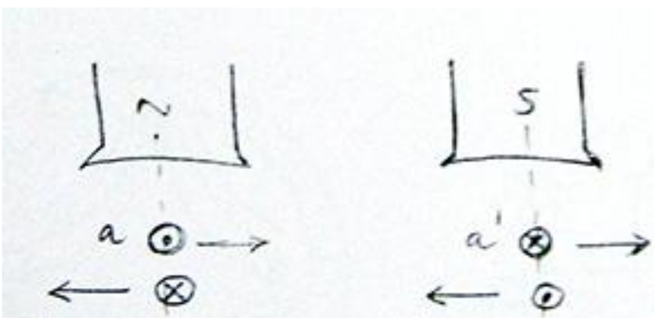
UNIT – II : SYNCHRONOUS MOTORS

It is known , that the direct current generator operates satisfactorily as a motor. Moreover, there is practically no difference in the construction of the DC generator and the DC motor, and there is no substantial difference in the rating of a machine as a motor or as a generator.

Likewise, an alternator will operate as a motor without any change being made in the construction.When so operated; the machine is called as synchronous motor.

Except in special high speed two pole types, synchronous motors are almost always salient pole machines, whereas alternators may be of either salient pole or non-salient pole type.

Principles of operation of Synchronous motor:

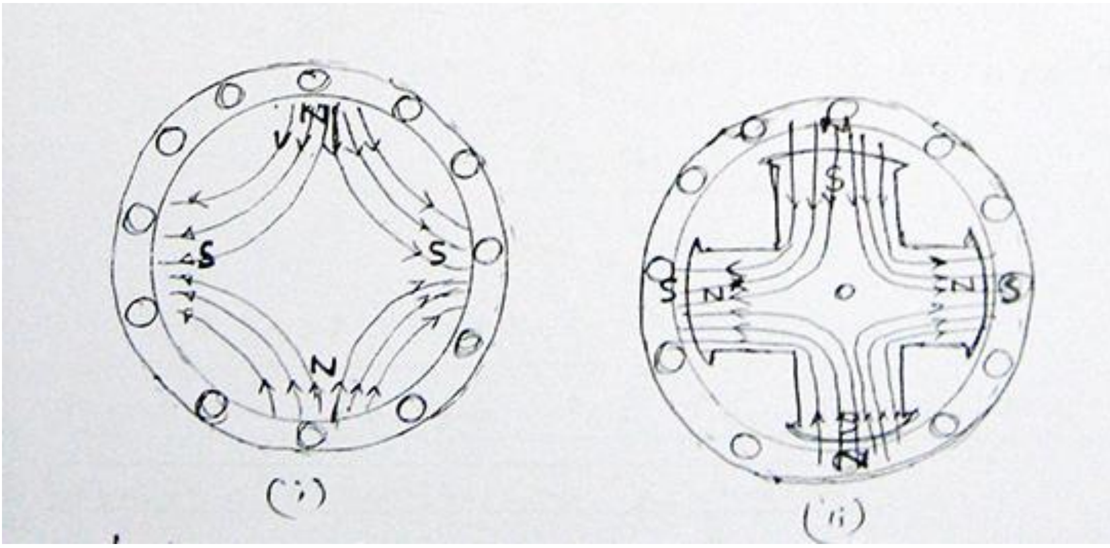


When conductors **a** and **a’** are under N pole and S pole respectively, the torque produced is in a direction to move the conductors from left to right. But, since the input applied to the conductors **a** & **a’** is ac, within half-a-cycle the current in ‘**a**’ changes to ‘cross’ and the current in ‘ **a’** ’ changes to ‘dot’ making the conductors to move from right to left as shown in the fig.

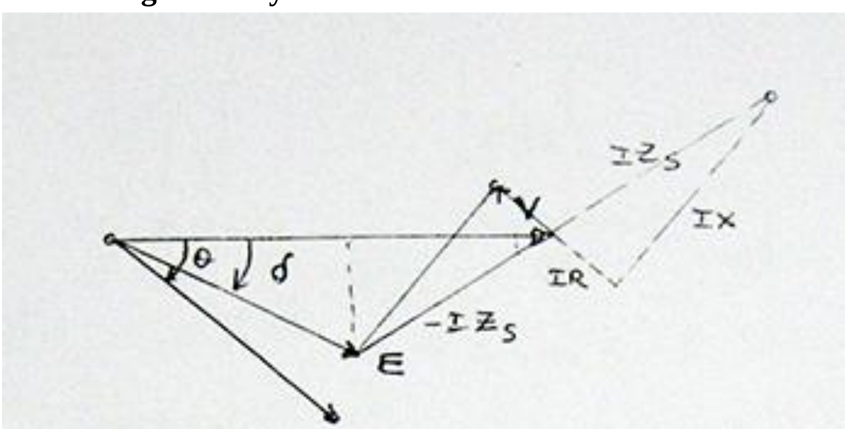
When the input frequency is ‘f’, the time taken for one cycle is 1/f sec;

When the conductor ‘**a**’ is brought under south pole within a time of exactly ‘1/f’ sec, the current changes to a ‘dot’ and the torque remains in the same direction is from left to right. Similarly the current in conductor ‘ **a’** ’ changes from ‘dot’ to ‘cross’ by the time it comes under ‘N’ pole , making the conductors move in the same direction. Hence , if the conductors are rotated at synchronous speed initially , it will continue to rotate only at synchronous speed, $N_s = 120\ f / p$ rpm.

Interlocking action of salient poles:



Vector diagram of synchronous motor:



