SYNCHRONISED ASYNCHRONOUS MACHINES

By

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D.N. BUTAN.

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SYNCHRONISED ASYNCHRONOUS MACHINES.

SECTION . 1.

INTRODUCTION.

1.1. GENERAL THEORY :

The synchronised Asynchronous machine is fundamentally a slipring asynchronous motor. To give it a high starting torque, some resistance is introduced in the rotor circuit, which is cut in steps. When full asynchronous motor speed almost equal to synchronous speed is obtained, the rotor is connected to the d.c. exciter and the machine pulls into step and runs as synchronous motor.

In the asynchronous motor action, the secondary carries power currents only. Being produced by induction, this current automatically increases with load and so within limits (decided by rotor heating and consequently stator heating) provides for a certain overload capacity.

In the synchronous motor action, the secondary may carry in addition to power currents a part or whole of the magnetising current and possibly an over magnetising current which gives a leading component to stator current. The rotor current is however controlled by external means and must be large enough to allow for reasonable overload capacity.

1.2. COMPARISON WITH OTHER TYPES OF MACHINES :

The principal advantage which the machine possesses over a normal synchronous motor lies in its starting characteristics. It is well known that synchronous motor with damper windings for starting will only start against some 40 to 50 percent of full load torque and even then requires large currents at low power factor for an appreciable time where as the synchronised asynchronous motor starts up from rest like an asynchronous motor and easily synchronises itself almost instantaneously against full load or more than full load.

Its advantages over synchronous and asynchronous motors may be enumerated as follows:-

(1). It possesses a high starting torque.
(An advantage over synchronous motor)

(2). It runs at synchronous speeds.
(An advantage over asynchronous motor).

(3). No separate damper winding is needed. The low resistance of the rotor circuit serves both as damping windings and exciting windings.
Hence it is cheaper.
(Compared with synchronous motor which requires a separate damper winding)

(4). When loaded beyond its load limit as synchronous motor, it starts operating as an asynchronous motor.
(Compared to synchronous motor which comes to a dead stop.)

(5). It can operate at various power factors by the adjustment of load for constant excitation or by adjustment of excitation for constant load.

The excitation can be so adjusted to improve the power factor of the system.

1.3. CONSTRUCTION :

The stator of a synchronised Asynchronous motor is a standard asynchronous motor stator with semi-closed slots and either a concentric or a frame winding.

The rotor carries a three phase windings for asynchronous motor action. This winding can be re-arranged in several ways for d.c. excitation for synchronous motor action. The different types of rotor connections and their relative merits and demerits are given in great details in the later pages.

The motor must have an exciter which is driven either direct or in case of low-speed-machine by gearing or chain so as to give a higher speed and enable a smaller exciter to be used. However the modern practice is to use static exciters.

1.4. STARTING AND RUNNING CONNECTIONS :

The machine starts like wound rotor asynchronous motor. It starts up with resistance in the rotor circuit and is capable of starting against 2 to 2½ times full load torque. The rotor resistance is cut in steps till it is shorted. In order to synchronise, the rotor circuit is momentarily opened and closed again so as to include the exciter in the circuit. For a short period after the switch is closed, the rotor carries both, the induced alternating currents and the forced direct currents. The final action of these currents is to cause the machine to accelerate still further and in normal operation the synchronous speed is reached in a fraction of seconds.

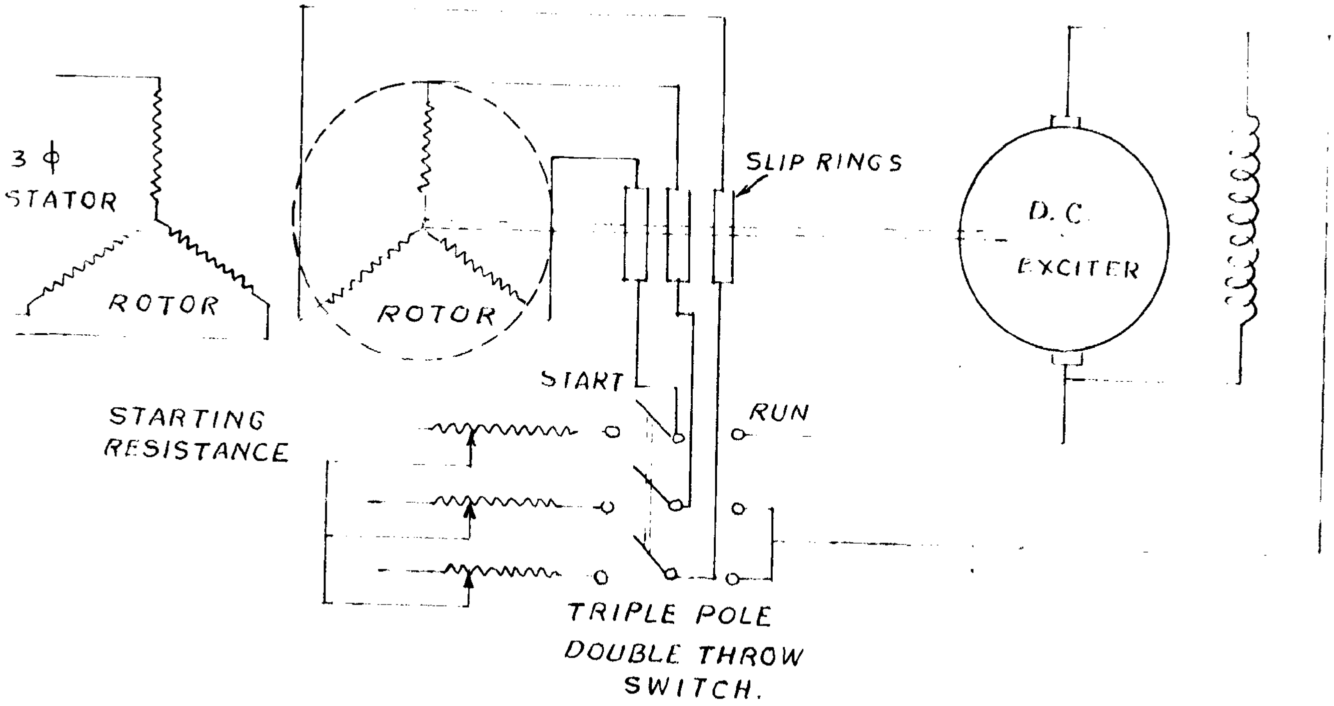


FIG. 1.4 STARTING AND RUNNING CONNECTIONS OF SYNCHRONISED ASYNCHRONOUS MACHINE.

SECTION - 2

BEHAVIOUR OF MACHINE AS ASYNCHRONOUS MOTOR

2.1. GENERAL :

The Behaviour of S.A.M. (synchronised Asynchronous motor) at starting is similar to that of a 3-phase slip-ring asynchronous motor. When a 3-phase supply is given to the stator, currents produced in the 3-phase windings create a magnetic field of constant strength which rotates at synchronous speed. The flux rotating at synchronous speed cuts the rotor conductors, produces e.m.fs and hence currents in the closed rotor circuit. The reaction between rotor currents and stator flux creates the torque which turns the rotor in the direction of the revolving field (stator flux).

2.2. LOCUS OF STATOR CURRENT.

The equivalent circuit of an asynchronous motor at a slip S is shown in the figure

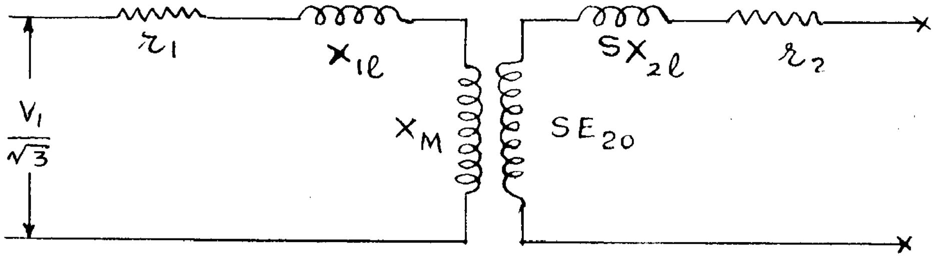


FIG. 2·21 :- THE EQUIVALENT CIRCUIT OF ASYNCHRONOUS MOTOR

where r_1 and r_2 are the stator and rotor resistances per phase, X_{1l} and X_{2l} are the stator and rotor leakage reactance per phase. and X_M is the magnetising reactance. E_{20} is the open circuit slip ring voltage per phase.

$$\text{Slip} \quad S = \frac{N_1 - N_2}{N_1}$$

Where N_1 is the synchronous speed and N_2 is the rotor speed.

$$\text{Rotor current } \bar{I}_r = \frac{S\bar{E}_{20}}{r_2 + j\,SX_{2l}} \quad \text{.....(i)}$$

$$I_r = \frac{SE_{20}}{\sqrt{[r_2^2 + (SX_{21})^2]}} \quad \text{.....(ii)}$$

$$I_r = \frac{E_{20}}{\sqrt{[(\frac{r_2}{S})^2 + (X_{2}l)^2]}}$$

when there is no slip i.e. $S = 0 \quad I_r = 0$

when there is infinite slip $S \rightarrow \infty \quad I_r = \dfrac{E_{20}}{j X_{21}}$

These two values of the current are represented by points P_0 and Z respectively.

