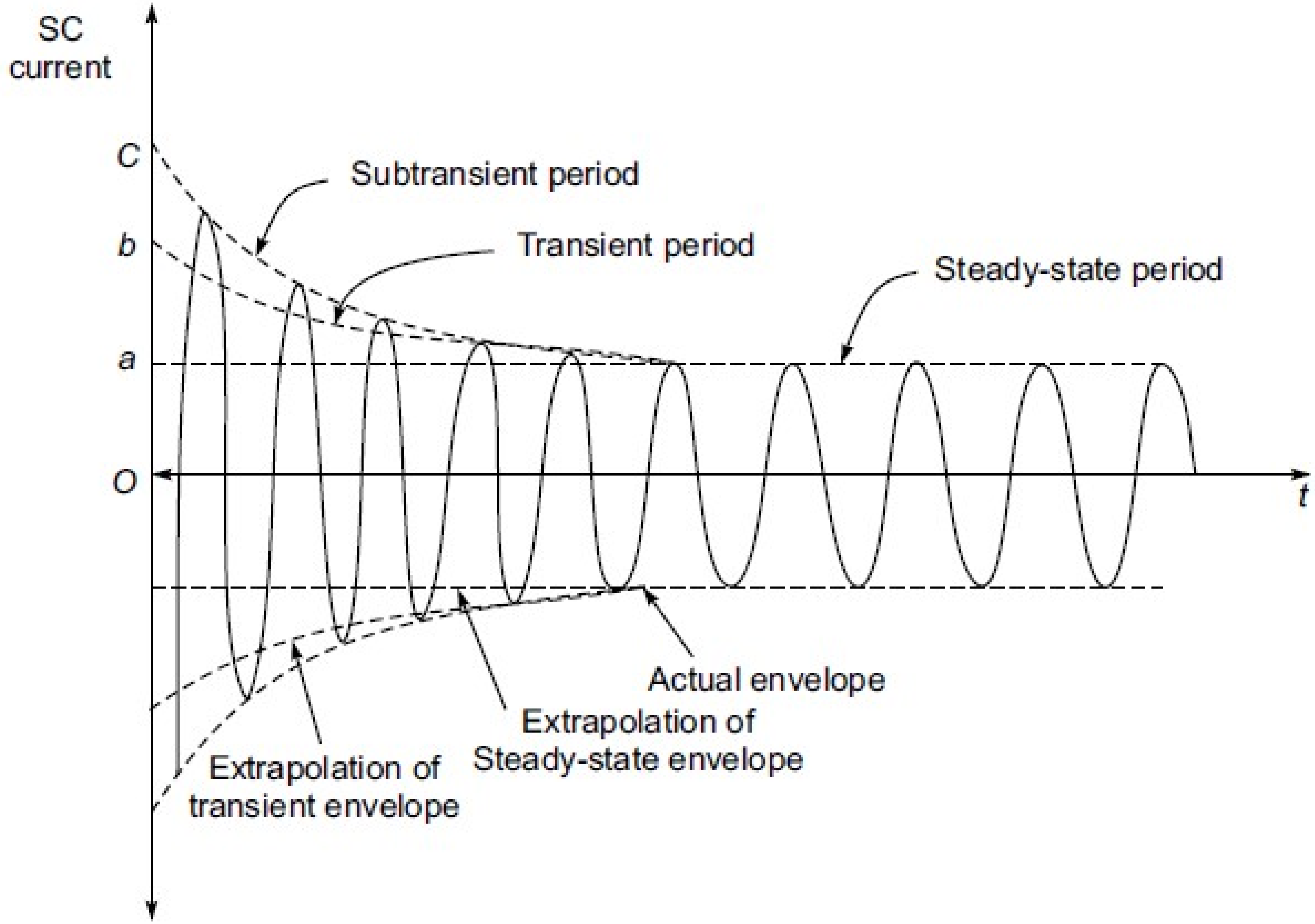
Constant Flux Linkage Theorem

- The behaviour of a synchronous machine just after short circuit can be understood by the use of constant linkages theorem.
- ***Flux linking with an inductive circuit having zero resistance cannot change, whatever may occur in other mutually coupled circuits.***
- If a closed circuit with resistance R and inductance L is considered without a source then the equation obtained using KVL will be $Ri + L\,(di/dt) = 0$.
- If R is very very small then $L\,(di/dt) = 0$ or $d/dt\,(Li) = 0$
- This shows that the flux linkages Li remain constant.
- In generator also the effective inductance of stator and rotor windings is large compared to the resistance which can be neglected for first few cycles.
- The rotor circuit is closed through exciter while stator is closed by short circuit.
- Thus the flux linking with either winding must remain constant.