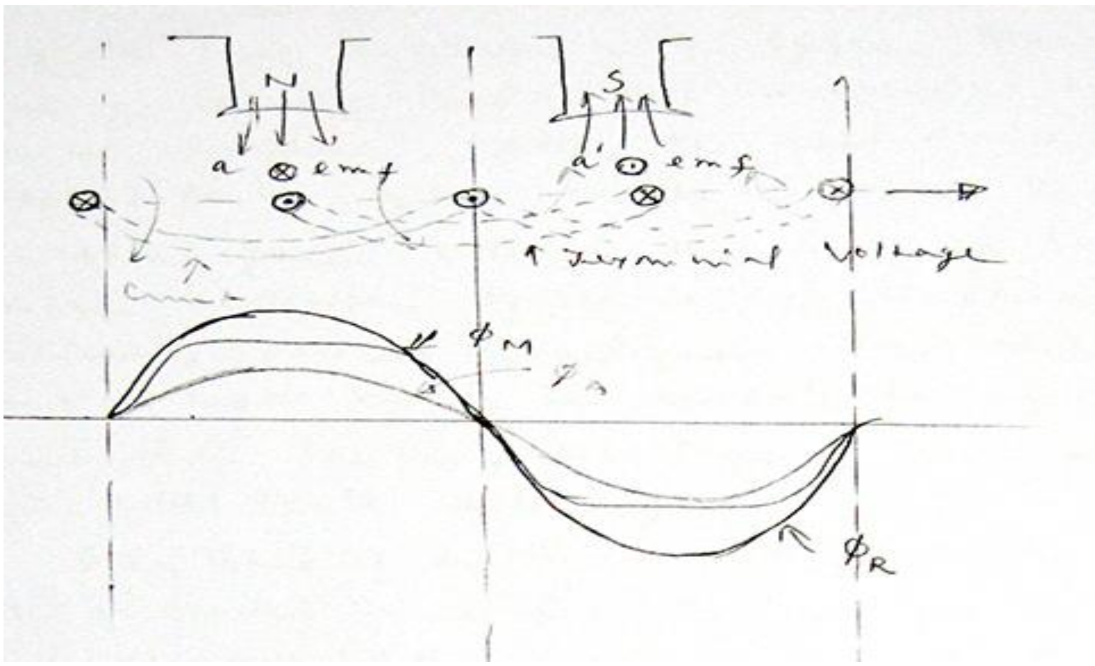
For a lagging pf, $E\angle-\delta = V\angle 0 - I\angle-\theta * Z_s \angle\beta$

Armature reaction in synchronous motor :

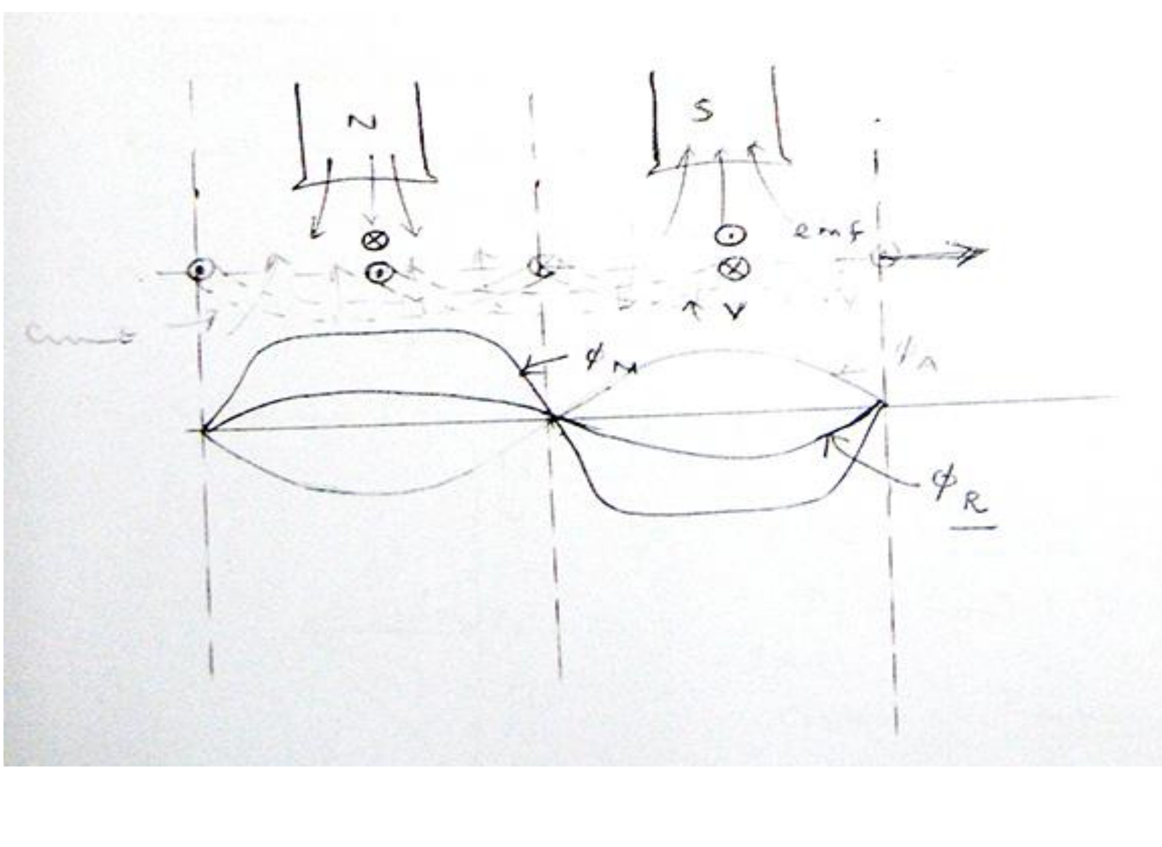
Effect of armature reaction in synchronous motors is just opposite to that of alternators:

(i.e.) for lagging current – it is magnetizing
for leading current -- it is demagnetizing

For lagging current (magnetising) :



For leading current (demagnetising):



Operation of synchronmotor on infinite bus bars:

In a constant potential system at a constant load, the total excitation in the system, that is, the sum of the DC and the AC excitation, tends to remain constant. Also, the total excitation supplied to the system tends to remain constant.

At a given voltage and load, it requires certain excitation . If its field is weakened , its excitation becomes inadequate. This deficit in part is made up by the motor's taking a lagging current from the line, as lagging current magnetises and adds to the deficiency.

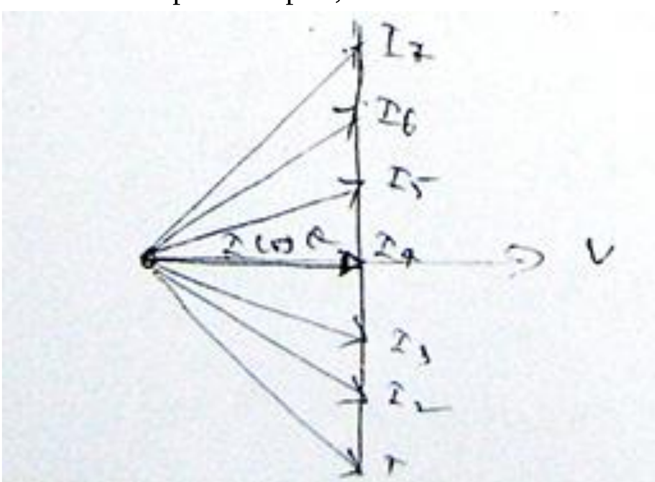
Other hand if the field is strengthened the motor takes a leading current from the line, as the leading current demagnetises and compensates for the increase in the DC field.