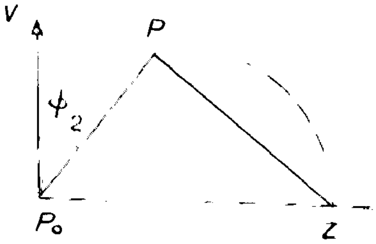


FIG. LOCUS OF ROTOR CURRENT

$$\text{Now } \sin \phi_2 = \frac{S X_{21}}{\sqrt{(r_2^2 + S^2 X_{21}^2)}} \qquad \ldots\ldots\ldots\ldots\ldots \text{(iv)}$$

where ϕ_2 = rotor power factor angle.

$$\text{or } \frac{S}{\sqrt{(r_2^2 + S^2 X_{21}^2)}} = \frac{\sin \phi_2}{X_{21}} \qquad \ldots\ldots\ldots\ldots\ldots \text{(v)}$$

Substituting (v) in equation (ii) it is found that

$$I_r = \frac{E_{20}}{X_{21}} \sin \phi_2 \qquad \ldots\ldots\ldots\ldots\ldots \text{(vi)}$$

$$\text{or } \frac{I_r}{E_{20}/X_{21}} = \sin \phi_2$$

Therefore $\angle P_0ZP = \phi_2$ and $\angle P_0PZ = 90^\circ$

Hence the locus of rotor current is a circle.

The stator current is the vector sum of rotor current $I_r \angle -\phi_2$ and the no load current $I_0 \angle -\phi_0$ so therefore the locus of stator current is also a circle as shown.

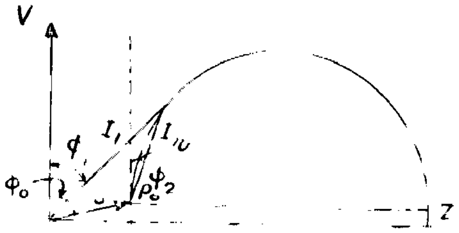


FIG 2.23 · LOCUS OF STATOR CURRENT

2.3. POWER AND TORQUE EQUATIONS:

Refering to the equivalent circuit Air gap power

$$P_g = E_{20}\, I_r \cos \phi_2$$

$$= E_{20} \frac{S E_{20}}{\sqrt{(r_2^2 + S^2 x_{2l}^2)}} \times \frac{r_2}{\sqrt{(r_2^2 + S^2 x_2 l)}}$$

$$= \frac{S E_{20}\, r_2}{r_2^2 + S^2 x_2 l^2}$$

Rotor copper loss $P_r = I_r^2\, r_2$

$$= \frac{s^2 E_{20}^2}{r_2 + s^2 X_2 1^2}\, r_2$$

Therefore the mechanical power developed PM

$$= P_g - P_r$$

$$= \frac{s E_{20}^2\, r_2}{r_2^2 + s^2 X_2 1^2} (1 - s) = P_g (1 - s)$$

$$= \frac{E_{20}^2}{\left(\frac{r_2}{s}\right)^2 + (X_2 1)^2}\, r_2\, \frac{1 - s}{s}$$

If T be the torque developed in Killogramme-meters, then

$$\frac{T \times 2 \pi N_2}{0.138} \times \frac{1}{33000} \times 746 = 3 P_M$$

Therefore

$$T = \frac{2.91}{N_1} \frac{s E_{20}^2}{r_2^2 + (s X_2 1)^2}\, r_2 \qquad \text{Kg-m}$$

For Maximum torque

$$\frac{dT}{ds} = 0 = \frac{r_2^2 + (S x_2 l)^2 - S(2 S \times x_2 l^2)}{\left[r_2^2 + (S x_2 l)^2 \right]^2}$$

Or $r_2 = \pm s x_{2l}$

Or $s = \pm \frac{r_2}{x_{2l}}$

In case of motor, slip is positive, so considering only the positive value of slip, the maximum torque becomes

$$T_M = \frac{2.91}{N_1} \frac{E_{20}^2}{2 x_{2l}} \text{ Kg-m.}$$

If rotor leakage reactance is given in stator turns, then

$$T_M = \frac{2.91}{N_1} \frac{V_1^2}{3 \times 2 x_{2l}'} = \frac{0.77}{N_1} \frac{V_1^2}{2 x_{2l}'} \text{ Kg-m.}$$

It is seen that maximum torque is independent of the rotor resistance. The rotor resistance only determines the slip at which this torque occurs.

In order to have a maximum torque at starting, the rotor resistance should be equal to stand still leakage reactance of the rotor. Not only should the value of resistance and reactance be equal but they should be of small value if large starting torque is required. If the rotor resistance is more than the rotor reactance at stand still, torque instead of increasing will decrease.

2.4. MOTOR PERFORMANCE FROM CIRCLE DIAGRAM

The following is the data that can be obtained from the circle diagram. P is taken to be the full load point and tangent have been drawn at P' and L parallel to the output line and torque line respectively.-

thus establishing the maximum output and torque values.

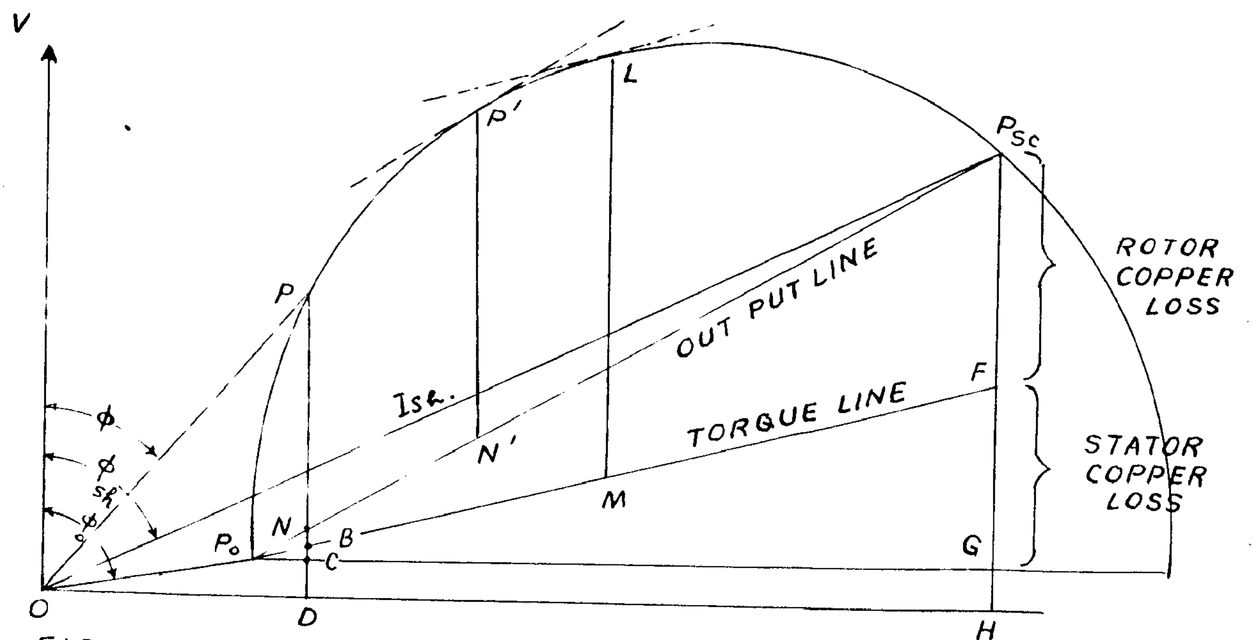


FIG. 2·4 :- CIRCLE DIAGRAM OF ASYCHRONOUS MOTOR.

OP_o = No load Current

Cos ϕ_o :- No load power factor.

Ish :- Short circuit current

Cos ϕ_{sh} :- Short circuit power factor

$P_{sc}G$:- Rotor input at stand still (S = 1)

= Stator copper loss + rotor copper loss at stand still.

P_{sc} F :- Rotor copper loss at stand still

FG :- Stator copper loss at stand still

OP :- Full load current.

Cos ϕ :- Full load power factor.

PN :- Full load output

NB :- Full load rotor copper loss

BC :- Full load stator copper loss

CD :- Iron and friction loss (No load loss)

PB :- Rotor input (Torque in synchronous watts)

$\frac{PN}{PD}$ = Efficiency

$\frac{NB}{PB}$ = Slip

$\frac{P'N'}{PN}$ = Over load capacity = $\frac{\text{Maximum load}}{\text{Full load}}$

$\frac{LM}{PB}$ = Stalling torque/full load torque

$\frac{PS_oF}{PB}$ = Starting torque/full load torque

2.5. SPEED TORQUE CHARACTERISTICS

The speed torque characteristics of an asynchronous motor are as shows

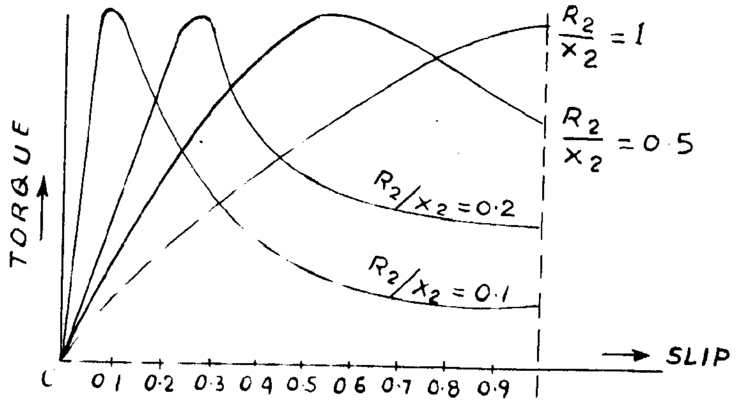


FIG. 2·5 : SPEED TORQUE CHARACTERISTICS

The curves show how the increase of resistance increases the starting torque. The value of resistance has absolutely no effect on the magnitude of maximum torque. It only controls the slip at which it occurs.

