Differences between salient pole and non-salient pole type rotor of synchronous machine :—

Salient pole Synchronous machine	Non-salient pole synchronous machine
1. The poles are projected out from the rotor surface.	1. The poles are not projected out but have smooth rotor surface.
2. It uses damper winding.	2. It does not use damper winding.
3. It has a non-uniform airgap.	3. It has a uniform airgap.
4. Air friction is large.	4. Air friction is minimal.
5. Used in low speed operation.	5. Used in high speed operation.
6. Efficiency is lower than that of non-salient pole.	6. Efficiency is higher than that of salient pole.
7. It has large diameter and short axial length.	7. It has short diameter and long axial length.
8. It is used in hydro, diesel power station.	8. It is used in theromal and nuclear power station.

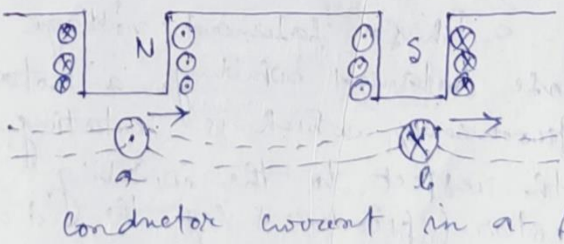
— Synchronous Motor :—

A synchronous motor is electrically identical with an alternator. A synchronous machine may be used as an alternator when driven mechanically or as a motor when driven electrically.

Some characteristic features of a synchronous motor are —

1. It runs either at synchronous speed or not at all, i.e., while running, it maintains a constant speed.
2. It is not inherently self starting. It has to be run up to or near synchronous speed by some means before it can be synchronised 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 factor correction purposes in addition to supplying torque to drive loads.

Principle of operation:-



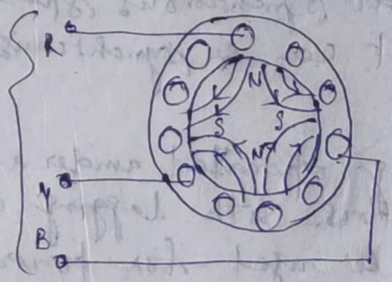
Conductor current in a synchronous motor

(a)

Fig. (a) shows a coil ab carrying current. Conductor 'a' carries current towards the observer and conductor 'b' away from the observer. By motor action, a torque is developed, tending to drive the conductor from left to right. If the current is alternating it will reverse its direction for the next half-cycle and the torque then acts from right to left. Therefore, the net torque over any given no. of complete cycles is zero and no continuous motion can result.

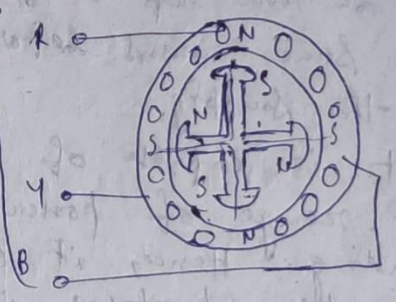
This is the condition existing in a synchronous motor at standstill. Therefore, the synchronous motor as such develops no starting torque.

If however, conductor 'a' by some manner can be brought under the next pole, which is a S-pole, for the half cycle during which the current is in the reverse direction, the resulting torque will still be from left to right and continuous motion will result. Therefore, in a synchronous motor, a given conductor must move from one pole to the other in each half cycle.



(b)

Rotating magnetic field produced in a 3 phase winding



(c)

Interlocking of rotor poles with the rotating magnetic field

Whenever a 3 phase balanced voltage is applied to a 3 phase balanced winding, a rotating magnetic field is produced, which is rotating at synchronous speed with respect to the winding. The S-poles of the rotor (produced by the d.c. field) will lock in with N-pole of the rotating magnetic field in the stator and the N-poles of the rotor will lock in with S-poles of the rotating magnetic field. Therefore, the rotor must rotate at synchronous speed with the stator rotating magnetic field.