V & inverted V curves:

V curves - the variation of armature current (line current) against field current

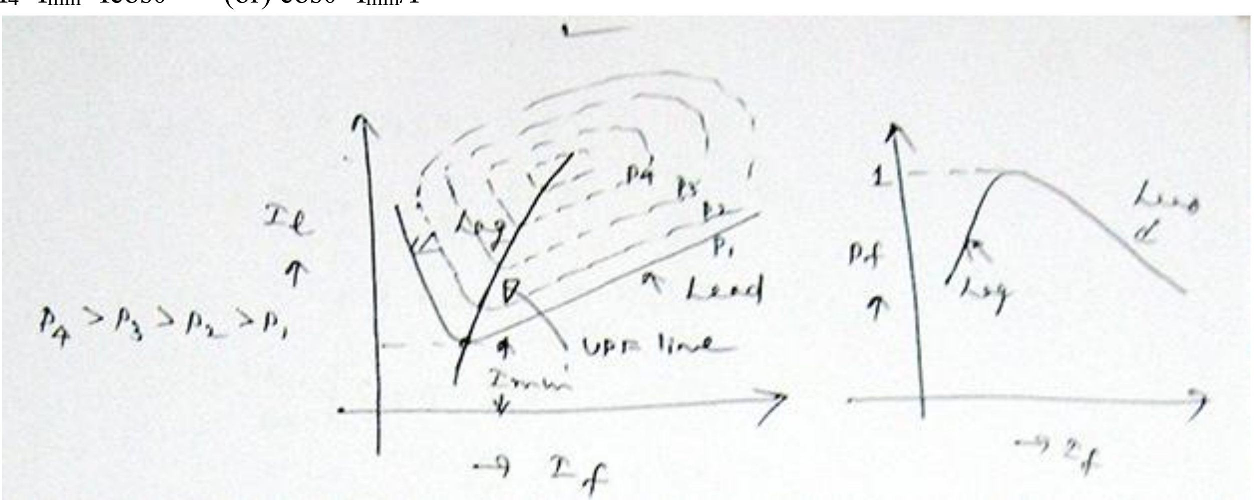
Inverted V curves- the variation of power factor against field current

For constant power input ,:



P_i=VI cos θ

$I_4=I_{min}=I\cos\theta$ (or) $\cos\theta=I_{min}/I$



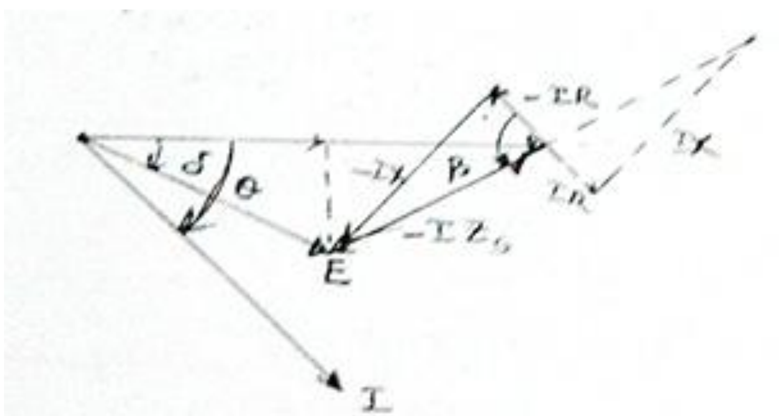
Power input & power developed equations:

$P\delta = EI\cos(\theta-\delta) = [E\cos\delta * I\cos\theta] + [E\sin\delta * I\sin\theta]$

Power due to real part   power due to imaginary part

$E\angle -\delta = V\angle 0 - I\angle -\theta * Z_s\angle\beta$

$I\angle -\theta = (V\angle 0 - E\angle -\delta)/Z_s\angle\beta = [(V/Z_s)\ \angle -\beta] - [(E/Z_s)\ \angle -\beta-\delta]$



$E\angle -\delta = V\angle 0 - I\angle -\theta * Z_s\angle\beta$

$I\angle -\theta = (V\angle 0 - E\angle -\delta)/Z_s\angle\beta = (V/Z_s)\ \angle -\beta - (E/Z_s)\ \angle -\beta-\delta$

$= (V/Z_s)[\cos\beta - j\sin\beta] - (E/Z_s)[\cos-(\beta+\delta) + j\sin-(\beta+\delta)]$

$= [(V/Z_s)\cos\beta - (E/Z_s)\cos(\beta+\delta)] - j[(V/Z_s)\sin\beta - (E/Z_s)\sin(\beta+\delta)]$

$I\angle -\theta = I\cos\theta - jI\sin\theta$

Hence $I\cos\theta = (V/Z_s)\cos\beta - (E/Z_s)\cos(\beta+\delta)$

$I\sin\theta = (V/Z_s)\sin\beta - (E/Z_s)\sin(\beta+\delta)$

$E\angle -\delta = E\cos\delta - jE\sin\delta$

$P\delta = EI\cos(\theta-\delta)$

$= E\cos\delta[(V/Z_s)\cos\beta - (E/Z_s)\cos(\beta+\delta)] + E\sin\delta[(V/Z_s)\sin\beta - (E/Z_s)\sin(\beta+\delta)]$

$= (VE/Z_s)[\cos\beta\cos\delta + \sin\beta\sin\delta] - (E^2/Z_s)[\cos(\beta+\delta)\cos\delta + \sin(\beta+\delta)\sin\delta]$

$\mathbf{P\delta = (VE/Z_s)\cos(\beta-\delta) - (E^2/Z_s)\cos\beta}$

Power input P_i= VI cosθ

$=V[(V/Z_s)\cos\beta-(E/Z_s)\cos(\beta+\delta)]$

$\mathbf{P_i= (V^2/Z_s)\cos\beta-(VE/Z_s)\cos(\beta+\delta)}$

When armature copper loss is neglected i.e. R<<< X_s $\beta \cong 90^0$

Hence **$P\delta=(VE/X_s)\sin\delta=P_i$**

Current loci for constant power developed (P_d), Constant power input (P_i) and for constant Excitation (E):