2.6. THE EFFECT OF AIR GAP ON THE MAXIMUM OUTPUT

Considering the ideal circle diagram of an asynchronous motor in which the losses are neglected. The stator current taken by the motor when running light is I_μ represented by OP_0 is purely reactive. The machine under such conditions runs at synchronous speed.

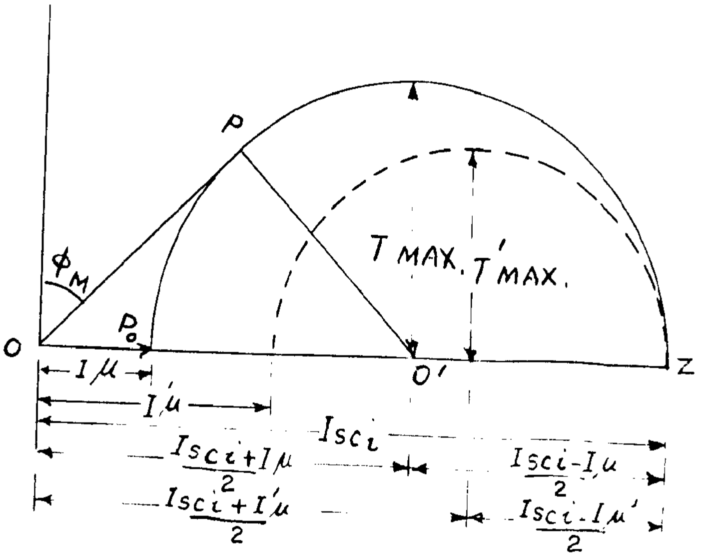


FIG. 2·6.

Next consider that the rotor is locked. This time asynchronous motor acts like a transformer with its secondary short-circuited The ideal short circuit current taken by that stator is I_{sci} represented by OZ.

Having obtained the magnetising current and the short circuit current, the stator current locus can be drawn with P_0Z as diameter.

The maximum power factor is that given by the tangent OP. Therefore $\cos \phi_M = \dfrac{I_{sci} - I_\mu}{I_{sci} + I_\mu}$.

The ratio of maximum torque to the full load torque is

$$\frac{T_{MAX}}{T_{RATED}} = \frac{(I_{sci} - I_\mu)/2}{I_n \cos \phi}$$ where I_n = rated current.

If the value of I_μ increases to I_μ', the over load capacity decreases. In order to have improved power factor the value of I_μ should be as small as possible and to have a large overload capacity the value of I_{sci} should be as large as possible.

Now the magnetising current I_μ has to set up certain amount of flux in the magnetic circuit and the air gap. The air gap ampere turns constitute the major percentage of no load ampere turns. If B_g be the flux density in air gap in lines per square centimeter and S be the length of air gap in centimeters, then air gap ampere turns/pole $= 0.8\, B_g \times S$

Taking the ampere turns for other parts like stator core, teeth and rotor yoke to be K times the air gap ampere turns, the total no load ampere turns for the machine are

$= 0.8\,(1+K)\; B_g \times S$ where the value of K may vary between 0.05 to 0.2

The amplitude of the fundamental of the ampere - turn wave set up by 3-phase currents is

$f(x) = 0.9\frac{m}{2}\, n_s\, q\, Kdp_1\, I_\mu$ (Derived in Appendix)

The total no load ampere turns/pole for the machine, must equal the amplitude of the fundamental of the ampere-turn wave

$$\therefore\quad 0.9\frac{m}{2}\, n_s\, q\, Kdp_1\, I_\mu = 0.8(1+K)\; B_g \times S$$

$$\therefore\quad I_\mu = \frac{0.8(1+K)\; B_g \times S}{0.9\frac{m}{2}\, n_s\, q\, Kdp_1}$$

or $I_\mu \propto S$.

Therefore it is evident that magnetising current I_μ is directly proportional to the air gap length. So in order to secure a small magnetising current, air gap should be as small as possible. However, the mechanical considerations like peripheral speed, deflection etc. limit the smallness of the air gap.

The ideal short circuit current is given by

Impressed voltage/ Total leakage reactance.

Total leakage reactance consists of slot leakage reactance, and winding leakage reactance and harmonic leakage reactance. The slot leakage reactance depends upon the geometry of the slot and does not depend upon the air gap. Similarly the over hang leakage reactance depends upon the length of end conductors, their shape and the type of winding connections. So it is also not dependant upon air gap length. The harmonic leakage is however inversely proportional to the length of air gap.

Hence a decrease in the length of air gap decreases the value of I_μ in direct proportions and decreases the value of I_{sc1} by a very short amount. So the power factor is improved and the overload capacity is increased.

SECTION - 3

3.1. ROTOR CONNECTIONS FOR D.C. EXCITATION

GENERAL :

Any A.C. machine must have equal no. of poles on stator and rotor but need not have equal number of phases. The supply normally 3-phase governs the stator but 3, 2, or single phase rotors may all be used.

The rotor having a 3-phase winding can not be directly used for D.C. excitation. Some alterations are to be done in the rotor connections for d.c. excitation. The alterations so performed must conform to the following requirements:

1. To give a sinusoidally distributed m.m.f to the rotor.
2. To distribute the power loss as evenly as possible.
3. To cause the damping currents to be generated if the load pulsates.
4. To keep the secondary stand-still voltage to a reasonabl value.
5. To permit temporary asynchronous operation if the maximum synchronous torque is exceeded.

All the above requirements have been dealt separately.

3.2. SINUSOIDALLY DISTRIBUTED M.M.F

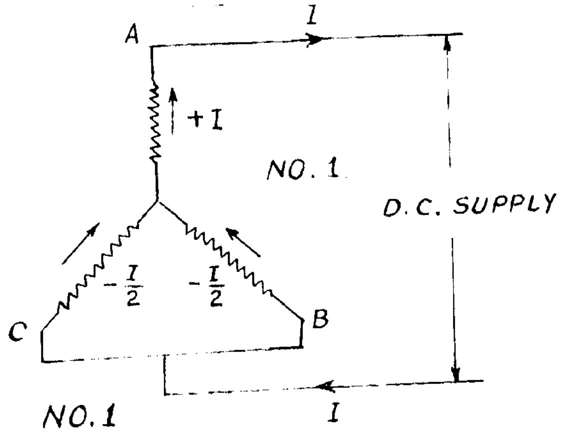
In case of S.A.M. working as asynchronous motor, slip frequency currents are induced in the rotor which produce m.m.f wave which travels with respect to rotor at a speed which is slip times the synchronous speed and is in the direction of motion. Superimposed upon this rotation is the speed of rotor. So the stator and the rotor poles are therefore stationary with respect to each other. But when d.c excitation is switched on, it produces m.m.f wave which remains fixed w.r.t rotor windings and does not creep forward like the A.C. m.m.f.

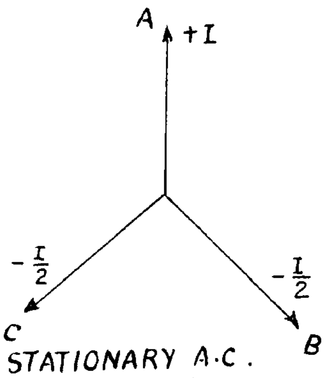
The D.C. m.m.f wave contains certain harmonics. These harmonics may produce harmonic voltages which will circulate parasitic currents in the stator, though various arrangements are available to eliminate harmonic voltages. For example two thirds chording will eliminate phase third harmonic and star connection line third harmonic in a 3-phase winding. The stator leakage impedance presented to any harmonic will rise with the order of the harmonic. A quiter machine will require to have a sinusoidally distributed m.m.f. The various systems of

D.C. excitation are considered below in the light of their harmonic contents.

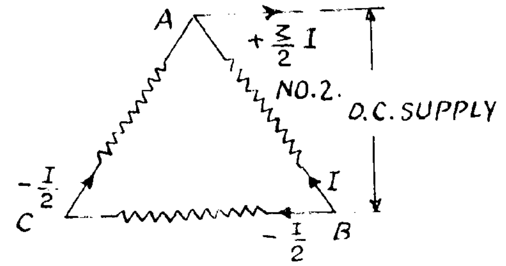
3.2.1 3-PHASE SYSTEM:

If the windings are excited as shown by methods No 1 and 2

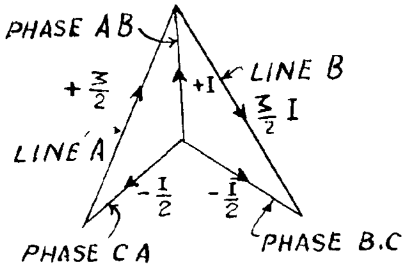




STATIONARY A.C. VECTORS.