Except in special high speed 2 pole machines, synchronous motors are almost salient pole machines.

Phasor diagram of synchronous motor:-

Effect of loading of synchronous motor:-

When load is applied to a synchronous motor, its average speed can not decrease, since the motor must operate at constant speed. Hence, it can not cause the necessary increase in armature current in the same manner that the shunt motor does, that is, by operating at decreased speed.

Referring to the vector diagram,

P_i = Power input to the motor

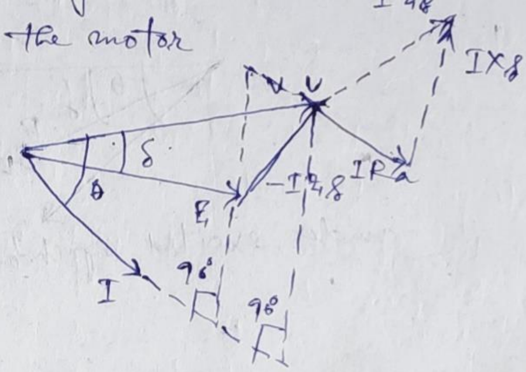
$= VI\cos\theta$

P_δ = Power developed

$= E_1 I\cos(\theta-\delta)$

$= I\left[E_1\cos(\theta-\delta)\right]$

$= I\left[V\cos\theta - IR\right]$



$\therefore P_\delta = VI\cos\theta - I^2R$

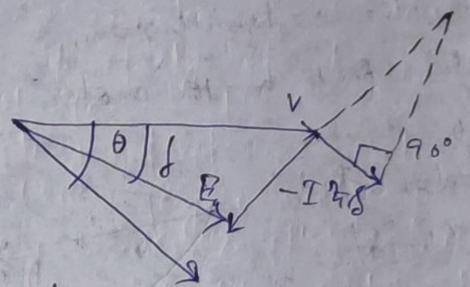
$\therefore$ P_{input} = Power developed + I^2R

From the vector diagram, it can be noted that as the load is increased, the phase difference between the applied voltage V and induced e.m.f. E_1 increases, thereby increasing IZ_s drop in the armature winding. This means that as Z_s being constant, the armature current increases for increasing load. As the angle δ increases with increasing load on the synchronous motor, it is called the load angle. Hence, in a synchronous motor, the rotor by shifting its phase backward when load is applied, causes the motor to take an energy current from the line that supplies the power demanded by the increasing load.

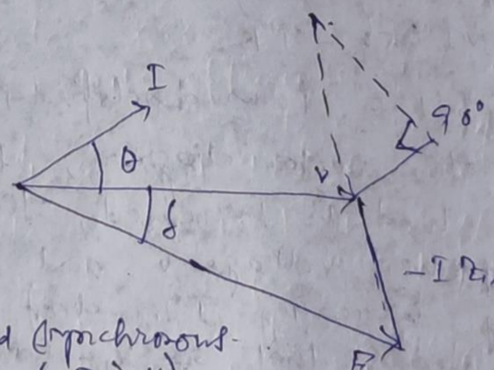
Synchronous motor operating on infinite busbar:-

Figure shows the vector diagram of a synchronous motor operating on a constant voltage mains with a lagging current and a leading current.

When synchronous motor works at given voltage, it requires a certain excitation (that is, certain value of induced e.m.f. E_1). If its field is weakened, its excitation becomes inadequate. The deficit, is, in part, made up by the motor taking a lagging current from the line. On the other hand, when the synchronous motor is overexcited (that is, higher value of e.m.f. E_1), it has a surplus of excitation and it takes a leading current.

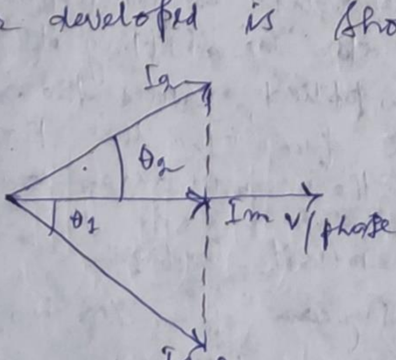


under excited synchronous motor, $E_1 < V$.