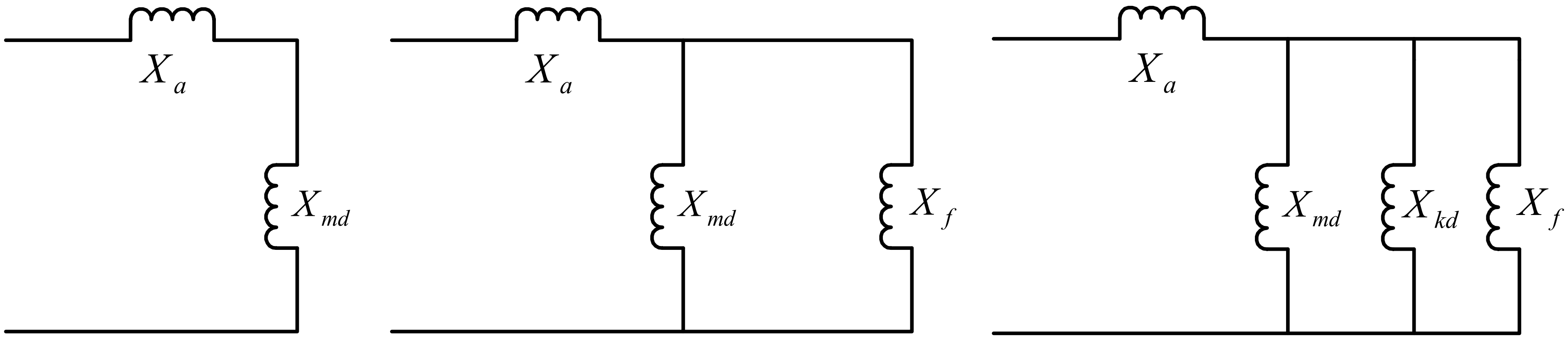
- If a generator having negligible resistance, excited and running on no load is suddenly undergoing short-circuit at its terminals, the short-circuit armature currents tend to reduce the air gap flux (and hence the flux linkage) due to the demagnetizing effect of armature reaction. Short-circuit armature currents lags by almost 90^0 as X >> R i.e. ZPF lag condition.
- In order to keep the total flux linkage constant, additional currents are induced in the stator windings as well as field and damper windings.
- These additional currents contain AC and DC components.
- Under the presence of winding resistance, the DC components of will decay exponentially to zero with a time constant T = L/R of that winding.
- The damper winding resistance is much larger than that of the field winding. The damper winding comprising a few thick bars has a much lower time-constant
- First the damper winding current will decay and then the field wing current will decay to zero.


dc component
Phase-a current
0
Time
Phase-b current
0
Time
dc component
Phase-c current
0
Time
dc component

Oscillograms of the short-circuit armature current

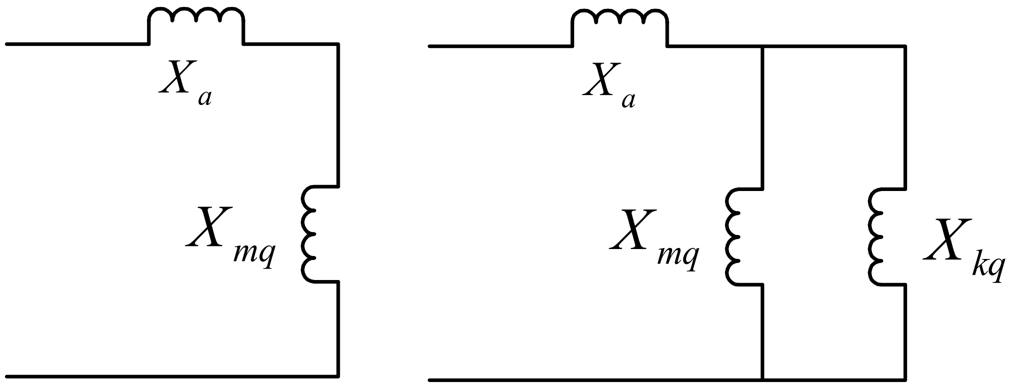


Direct-axis reactance



Steady-state period   Transient period   Sub-transient period

Quadrature-axis reactance



Steady-state period   Sub-transient period

Direct axis and Quadrature axis Reactances

- $\boldsymbol{X_d}$ = direct-axis reactance $X_d = (X_a + X_{md})$
- $\boldsymbol{X_d}$' = direct-axis transient reactance

$$X_d' = X_a + \frac{X_{md} X_f}{X_{md} + X_f}$$

- $\boldsymbol{X_d}$" = direct-axis sub-transient reactance

$$X_d'' = X_a + \frac{X_{md} X_f X_{kd}}{X_{md} X_f + X_{md} X_{kd} + X_f X_{kd}}$$

- $\boldsymbol{X_q}$ = quadrature-axis reactance $X_q = (X_a + X_{mq})$
- $\boldsymbol{X_{qo}}$" = quadrature-axis sub-transient reactance

$$X_q'' = X_a + \frac{X_{mq} X_{kq}}{X_{mq} + X_{kq}}$$