For constant power developed Pδ:

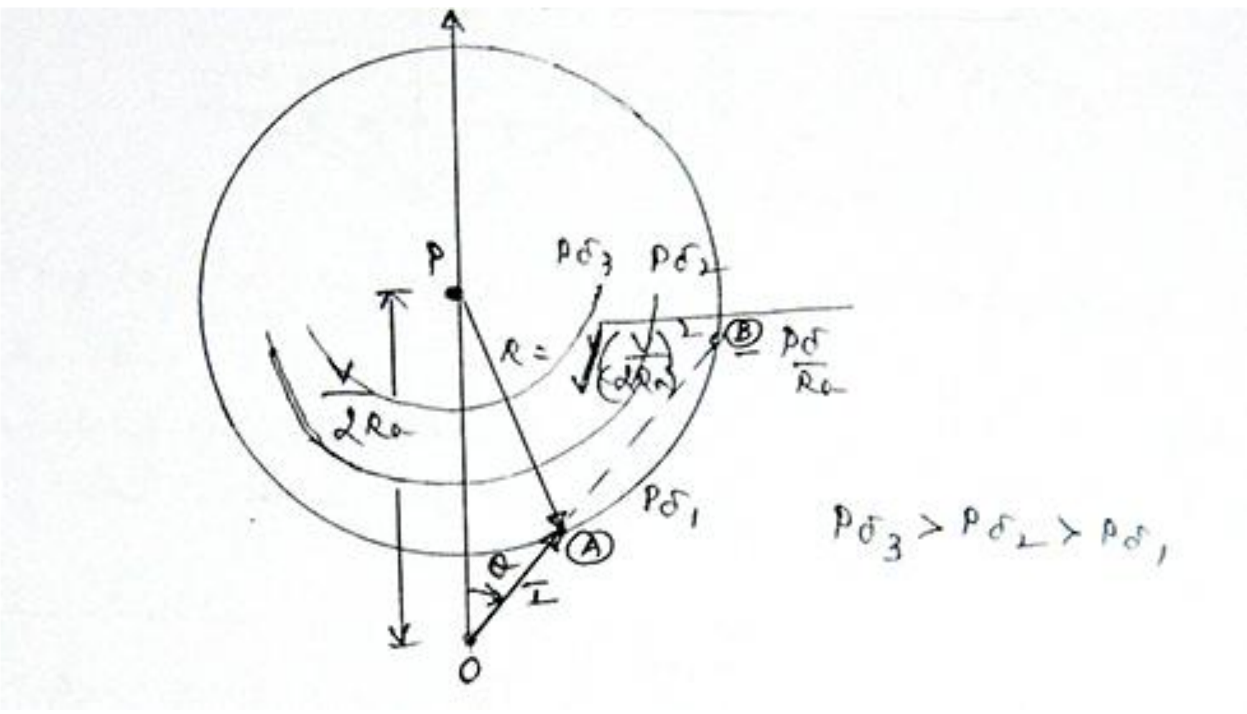
$P\delta= VI\cos\theta-I^2R_a$

$I^2R_a-VI\cos\theta=-P\delta$

$I^2-(V/R_a)I\cos\theta=-(P\delta/R_a)$

$I^2-(V/R_a)I\cos\theta+(V^2/4R_a^2)-(P\delta/R_a)$

$I^2-2(V/2R_a)I\cos\theta+(V/2R_a)^2=(V^2/4R_a^2)-(P\delta/R_a)$



The above equation shows the locus of current for constant Pδ is a circle with radius $((V/4R_a^2)-(P\delta/R_a))^{1/2}$ with centre at $(V/2R_a)$ from the origin 'O'.

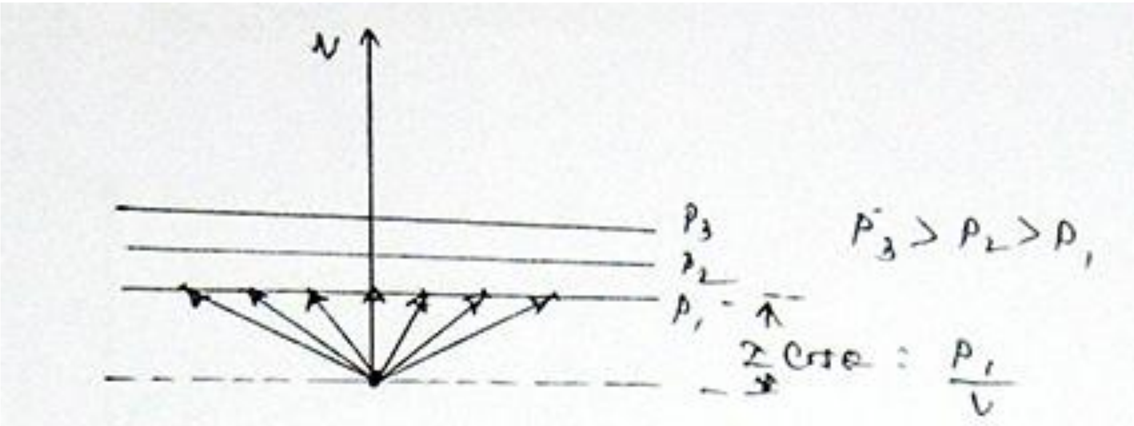
For the same Pδ , the current values are OA and OB. OA is the stable operating current and OB is in the unstable region.

As the value of Pδ increases , the radius for the circle decreases and the maximum Pδ is obtained when the radius is zero.