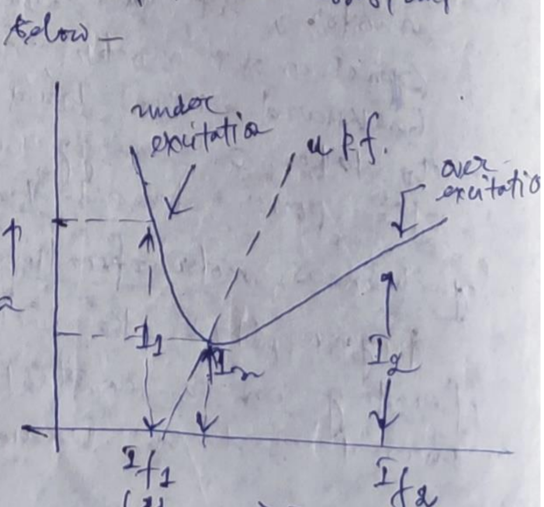
Over excited synchronous motor ($E_1 > V$)

The relation existing between the armature current and the field current for constant power input or constant power developed is shown below –



Vector diagram for constant power input

(a)



(b) → I_f

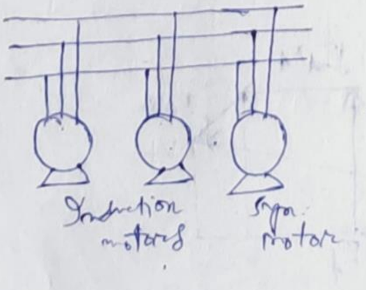
Relation between armature ct. and field

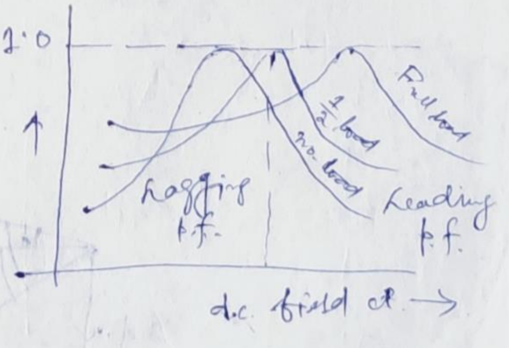
V-curve of synchronous motor for constant power input

Referring to fig. (a), the synchronous motor draws a constant power input of $V_p I_m$ per phase. When the motor is under excited, it takes a lagging current (I_1) and when it is over-excited, it takes a leading current I_2, corresponding to field currents of I_{f1} and I_{f2} respectively. The excitation corresponding to minimum armature current I_m is known as normal excitation. The relation between the armature current (I_a) and the field current (I_f), shown in fig. (b), is known as V- curve.

Synchronous condenser :-

When a synchronous motor is used for p.f. correction alone, with no mechanical out put, it is known as a synchronous condenser. It is seen that an over-excited synchronous motor can be run with leading p.f. This property of the motor renders it extremely useful for phase advancing and so power factor correcting purposes in the case of industrial loads driven by induction motors and lighting and heating loads supplied through transformers. Both transformers and induction motor draw lagging currents from the line. Especially, on light loads, the power drawn by them has a large reactive component and the power factor has a very low value. This reactive component entails appreciable loss in many ways. By using synchronous motors in conjunction with induction motors and transformers, the lagging reactive power required is supplied locally by the leading reactive component taken by the synchronous motor, thereby relieving the line and generators of much of reactive component. When used in this way, a synchronous motor is called a synchronous capacitor, because it draws leading current from the line like a capacitor.





Synchronous Motor applications:-

Synchronous motors are rarely used below 50 h.p. in the medium range, because of their higher initial cost compared to induction motors. In addition, they require a d.c. excitation source and the starting and control devices are usually more expensive, especially where automatic operation is required.