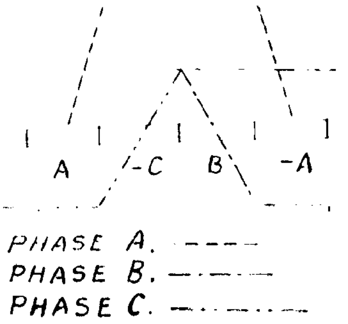


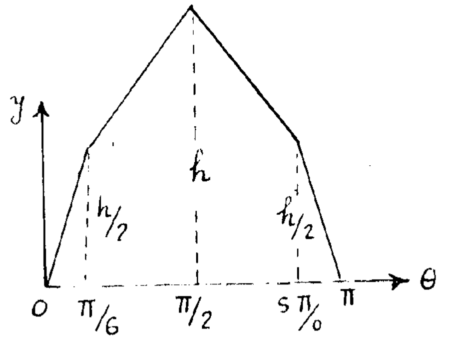
NO.2. EXCITATION METHOD



STATIONARY A.C. VECTOR.

The corresponding m.m.f wave form for both the above methods is





SHAPE OF RESULTANT m m f

The above wave form can be analysed into

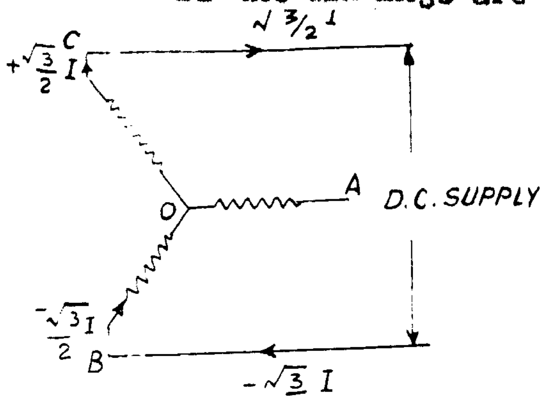
$$\frac{9h}{\pi^2}\left[\sin\theta + \frac{1}{5^2}\sin 5\theta - \frac{1}{7^2}\sin 7\theta - \frac{1}{11}\sin 11\theta \cdots\cdots\right]$$

Where h = m.m.f at the centre of the pole = $\frac{4\pi n I}{10}$

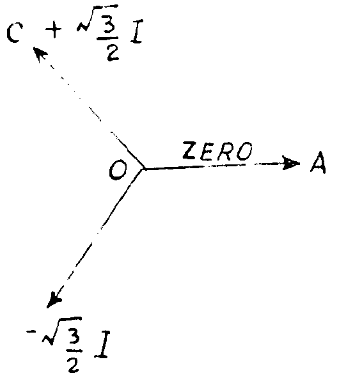
n = No. of conductors/pole/phase

I = Maximum phase current.

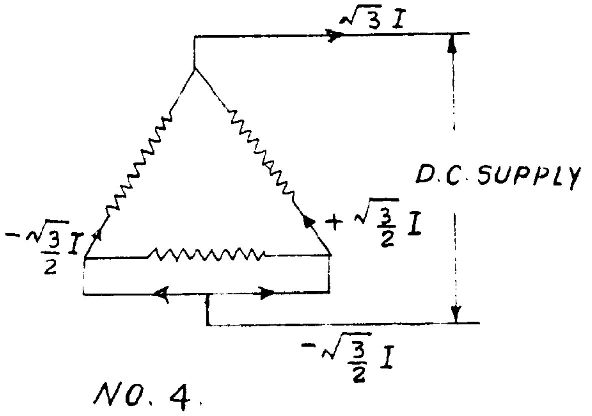
If the windings are excited as shown by method No.3 and 4



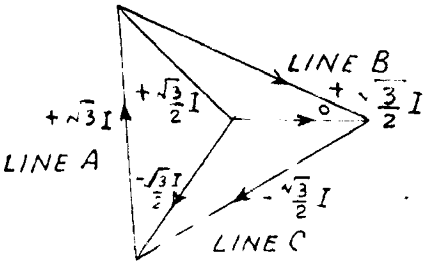
NO. 3.



STATIONARY A.C. VECTORS

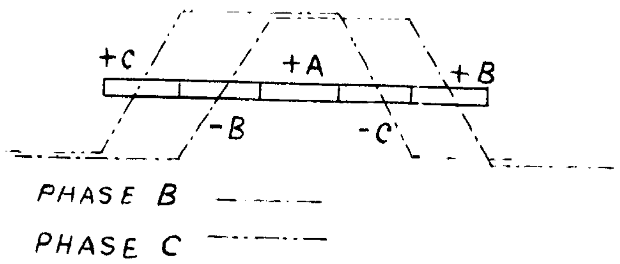


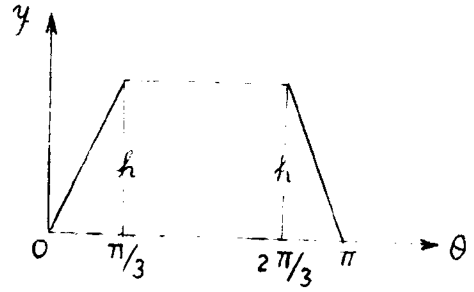
NO. 4.



STATIONARY A C VECTORS

The corresponding wave form for the above methods is





SHAPE OF RESULTANT m m f

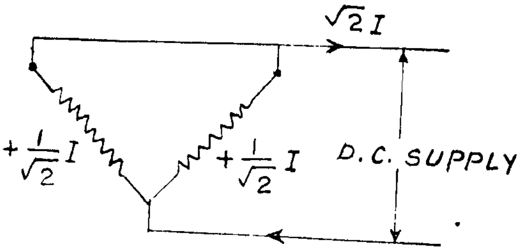
The above wave form can be analysed into

$$\frac{6\sqrt3\,h}{\pi^2}\left[\sin\theta - \frac{1}{5^2}\sin 5\theta + \frac{1}{7}\sin 7\theta - \frac{1}{11^2}\sin 11\theta \,\cdots\right]$$

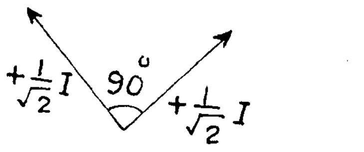
Where h = m.m.f at the centre of pole $= \frac{4\pi}{10}\,\frac{\sqrt3}{2}\,I.n.$

3.2.2. TWO PHASE SYSTEM

If the rotor is wound only for two phases and excited as shown ~~in~~ by method No. 5

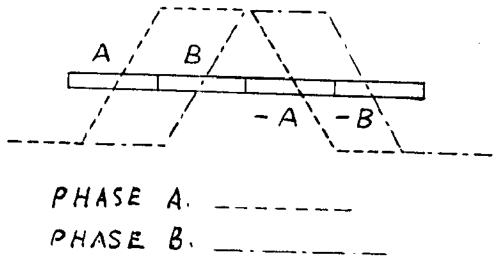


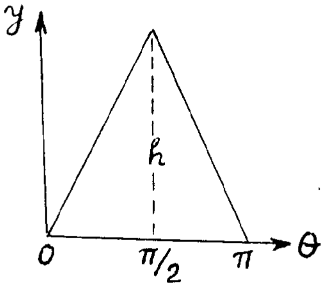
NO. 5



STATIONARY A.C. VECTOR

The m.m.f wave form for the above excitation is





SHAPE OF RESULTANT m.m.f

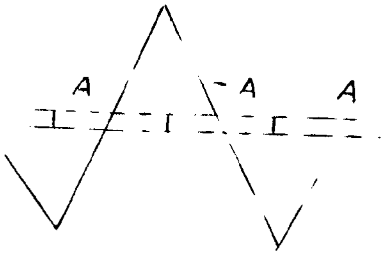
The above m.m.f wave form can be analysed into

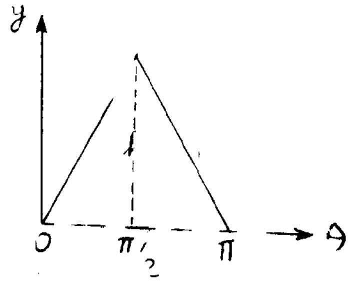
$$\frac{8h}{\pi^2}\left[\sin\theta - \frac{1}{3^2}\sin 3\theta + \frac{1}{5^2}\sin 5\theta \cdots\cdots\right]$$

where $h = \frac{4\pi}{10} n \cdot \frac{I}{\sqrt{2}}$

3.2.3. SINGLE PHASE SYSTEM

If rotor is wound only for one phase, the m.m.f wave form is shown.





SHAPE OF m.m.f. CURVE

The above m.m.f wave form can be analysed into

$$\frac{8h}{\pi^2}\left[\sin\theta - \frac{1}{3^2}\sin 3\theta + \frac{1}{5^2}\sin 5\theta \cdots\cdots\right]$$

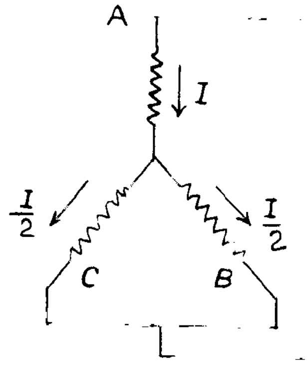
where $h = \frac{4\pi}{10} nI$

3.2.4. CONCLUSIONS.

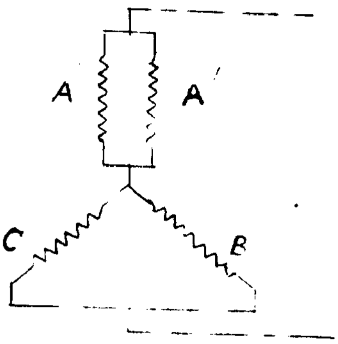
1. In all the 3-phase systems, the fundamental m.m.f has the value $\frac{3.6n.I}{\pi}$. Also there are smaller harmonic m.m.fs.
2. In all the two phase systems, the fundamental m.m.f has the value $\frac{2.26\,nI}{\pi}$. Also there are smaller harmonic contents.
3. The harmonic contents are of greater magnitude in one phase and two phase system than with 3-phase system. Hence three phase system is to be prefered to other systems.