$(V^2/4R_a^2)=(P\delta/R_a)$ and the power input at maximum Pδ, $P_i=(V^2/2R_a)$

i.e. $P\delta=(V^2/4R_a)$

For the contant power input P_i :



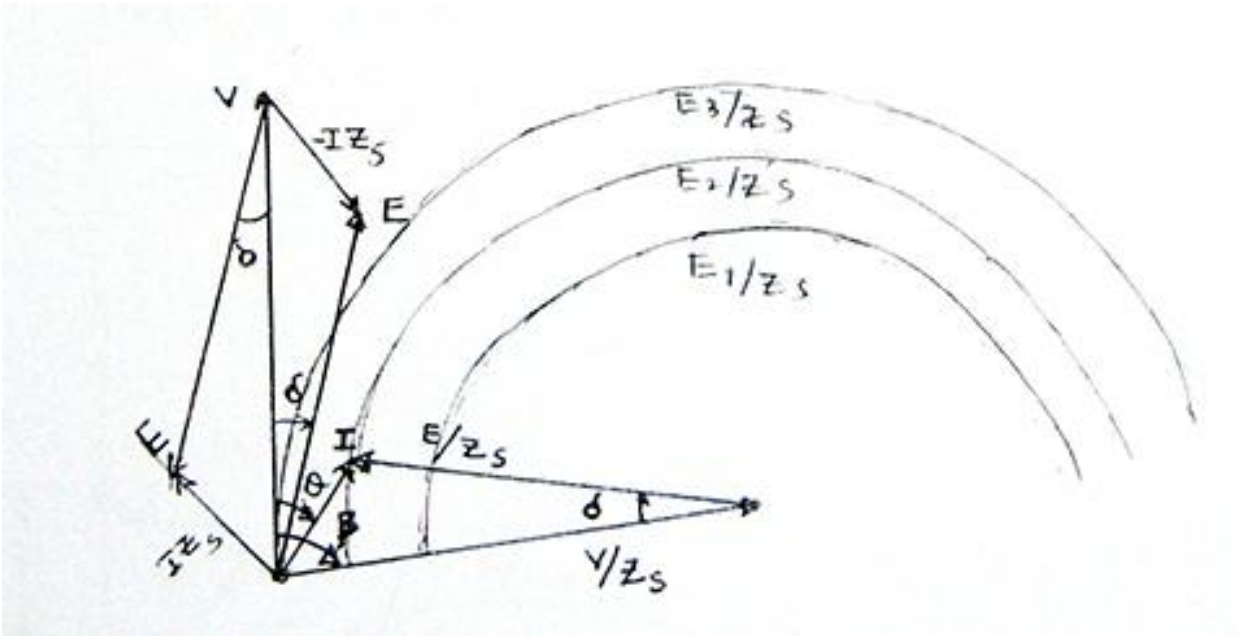
Referring to Pδ equation, when R_a is neglected, i.e. $R_a=0$,

The radius for the current locus for constant $P\delta= ((V/4R_a^2)-(P\delta/R_a))^{1/2}=\infty$

i.e the circle becomes a straight line

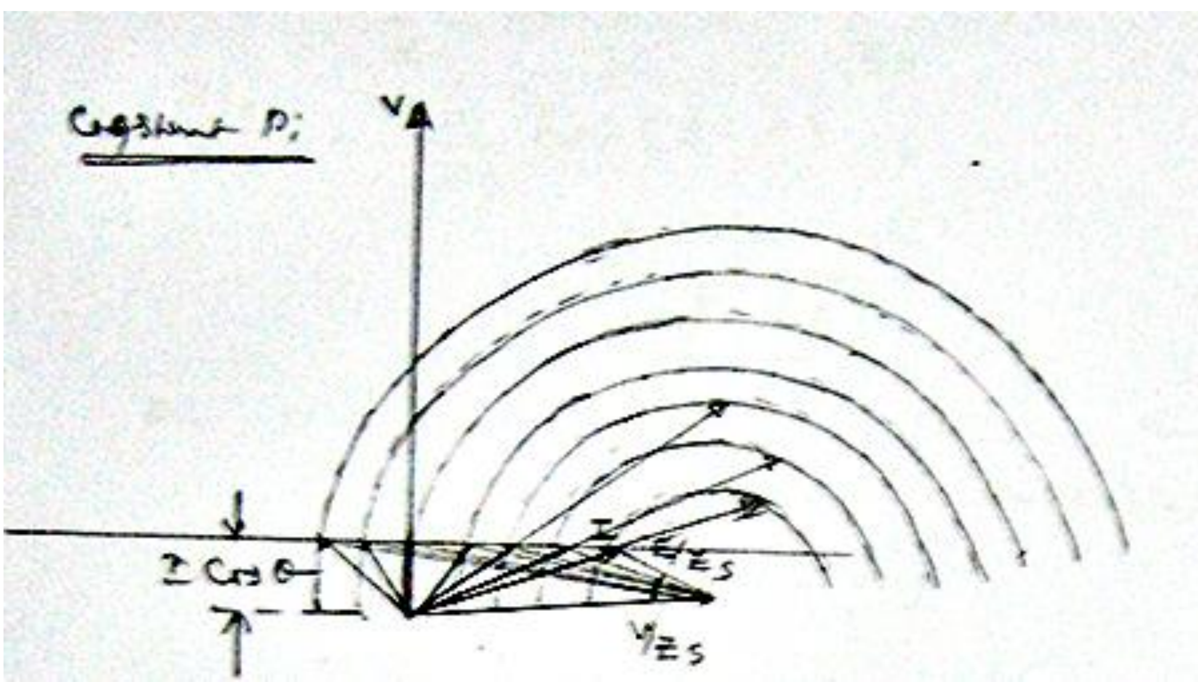
$P_i=P\delta=VI\cos\theta$

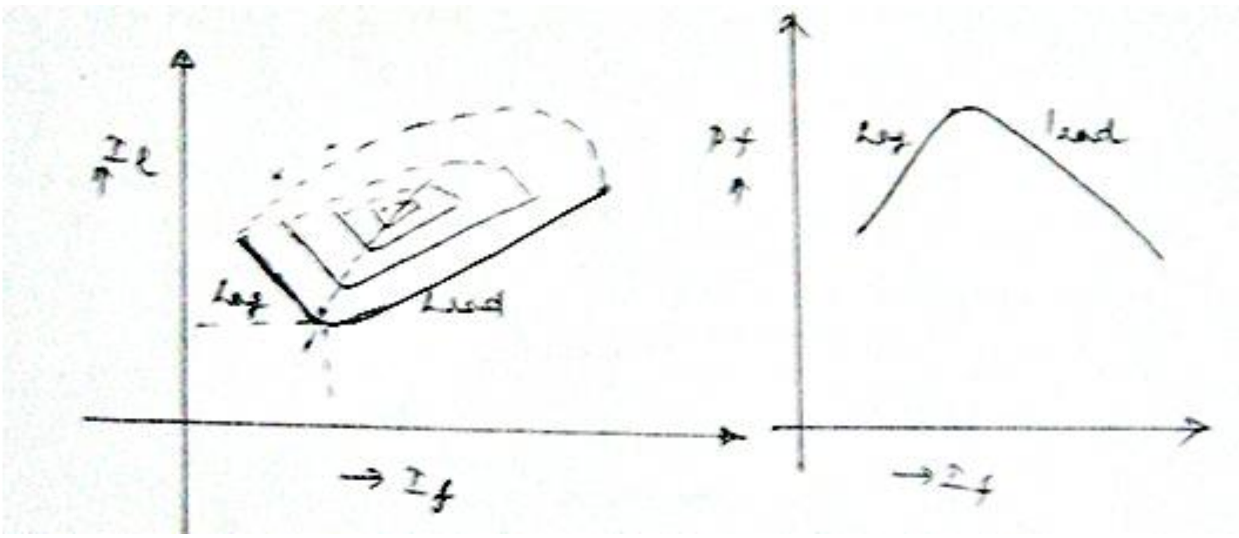
For constant excitation, E:

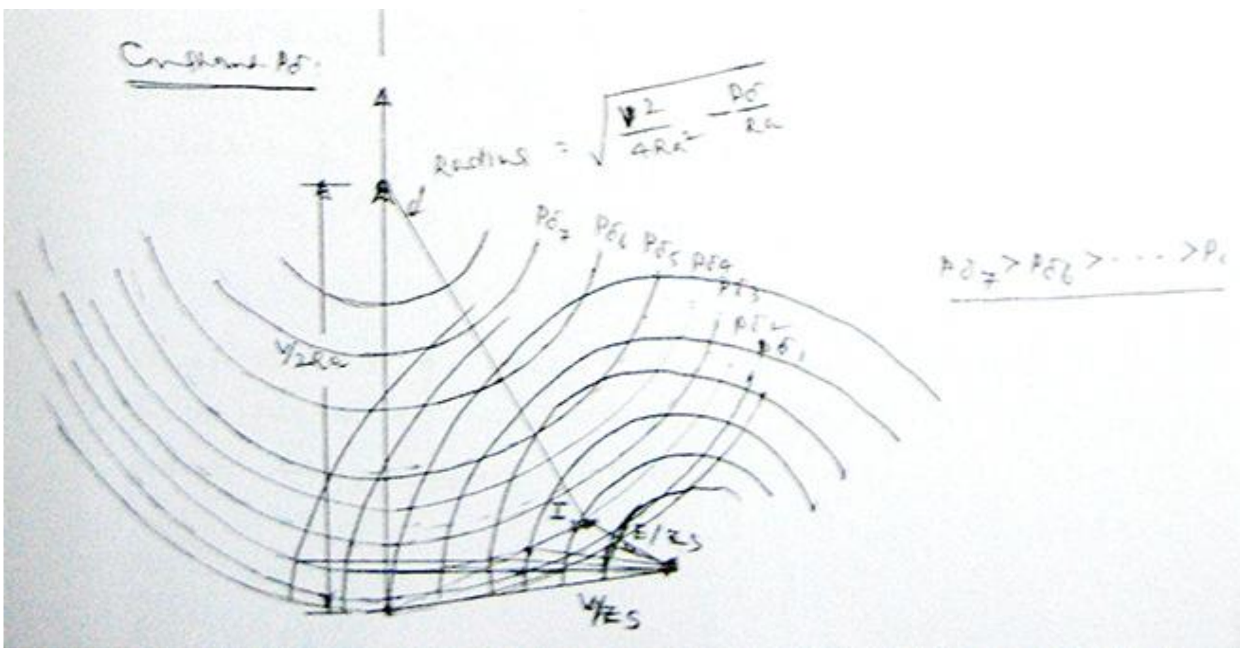


The current locus for costant excitation , is a circle drawn taking the centre at a distance of (V/Z_s) and radius equal to (E/Z_s).

Predetermination of V and inverted V curves for constant P_δ and constant P_i:







Condition for maximum power developed :

$P\delta=(V/Z_s)\cos(\beta-\delta)-(E^2/Z_s)\cos\beta$

$\partial P\delta/\partial \delta=(VE/Z_s)\sin(\beta-\delta)=0$

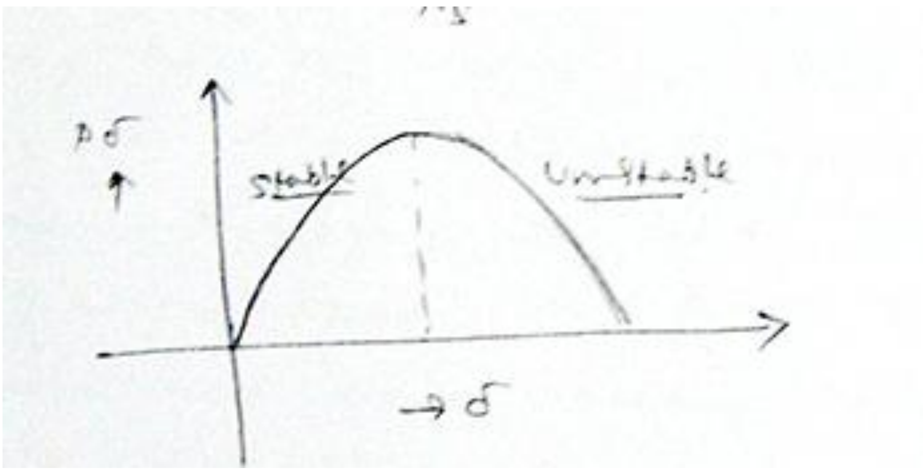
$(\beta-\delta)=0$ i.e. $\delta=\beta$

For $\delta<\beta$ the system is stable

For $\delta > \beta$ the system is unstable.

When $\beta = 90^{0+}$ i.e. $R_a = 0$

$P\delta = (VE/X_s)\sin\delta$



Salient pole synchronous motors are more stable than wound rotor motors due to interlocking of DC poles with rotating magnetic flux.

Salient pole motors would be able to develop small amount of power ($P\delta$) even without DC field excitation , and takes input line current at a very lagging power factor.

Starting of synchronous motors:

As such synchronous motors are not self starting and the following methods of starting are used:

(i) Auxiliary motor method
(ii) Induction motor start
(iii) Using resistance in the field winding
(iv) Using phase connected damper windings.
(v) Super synchronous start

Auxiliary motor method:

This method is generally practiced in laboratories. The synchronous motor is supplied with low ac voltage during starting and the rotor is run by auxiliary motor to near synchronous speed without energizing DC field . When it is run at synchronous speed DC field is excited and the rotor and stator rotating magnetic field interlock each other. The machine afterwards continues to rotate only at synchronous speed.