However, synchronous motor offer the following advantages —

(i) constant speed operation
(ii) power factor control
(iii) High operating efficiency.

Synchronous motors are preferred for driving the loads requiring high powers at low speeds, for example, large low head pumps, reciprocating pumps and compressors, rolling mills, ball mills, crushers, pulp grinders etc. Over excited synchronous motors are also used for improving the p.f. of many supply systems, where static capacitors become more costly.

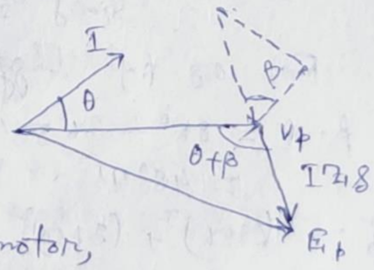
Problems:- ① A 3-phase, 400V synchronous motor takes 52.5 A. at a p.f. of 0.8 lead. Calculate the power supplied and the induced e.m.f. The motor impedance per phase is $(0.25 + j3.2)$ ohms.

Soln:- Power supplied,

$P_i = \sqrt{3}\, V_L I_L \cos\theta$

$= \dfrac{\sqrt{3} \times 400 \times 52.5 \times 0.8}{1000}$

$= 29.1$ kW.



Assuming a star connected motor,

$Z_s = 0.25 + j3.2 = 3.21$ ohms.

Impedance angle, $\beta = \tan^{-1}\dfrac{3.2}{0.25} = 85.53^\circ$

$\theta = \cancel{\tan^{-1} 0.8} = \cancel{38.66^\circ}$ 36.87° $\cos^{-1}(0.8)$

Phase voltage $= \dfrac{400}{\sqrt{3}} = 230$ V.

IZ_s drop $= 52.5 \times 3.21 = 168.5$ V.

$\beta + \theta = 85.53^\circ + 38.66^\circ = 124.19^\circ$.

Induced e.m.f. per phase,

$E_p = \sqrt{V_p^2 + (IZ_s)^2 + 2V_p\, IZ_s \cos(180^\circ - 124.19^\circ)}$

$= 353.35$ V.

Line e.m.f. $= \sqrt{3} \times 353.35 = 612$ V.

(2) A 1000 KVA, 11000 V., 3 phase star connected synchronous motor has an armature resistance and reactance per phase of 3.5 ohms and 40 ohms respectively. Determine the induced e.m.f. and angular retardation of the rotor when fully loaded at (i) unity p.f. (ii) 0.8 p.f. lagging and (iii) 0.8 p.f. leading.

Soln:- Full load line current $I_p = \frac{1000 \times 1000}{\sqrt{3} \times 11000}$

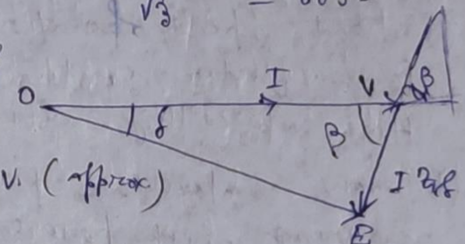
$= 52.5$ A.

Voltage per phase $= \frac{11,000}{\sqrt{3}} = 6351$ V.

Armature impedance drop

$= 52.5(3.5 + j40)$

i.e., $I Z_s = 2100$ V. (approx)



$\beta = \tan^{-1}\frac{40}{3.5} = 85°$.

(i) For unity p.f. :—

$E_p^2 = (6351)^2 + (2100)^2 - 2 \times 6351 \times 2100 \times \cos 85°$

$\Rightarrow E_p = 6513$ V.

Induced line e.m.f $= \sqrt{3} \times 6513 = 11,280$ V.