3.3. DISTRIBUTION OF HEATING IN ROTOR

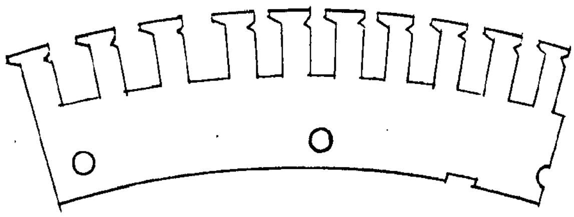
In 3-phase system of excitation, one phase carries double the current than the other two phases and since all the phases have the same resistance, the relative heating in the phase A;B;C is 1 : 0.25 : 0.25.



If the thermal conductivity of the secondary insulation is very high, this uneven generation of heat will very nearly smooth out. But if it is otherwise, temperature reached will be different in different parts of the windings. This difference of the temperature can be avoided by making the slot for phase A of approximately double the size than that for the phase B and C. Instead of having one winding in phase A, two parallel circuits of winding each having the same no. of turns and resistance as phase B and C can be arranged. The relative heating in the phase A: A' : B : C is now 1 : 1 : 1 : 1 So the machine issaved of the ill-effects of uneven heat generation.



The rotor stampings have, slots of this type is shown in fig.



STAMPING OF 1200 K.W. MACHINE.

3.4. SELF- DAMPING PROPERTIES :

All the synchronous machines may hunt on pulsating loads. The low resistance of the secondary permits its use both as damping and exciting windings.

Fig. (a) and (b) show the stator field, the rotor circuit corresponding to excitation methods No. 1 and 3 and the exciter circuit

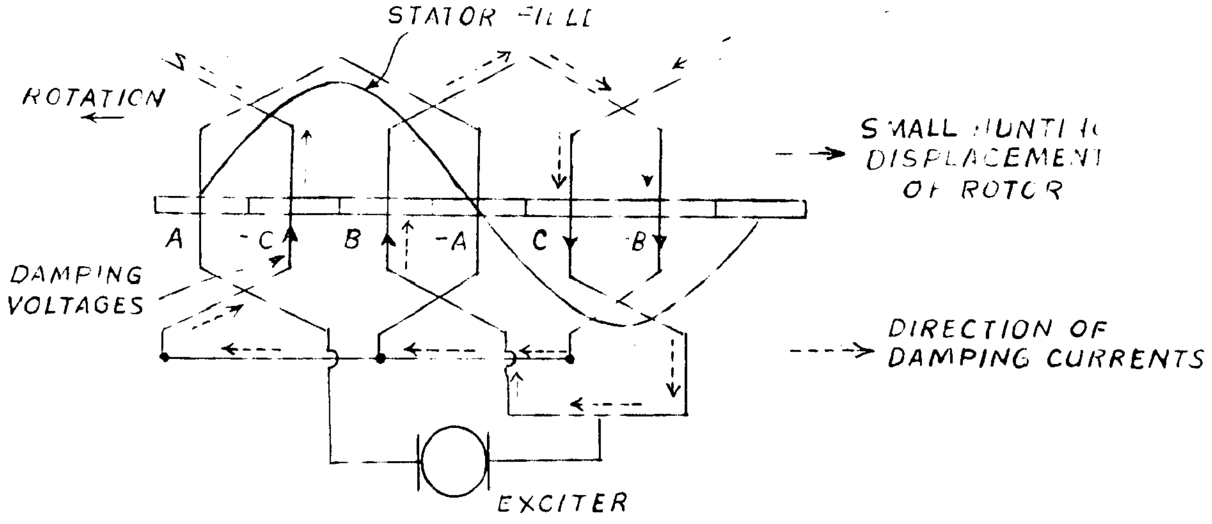


FIG. (a)

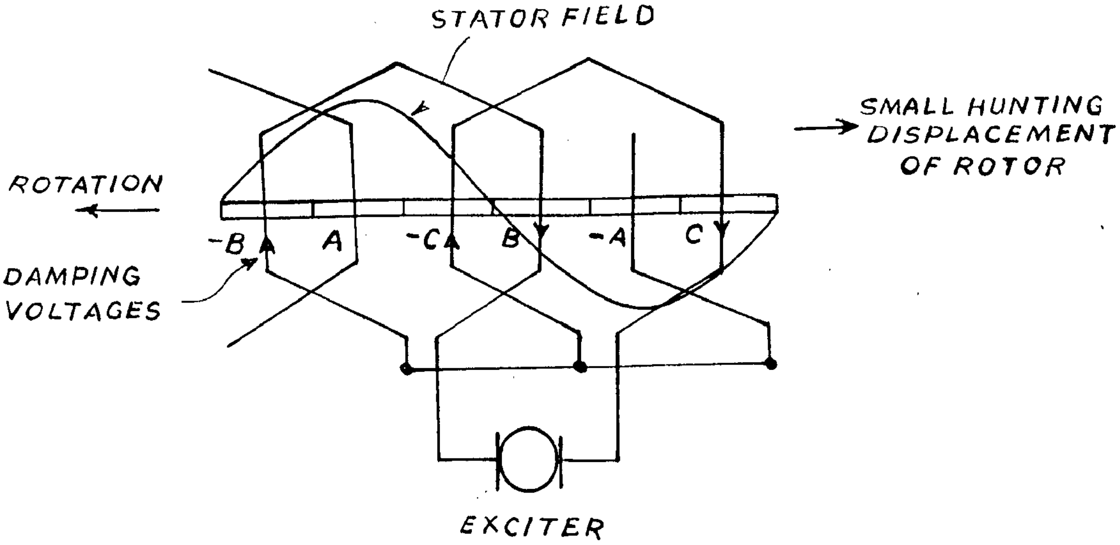


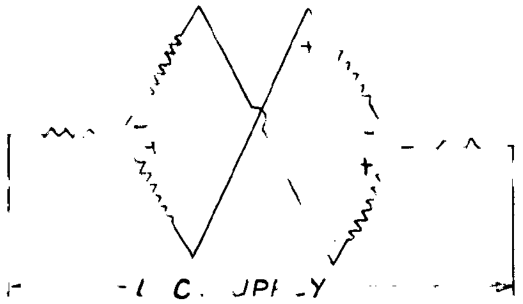
FIG. (b)

As the rotor moves relative to the stator field, owing to the pulsations of load, extra voltages are generated in all the phases which may assist or oppose one another in the windings. If they assist one another in a closed path as shown in fig. (a) currents will be induced in the rotor which will tend to damp out the pulsations. If they oppose one another as shown in fig. (b) there is no damping.

It is seen that when phases are fed in parallel damping in satisfactory but it is not so when they are in series.

3.5. SECONDARY STAND-STILL VOLTAGES:

The secondary stand-still voltages should be less than 2500 volts in any case. If however, the turns disposition is such that stand-still voltage is more than this value, each phase may be wound in two halves so that the whole winding forms double inverted star. Either one star may be used for starting or both in parallel. The two are connected in series for running. The interconnection must be made as shown,



so that the damping voltages are additive. The relative polarities of damping voltages are as shown.

3.6. SHORT -TIME ASYNCHRONOUS OPERATION

The pull out torque of S.A.M. if used as asynchronous motor is usually higher than as synchronous motor. It is therefore best to use a winding which leaves the rotor connected for asynchronous operation.

If the peak load occurs, the machine may work for an instant as asynchronous motor and return to synchronism after the peak. The asynchronous action is unsteady due to superimposed synchronous torque but it is permissible for a brief period.

3.7. GENERAL COMMENTS ON CHOICE OF ROTOR CONNECTIONS

In case of single phase rotor, the machine has got less of starting torque because of increased leakage reactance as compared with 3-phase and 2-phase rotors, and also the machine depicts crawling tendency at half speed, so single phase rotors are not at all used.

The two phase system of rotor connection has greater proportions of harmonic contents in the m.m.f wave form than three phase system. Hence it is not prefered to three phase system.

In three phase system, there are no. of ways in which d.c. excitation may be supplied, but it is only method No.1 which possesses good damping action. The other methods have very poor damping action.

SECTION - 4

BEHAVIOUR AS SYNCHRONOUS MACHINE

4.1. GENERAL

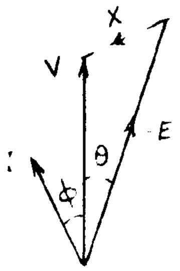
The synchronous motor has got two unique characteristics namely the absolute constant speed and the adjustable power factor. If the machine is over excited, the stator current takes the leading power factor and if it is underexcited, it takes lagging power factor.

The S.A.M. combines the good starting performance of wound rotor asynchronous motor with the desirable running characteristics of synchronous motor. Since the design requirements for the synchronous motor and the asynchronous motor are diametrically opposed, so the starting performance to some extent is sacrificed to obtain the best synchronous motor characteristics. The behaviour of machine as synchronous motor is contained in the following paragraphs.