Induction motor start: The damper windings in the rotor poles are short circuited windings which is turns to damp out oscillations in synchronous motors. The damper windings are used here to start the synchronous motor as an induction motor and when the motor reaches near synchronous speed the rotor DC field is excited interlocking with stator rotating magnetic field.

Using resistance in the field current:

When synchronous motor is started using damper windings, a very high voltage is induced in the field windings at start, which may raise to a dangerous value. Hence, the field winding is opened and sectionalized to limit the induced e.m.f . Instead, a high resistance can be connected across field winding, resulting in increase of starting torque. And when the rotor reaches near synchronous speed, the resistance can be disconnected and DC field is energized.

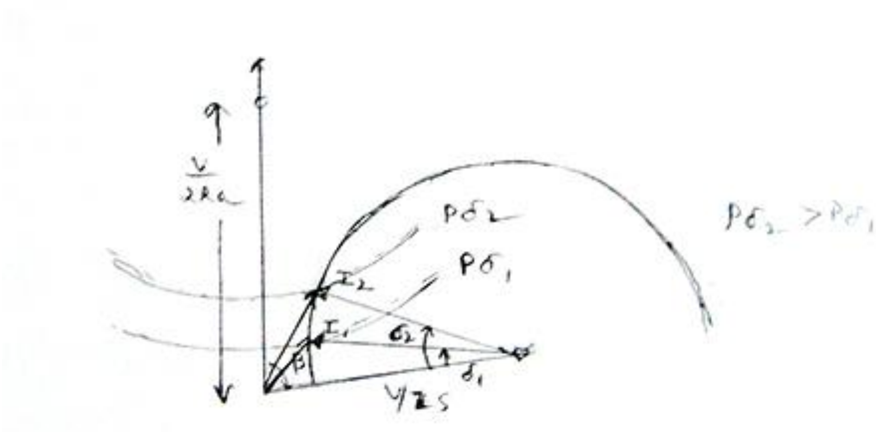
Using phase connected damper windings:

The damper windings in the pole faces can be connected as phase connected windings with external resistance connected to improve the starting torque.

Super synchronous start:

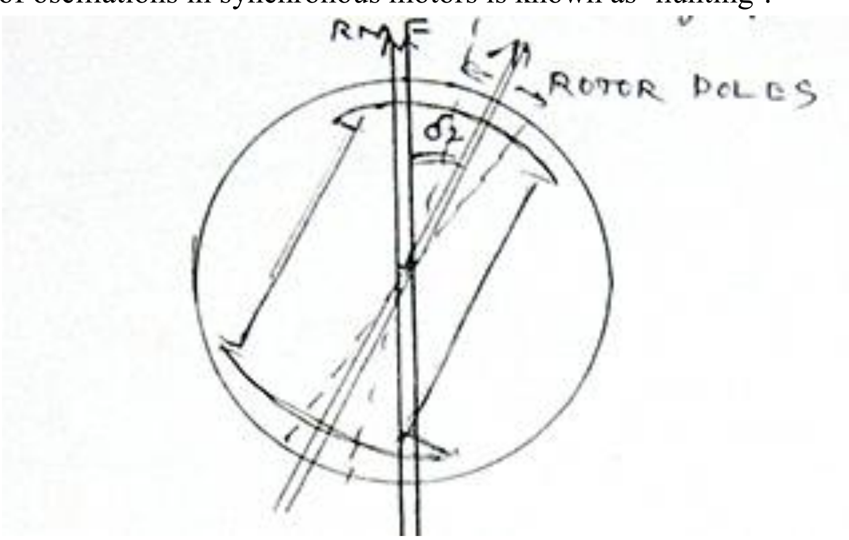
When synchronous motors are to be started with high loads this method is adopted .In these motors both stator and rotor are designed to rotate. The stator is mounted with Quill bearings allowing it to rotate. The rotor is connected with high load and has damper windings. When the stator is applied with AC voltage the torque produced is not sufficient to rotate the rotor and hence the stator will start rotating in the opposite direction to that of rotating magnetic field. When the stator reaches near synchronous speed DC field is fed to the rotor windings and the stator runs at synchronous speed .Now the stator is subjected to rope brake and the speed of the stator reduces to less than synchronous speed. Hence the rotor slowly starts picking up speed and ultimately,the stator stops running .Finally, the rotor reaches synchronous speed and continuous to run only at synchronous speed.

Hunting of synchronous motors:



When the load is increased suddenly, the rotor momentarily reduced in speed increasing the value of load angle to ‘δ_2’ from ‘δ_1’ to develop more power to meet the increase in load. But it does not stop exactly at the required new value ‘δ_2’ but slightly over shoots developing more power than required.

Hence, the rotor accelerates and crosses ‘δ_2’and reaches to a position where the load angle is less than ‘δ_2’developing lesser power and hence rotor again decelerates. This oscillation around the new load angle ‘δ_2’ continuous till it reaches a final steady state value of ‘δ_2’. This phenomenon of oscillations in synchronous motors is known as ‘hunting’.



Hunting is reduced by using damper windings provided in the pole faces of rotor. This winding which is shorted, produces a torque in opposition and reduces the oscillations caused by sudden change in load.

Frequency of Hunting:

Let the change in load angle be ‘θ’ = (‘δ_2’-‘δ_1’) for a change in applied load.

θ° electrical corresponds to $(\theta*2/p)^{\circ}$ mechanical

The torque due to rotor acceleration = 2/p *J* $\frac{\partial^2\theta}{\partial t^2}$

The damping torque = K* $\frac{d\theta}{dt}$

The damping torque due to electromagnetic effect (i.e) = K_2*[$\frac{VE}{Xs}\sin(\beta-\delta)\theta$]