From the triangle OVE,

$\frac{2100}{\sin\delta} = \frac{6513}{\sin 85°} = \frac{6513}{0.9961}$

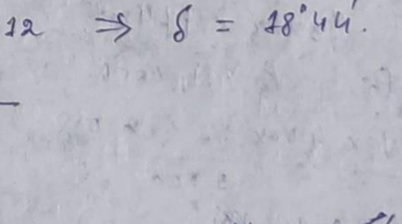
$\therefore \sin\delta = 0.3012 \Rightarrow \delta = 18°44'$.

(ii) For 0.8 p.f. lagging :—

$\beta - \theta = 85° - 36°53'$

$= 48°7'$

$E_p^2 = (6351)^2 + (2100)^2$
$- 2 \times 6351 \times 2100 \times \cos 48°7'$



$\Rightarrow E_p = 5190$ V.

$\therefore$ Line e.m.f
$= \sqrt{3} \times 5190 = 8989$ V.

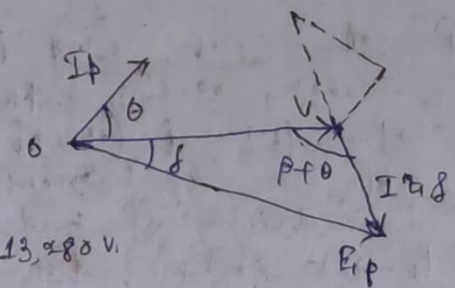
Referring to triangle OVE,

$\frac{2100}{\sin\delta} = \frac{5190}{\sin 48°7'} \Rightarrow \delta = 17°32'$.

(iii) $\beta + \theta = 85^\circ + 36^\circ 53'$
$= 121^\circ 53'$.

$E_p^2 = (6351)^2 + (2100)^2$
$- 2 \times 6351 \times 2100 \cos 121^\circ 53'$

$\therefore E_p = 7670$ V.



$\therefore$ Line e.m.f. $= \sqrt{3} \times 7670 = 13{,}280$ V.

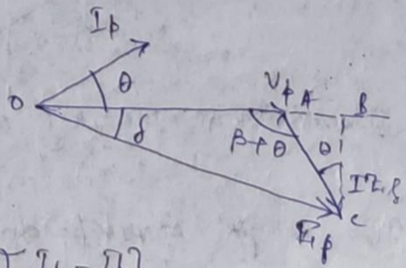
Also, $\frac{2100}{\sin \delta} = \frac{7670}{\sin 121^\circ 53'} \Rightarrow \delta = 13^\circ 27'$.

(3) The synchronous reactance per phase of a 3 phase star connected 6600 V synchronous motor is 20 ohms. For a certain load, the input is 915 kW. at normal voltage and the induced line e.m.f. is 8942 V. Evaluate the line current and the power factor. Neglect resistance.

Soln:- The synchronous motor is moving at leading p.f. as the induced e.m.f. is more than the applied voltage.

Applied voltage per phase,

$= \frac{6600}{\sqrt{3}} = 3810$ V.



Induced e.m.f. per phase

$= \frac{8942}{\sqrt{3}} = 5163$ V.

Input $= (915 \times 1000)$ W.

$= \sqrt{3} \times V_L I_L \cos\theta \quad [I_L = I_p]$

$\therefore I_p \cos\theta = \frac{915 \times 1000}{\sqrt{3} \times 6600} = 80$ A.

Referring to figure,

$OC^2 = \cancel{OA^2 + AC^2}\ OB^2 + BC^2$

$BC = AC\cos\theta = I_p X_s \cos\theta = 20 \times I_p \cos\theta$

$= 20 \times 80 = 1600$

$\therefore (5163)^2 = OB^2 + (1600)^2$

$\Rightarrow OB = 4908$ V.

$AB = OB - OA = 4908 - 3810 = 1098$ V.

$\tan\theta = \frac{AB}{BC} = \frac{1098}{1600} = 0.6862$

$\therefore \theta = 34^\circ 22'$.