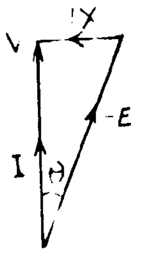
4.2. POWER OUT PUT OF THE MACHINE :

In the case of large electrical rotating machines the armature resistance is much smaller than various reactances and hence the armature resistance is neglected.

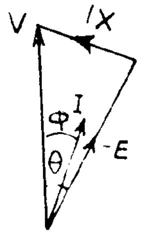
The vector diagrams for leading unity and lagging power factor are shown



(a) LEADING p. f.



(b) UNITY p. f.



(c) LAGGING p. f.

The supply voltage V impressed on the armature is balanced by the generated voltage E (by the field system) and the armature impedance drop IX (All these values are per phase). Power developed per phase = EI Cos (Ø ± θ) ; +ve sign for leading power factor and - ve sign for lagging power factors. If all the losses are neglected, then power developed is equal to power input, therefore

$$EI\ \mathrm{Cos}(\varnothing \pm \theta) = VI\ \mathrm{Cos}\,\varnothing \quad \ldots\ldots\ldots\ldots\ldots\ldots (i)$$

Considering the vector diagram, triangle

$$(XI)^2 = V^2 + E^2 - 2\,VE\ \mathrm{Cos}\,\theta$$

$$\text{or } I = \pm\frac{\sqrt{(V^2+E^2-2VE\ \mathrm{Cos}\,\theta)}}{X} \quad \ldots\ldots\ldots\ldots\ldots (ii)$$

$$\text{Also } \frac{IX}{\mathrm{Sin}\,\theta} = \frac{E}{\mathrm{Sin}\,(90 \pm \varnothing)} = \frac{\pm E}{\mathrm{Cos}\,\varnothing}$$

$$\text{Or } \mathrm{Cos}\,\varnothing = \frac{\pm E\ \mathrm{Sin}\,\theta}{IX} = \frac{E\ \mathrm{Sin}\,\theta}{(V^2+E^2-2VE\ \mathrm{Cos}\,\theta)} \quad \ldots (iii)$$

Power input/phase = VI Cos Ø

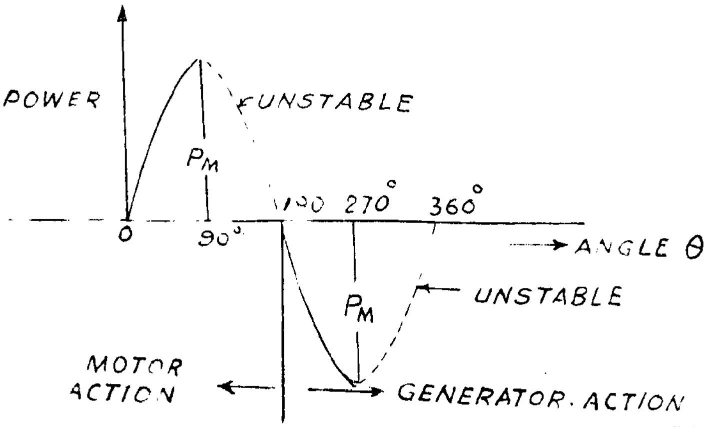
$$= V.\frac{\sqrt{(V^2+E^2-2VE\ \mathrm{Cos}\,\theta)}}{X} \cdot \pm \frac{E\ \mathrm{Sin}\,\theta}{\sqrt{(V^2+E^2-2VE\ \mathrm{Cos}\,\theta)}}$$

$$= \frac{VE}{X}\ \mathrm{Sin}\,\theta$$

The maximum load of synchronous motor which if exceeded will cause the motor to fall out of step is given by

$$P_M = \frac{VE}{X} \qquad \text{where } \theta = 90^\circ$$

The power angle diagram of synchronous machine is as shown



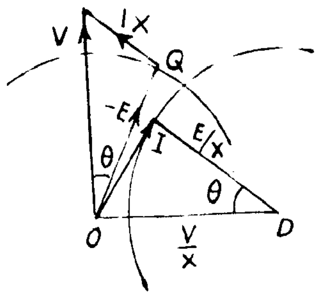
The maximum power as motor is that corresponding to $= 90^\circ$ After this the motor characteristics are quite unstable and the machine comes to rest ([redacted])

4.3. CURRENT LOCUS FOR CONSTANT EXCITATION:-

If saturation is neglected, E is directly proportional to excitation. Considering the vector diagram,

$$(IX)^2 = V^2 + E^2 - 2\,VE\cos\theta$$

If excitation is kept constant (which means to say E is constant), as the load varies locus of point Q is a circle having its centre at O and radius equal to E.

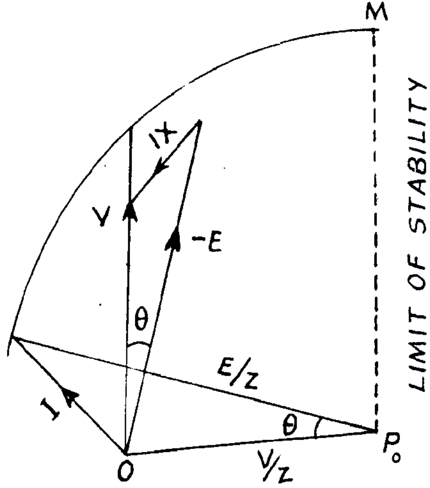


To determine the locus of I, it may be observed that since locus of IX is a circle and as X is a constant, that of I should be another circle.

$$(I)^2 = (V/X)^2 + (E/X)^2 - 2\, V/X .\, E/X \cos\theta$$

Which states that I is one side of the triangle whose other two sides are of constant lengths V/X and E/X including a variable angle θ. Consequently locus of I is a circle with radius E/X and its centre being D. Where phasor $OD = \frac{V}{X}$ lags behind the voltage by angle $\phi_0 = \tan^{-1} X/R$

Now if the excitation of the machine is increased I can be made leading as well. The maximum power of synchronous machine is VE/ X. This E/X is the radius of the circle. As voltage is constant, and the radius of circle $P_0M = E/X$ then P_0M to certain scale represents the maximum power of the machine



If the machine be under-excited, the radius of circle shrinks and the current may be lagging for all loads. The maximum power will obviously be much reduced.

4.4 EFFECT OF AIR GAP ON MAXIMUM POWER AVAILABLE IN A SYNCHRONOUS MACHINE.

The maximum power available in a non-salient synchronous machine is

$$P_M = VE / X$$

where V = Applied voltage which is constant

E = E.M.F. generated in stator due to excitation in rotor.

X = Synchronous reactance.

For a constant voltage V and constant excitation (i.e. E is also constant), maximum power available is inversely proportional to the synchronous reactance X.

But $X = x_l + x_a$

where x_l = Leakage reactance of stator

x_a = Armature reaction reactance.

Now armature leakage reactance $x_l = x_s + x_o + x_h$

where x_s = Slot leakage reactance

x_o = Overhang leakage reactance

x_h = Harmonic leakage reactance

Of course harmonic leakage reactance is almost absent in synchronous machines where the length of air gap is large. But here asynchronous machines to be run as synchronous machines are being considered.

The slot and over hang leakage reactance are independent of air gap length but harmonic leakage reactance varies inversely with air gap length. So total leakage reactance may be written as

$$x_l = a + b/g \text{ ------------------------------ } (1)$$

The behaviour of the armature reaction reactance is to be investigated. The maximum armature reaction ampere-turns of the fundamental of the Ampere-turn wave are

$AT_1 = m/2 \; 0.9 \; I \, N_c \, q \; kdp_1$ (Refer to Appendix)

where m = no. of phases

N_c = No. of conductors per slot

I = R.M.S. value of the current per phase.

q = No. of slots per pole per phase.

kdp_1 = Winding factor.

Flux density in air gap $B_{a1} = \frac{AT_1 \times 0.4\pi}{\delta}$

Flux per pole pitch $\Phi_{a1} = B_{a1} \frac{2}{\pi} l_e \tau_p$.

where l_e = equivalent length of armature.

= Pole pitch.

Voltage induced due to this flux

$E_{a1} = 4.44 \, f \, T_{ph} . kdp_1 \times 10^{-8} \; B_{a1} \frac{2}{\pi} \; l_e \tau_p$ Volts.

where T_{ph} = turns/phase.

or $E_{a1} = 4.44 \, f \, T_{ph} \, Kdp_1 \times 10^{-8} \left[\left(\frac{m}{2} \, 0.9 \, I \, N_c \, q \, Kdp_1 \right) \left(\frac{2}{\pi} l_e \tau_p \right) \left(\frac{0.4\pi}{\delta} \right) \right]$

X_a = Armature reaction reactance.

$$= \frac{E_{a1}}{I} = 4.44 \, f \, T_{ph} \, Kdp_1 \times 10^{-8} \times \left[\left(\frac{m}{2} \, 0.9 \, N_c \, q \, Kdp_1 \right) \left(\frac{2}{\pi} l_e \tau_p \right) \left(\frac{0.4\pi}{\delta} \right) \right]$$

$$\text{or} \quad X_a \propto \frac{1}{\delta}$$

$$\text{or} \quad X_a = \frac{k}{\delta}$$

$$\therefore \quad X' = a + \frac{b}{\delta} + \frac{k}{\delta}$$

$$= a + \frac{c}{\delta}$$

$$\therefore \quad P_M = \frac{VE}{a + c/\delta}$$

An increase in δ means decrease in denominator and hence increase in power developed. So machine with a large air gap can deliver more power and hence is more stable.