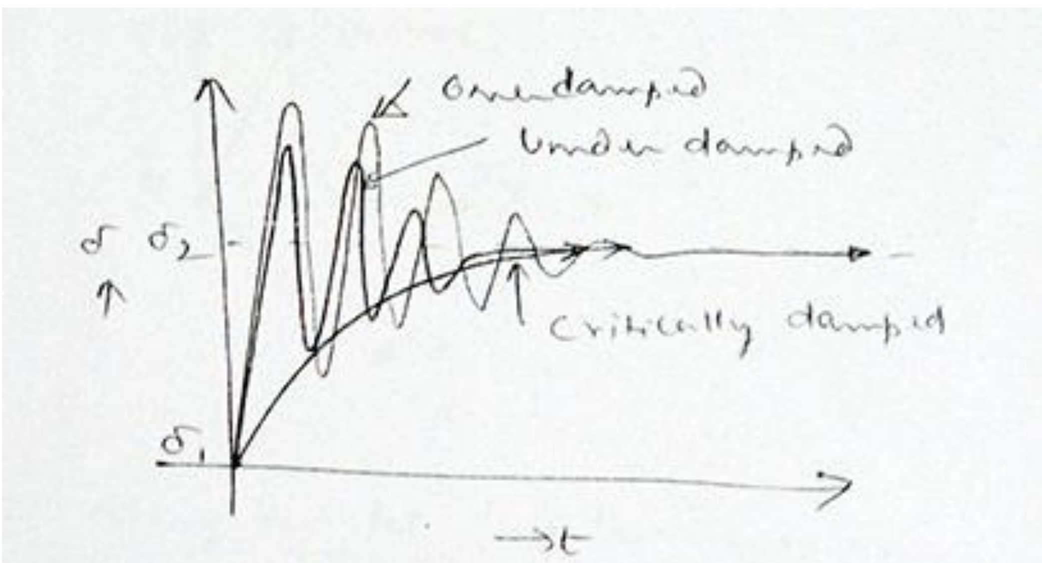
(the change in the torque developed)

(i.e) $\frac{2}{p}J\frac{\partial^2\theta}{\partial t^2}+K_1\frac{d\theta}{dt}+K_2\,[\frac{VE}{Xs}\sin(\beta-\delta)\theta]=\Delta T_l$

(D^2+2aD+b)θ = $\Delta T_l * \frac{2}{p}J$

Let a =K_1p/2J , b = K_2p/2J [$\frac{VE}{Xs}\sin(\beta-\delta)\theta$] $=\frac{p}{2J}K$

$$\theta = Ae^{(-a+\sqrt{a^2-b})t} + Be^{(-a-\sqrt{a^2-b})t}$$

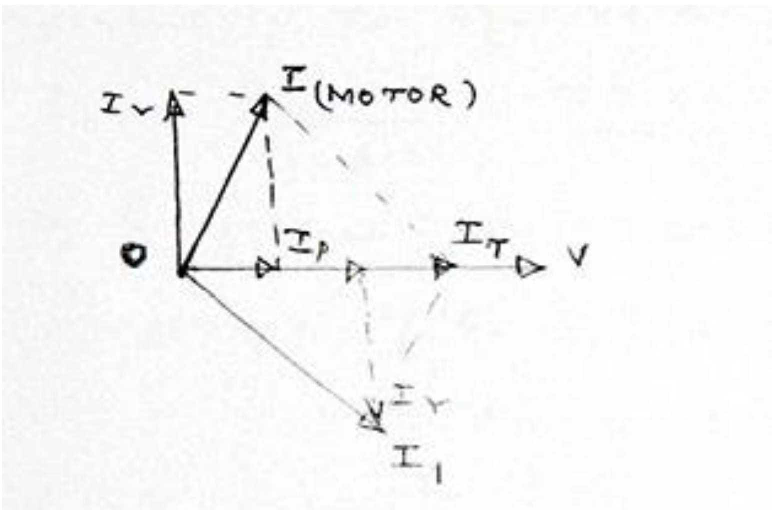


Frequency of Oscillation, ω = 2πf $=\sqrt{b-a^2}$ and f = $\frac{\sqrt{b-a^2}}{2\pi}$ c/s.

Synchronous condensers:

Over excited synchronous motors taking leading line current are known as ‘synchronous condensers’.

They are used for improving the power factor in a transmission line, from a very low lagging to unity pf. In addition to taking leading current it can also drive some mechanical load taking power component of the current.



The effects of very low pf line currents are,

- Reduced output
- Increase in line loss
- Low efficiency
- Demagnetizing armature reaction as the synchronous generators
- Poor regulation of alternators

Problem:

A manufacturing plant takes 200 kW at 0.6 pf from a 600 V, 60c/s ,3Φ system. It is desired to raise the pf of the entire system to 0.9 by means of a synchronous motor, which at the same time is driving a load requiring the synchronous motor take 80 kW from the line. What should be the rating of the synchronous motor in volts and amps?

Solution:

$$V_p = \frac{600}{\sqrt{3}} = 346 \text{ V} \quad \text{and} \quad I = \frac{200,000}{\sqrt{3}*600*.6} = 321\text{A}$$

I_1 = I cosθ = 321*0.6 = 192.6A

I_2 = I sinθ = 321*0.8 = 256.8A

@ 0.9 pf, θ = 25.8°

Energy component of the synchronous motor ,

$I_{1s} = \frac{80,000}{\sqrt{3}*600}$ = 77.0 A

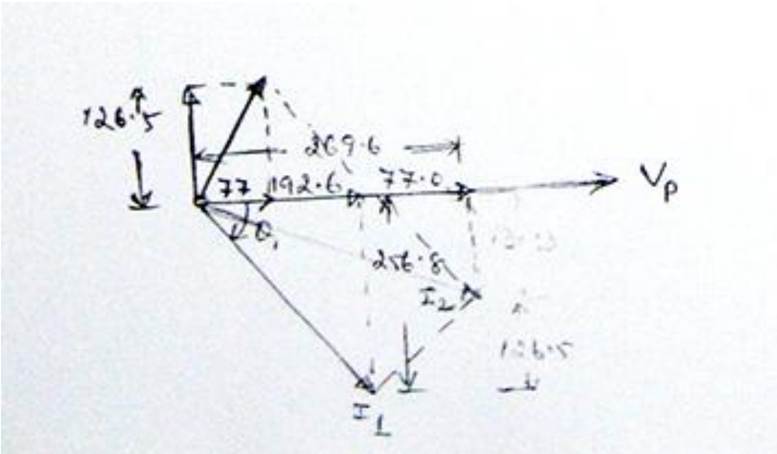
Total energy component of the system = 296.6*tan(25.8°)
= 130.3 A

Quadrature component synchronous motor = 256.8 – 130.3
= 126.5 A

Total current of the synchronous motor = $\sqrt{(77.0)^2+(126.5)^2}$

$=\sqrt{21,930}$ = 148 A

Hence the rating of synchronous motor $\sqrt{3}*148*600*10^{-3}$ = 154 kVA



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