Power factor $= \cos(34^\circ 22') = 0.8256$ (leading)

Line current $= \frac{I_L \cos\theta}{\cos\theta} = \frac{80}{0.8251} = 97$ A.

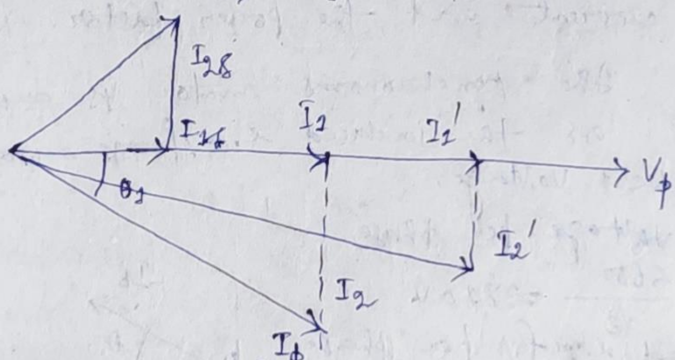
(7) A manufacturing plant takes 200 kW. at 0.6 p.f. from a 600 V., 60 c/s. 3-phase system. It is desired to raise the power factor of the entire system 0.9 by means of a synchronous motor, which at the same time is driving a load requiring the synchronous motor to take 80 kW., from the line. What should be the rating of the synchronous motor in volts and amperes?

Soln:- Phase voltage, $V_\phi = \frac{600}{\sqrt{3}} = 346$ V.

current per phase, $I_p = \frac{200 \times 1000}{\sqrt{3} \times 600 \times 0.6} = 321$ A

Energy current of load $= I_p \cos\theta_1 = 321 \times 0.6 =$

$\Rightarrow I_1 = 192.6$ A.



Quadrature current of load, $I_2 = I_p \sin\theta_1$

$= 321 \times 0.8 = 256.8$ A.

The angle corresponding to new p.f. of 0.9

$= \cos^{-1}(0.9) = 25.8°$.

Energy current of synchronous motor

$= \frac{80 \times 1000}{\sqrt{3} \times 600} \Rightarrow I_{1s} = 77$ A.

$\therefore$ Total energy current $= I_1' = I_1 + I_{1s}$

$= 192.6 + 77 = 269.6$ A.

Quadrature current of the system

$= I_2' = 269.6 \tan 25.8° = 130.3$ A.

$\therefore$ Quadrature current to be taken by the synchronous motor $= I_{2s} = I_2 - I_2'$

$= 256.8 - 130.3 = 126.5$ A.

$\therefore$ Total synchronous motor current

$I_s = \sqrt{(I_{1s})^2 + (I_{2s})^2}$

$= \sqrt{(77)^2 + (126.5)^2} = 148$ A.

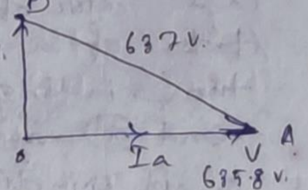
∴ Synchronous motor rating

$= \sqrt{3}\, V_L I_L \times 10^{-3}$

$= \sqrt{3} \times 600 \times 148 \times 10^{-3} = 154$ KVA.

(5) A 3-phase synchronous motor of 8000 watts at 1100 V. has synchronous reactance of 8 Ω/phase. Find the minimum current and the corresponding induced e.m.f. for full load condition. Neglect armature resistance. The efficiency of the machine is 0.8.

Soln:- The current in the machine is minimum when the power factor is unity.



Input to motor

$$= \frac{8000}{0.8} = 10000 \text{ W.} = 10 \text{ kW.}$$

Motor line current $= \dfrac{10,000}{\sqrt{3} \times 1100 \times 1} = 5.25$ A.

Impedence drop $= 5.25 \times 8 = 42$ V.

∴ Voltage per phase $= \dfrac{1100}{\sqrt{3}} = 635.8$ V.

∴ Induced e.m.f. per phase

$$= \sqrt{(635.8)^2 + (42)^2} = 637 \text{ V.}$$