4.5 PRACTICAL CIRCLE DIAGRAM OF SYNCHRONOUS MOTOR

If in the circle diagram of a synchronous motor a line be drawn corresponding to the I^2R loss in the machine, then the vertical intercept between the circle and the line, corresponding to a given value of the stator current, gives the power developed in the machine, which can be directly read.

UNDER-EXCITED MACHINE

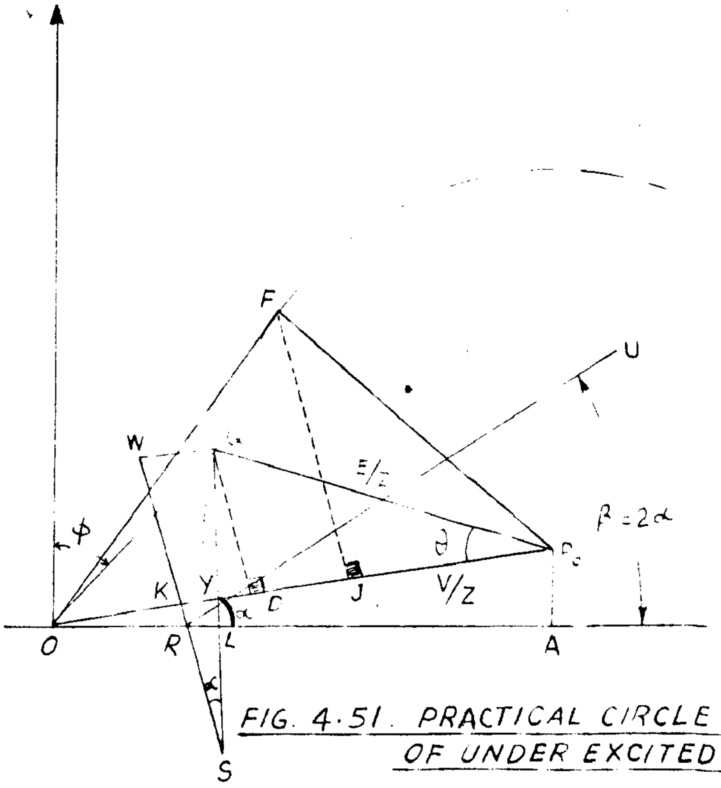


FIG. 4·51. PRACTICAL CIRCLE DIAGRAM. OF UNDER EXCITED MACHINE

Power input $= V.\,OQ.\,\mathrm{Cos}\,\phi$

$= V.\,QL.$

Copper loss $= OQ^2.\,R.$

$\mathrm{Cos}\,\alpha = X/Z$ and $\mathrm{Sin}\,\alpha = R/Z$

Co-ordinates of centre P_0 of the circle are

$$OA = OP_0\,\mathrm{Cos}\,\alpha = V/Z\,.\,X/Z = VX/Z^2$$

$$AP_0 = OP_0\,\mathrm{Sin}\,\alpha = V/Z.\,R/Z = VR/Z^2$$

Power developed $= V.\,QL - OQ^2\,.R.$

Now $OQ^2.R = R\,[QP_0^2 - OP_0^2 + 2.OQ.OP_0\,\mathrm{Cos}\,\angle QOP_0]$

$= R\,[QP_0^2 - OP_0^2 + 2.OP_0.\,OD]$

$= 2R.\,OP_0.\,OD. + R\,[QP_0^2 - OP_0^2]$

$= 2R.\,OP_0.\,OD - R.\,OF^2.$

where OF is tangent to circle.

Now triange OFP_0 and OFJ are similar.

$$\frac{OF}{OJ} = \frac{OP_0}{OF} \quad \text{Therefore} \quad OF^2 = OJ.\,OP_0$$

$\therefore\ OQ^2.R = 2\,R.\,OP_0.OD - R.\,OJ.\,OP_0$

$= 2R.OP_0.OD - R.OP_0\ 2\,OK$

Where $OK = OJ/2$

$= 2R.\,OP_0\,(OD - OK)$

$= 2R.OP_0\,.KD$

$= 2R.OP_0.Qw$ where Qw is parallel to and equal to KD.

$= 2R.OP_0\ QS\ \mathrm{Sin}\,\alpha$

Power Delveloped $= V.QL. - 2\,R\,OP_0.QS\,.\,\mathrm{Sin}\,\alpha$

$= V.QA - V.L.S - 2R.OP_0.QS\ \mathrm{Sin}\,\alpha$

$= V.QS. - V.L.S - 2R.\,QS.\,AP_0$

$= QS\,(V - 2R.\,AP_0) - V.L.S.$

Let y be any point on QS

Useful power = Qy $[V-2R.AP_0]$ + YS $[V-2R.AP_0]$ $- V.LS$

If $Y_S(V - 2R.AP_0) = V.LS.$

$$\text{or } \frac{YS}{LS} = \frac{V}{V - 2R.AP_0}$$

Power developed is then given by

$$QY(V-2R.AP_0)$$

If from R a line is drawn making an angle and cutting QL in Y_1 then.

$$\tan\beta = \frac{YL}{RL} = \frac{YS-LS}{RL} = \frac{YS-LS}{LS\tan\alpha} = \frac{YS}{LS\tan\alpha} - \cot\alpha = \left(\frac{YS}{LS} - 1\right)\cot\alpha$$

$$\text{or } \tan\alpha \tan\beta = \frac{YS}{LS} - 1$$

$$= \frac{V}{V-2R.AP_0} - 1 = \frac{2R.AP_0}{V-2R.AP_0} = \frac{2R\frac{VR}{Z^2}}{V-2R\frac{VR}{Z^2}}$$

$$= \frac{2R^2}{Z^2-2R^2} = \frac{2R^2}{x^2-R^2} = \frac{2(R/x)^2}{1-(R/x)^2} = \frac{2\tan^2\alpha}{1-\tan^2\alpha}$$

$$\tan\beta = \tan 2\alpha$$

$$\beta = 2\alpha$$

So the vertical intercept between the circle and the line R.Y.U will represent the power developed.

OVER-EXCITED MACHINE:

In case of an over excited machine, since the origin is enclosed by the excitation circle, the tangent OF can not be drawn, So the graphical construction is to be little modified. From O draw OF perpendicular to V/Z meeting the circle at F.

Through F draw a tangent meeting V/Z produced at J

Now power developed $= V.QL - OQ^2.R$

$$OQ^2.R = R\left(QP_o^2 - OP_o^2 + 2OQ.OP_o \cos \angle QOP_o \right)$$

$$= R\left(QP_o^2 - OP_o^2 - 2OP_o \times OD \right)$$

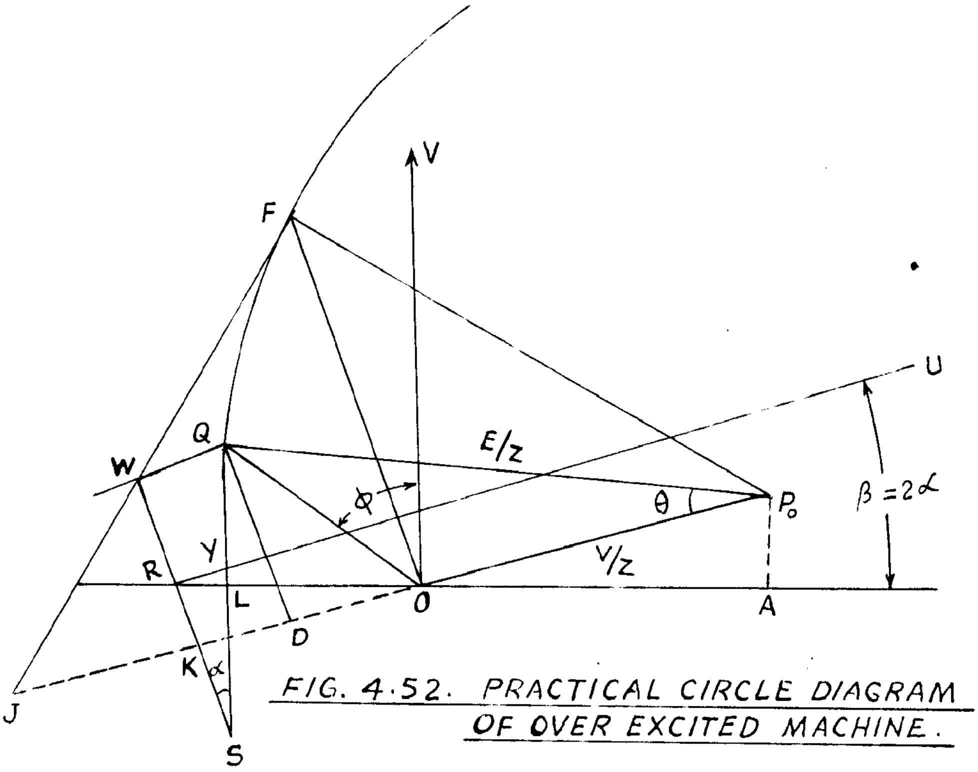


FIG. 4·52. PRACTICAL CIRCLE DIAGRAM OF OVER EXCITED MACHINE.

Considering triangle OFP_o and JFP_o

$$\frac{OP_o}{FP_o} = \frac{FP_o}{JP_o}$$

$$FP_o^2 = OP_o \cdot JP_o$$

$$QP_o^2 = OP_o\left(OP_o + JO \right) \qquad \because FP_o = QP_o$$

$$= OP_0^2 + OP_0 . JO$$

$$\therefore \quad QP_0^2 - OP_0^2 = OP_0 . JO$$

$$= OP_0 . 2OK \quad \text{where } OK = OJ/2$$

Substituting $QP_0^2 - OP_0^2 = 2P_0 . 2OK$ in the equation of power developed.

$$OQ^2 . R = 2R . OP_0 \; (OK - OD)$$

$$= 2R . OP_0 . KD.$$

The rest of proof is same.

The line RYU passing through R can be drawn making an angle of $\beta = 2\alpha$ with the horizontal.

SECTION - 5

BEHAVIOUR AS SYNCHRONISED ASYNCHRONOUS MOTOR.

5.1. STATIC BEHAVIOUR :

In order to explain the operation of S.A.M. with constant excitation and varying loads, it is assumed that the magnetising m.m.f is same for asynchronous and synchronous motor or in other words the impedance of asynchronous motor run at synchronous speed is practically identical with the magnetising impedance of the asynchronous motor, so that the no load vector OP_0 in the circle diagram of asynchronous motor fixes the centre for the excitation circle for synchronous motor operation. The diagram for S.A.M has the form as shown.

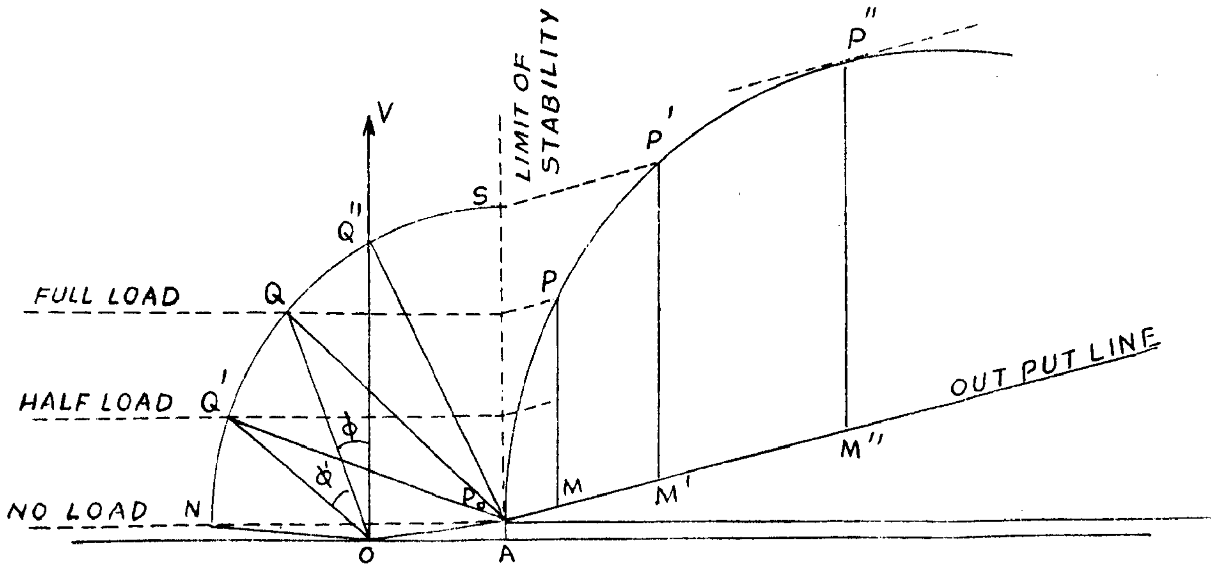


FIG. 5.1. CURRENT DIAGRAM OF S.A.M.

OP is the full load current and PM to the power scale represents the full load out put as asynchronous motor. The limit of stability as synchronous motor is P_0S. The output lines are practically straight lines parallel to the abscissa. The no load line is drawn horizontally from P_0 and the full load line is parallel to the horizontal and distant PM from the no-load line. This diagram assumed all losses constant and equal to P_0A. The vector OQ gives the stator current and its phase relationship with voltage.

Now suppose, as is the normal condition that the direct exciting current remains fixed at the full load value, the length P_0Q is constant. The locus of Q is a circle of radius P_0Q and centre P_0. Now neglecting minor efficiency variations, the power component of the stator current will be proportional to mechanical output. If the load is halved, the point Q will take the new position Q' so that the vertical component of stator current is halved and the power factor becomes more leading.

If the load is increased, the point Q will move up the circle towards S. At the point Q", the value of stator current will be OQ" and its power factor unity. If the load further increases, the stator current will increase and its power factor lagging till at point S, where the maximum pull out torque is reached, the machine goes out of step and the load will transfer on the asynchronous motor characteristics at the point P' so that now stator current will be OP' and output P'M'. The motor will continue to run as an asynchronous motor with fluctuations of slip and torque and will come into step once again when the value of load becomes less than P_0S.

(Please see after page

SECTION 6

EXPERIMENTS ON SYNCHRONISED ASYNCHRONOUS MACHINE

Experiments were perfomed on a machine with following specifications :-

4 KVA ; 3 -phase ; 110/220 V
21/10.5 A; 0.8 p.f
Synchronous speed - 1000 r.p.m.

SLIP RING ASYNCHRONOUS MOTOR

The resistance of stator and rotor were found by Kelvin's double bridge and the following values were obtained.

Stator resistance per phase = 0.388 ohms
Rotor resistance per phase = 0.0478 ohms

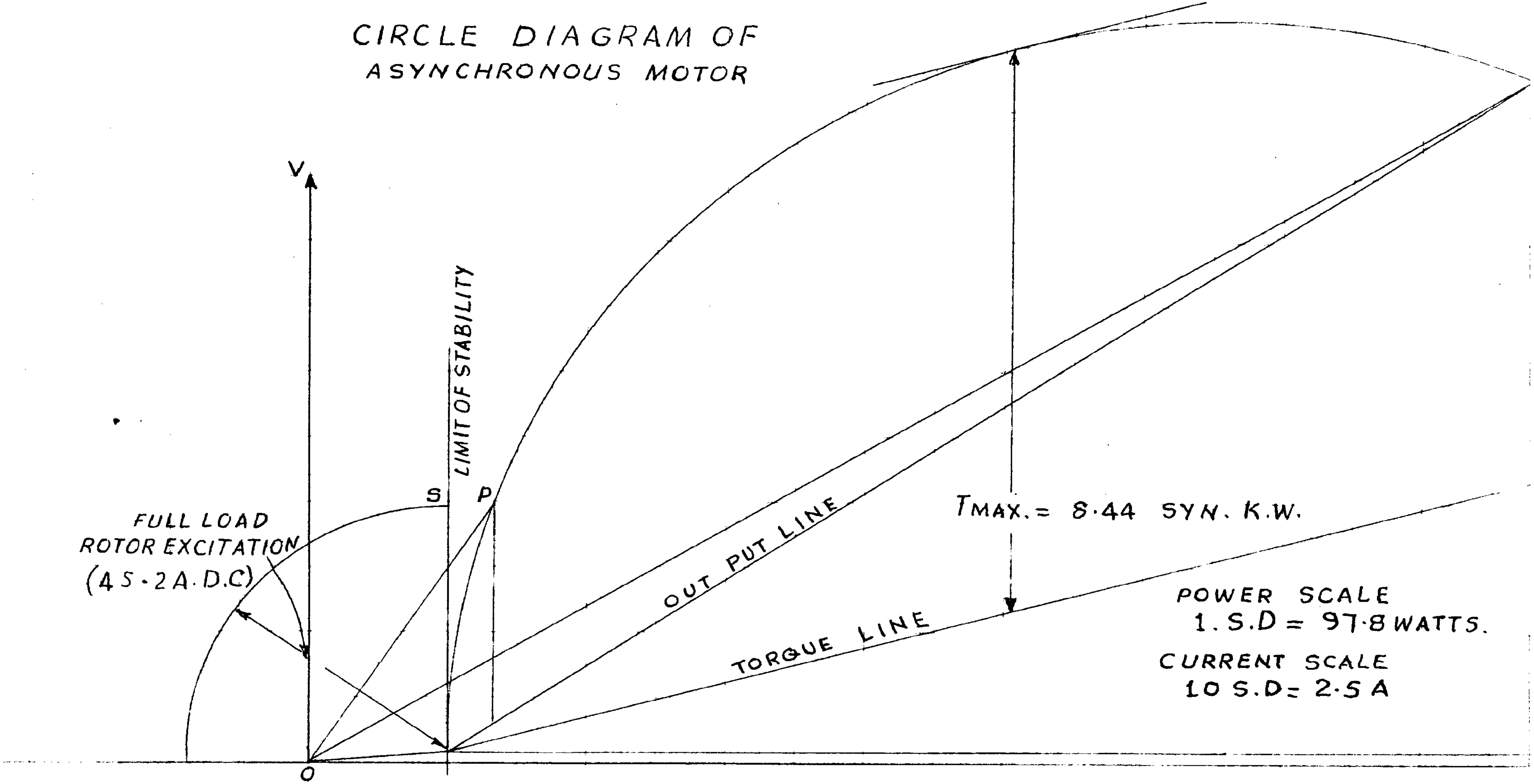
The ratio of transformation (stator : Rotor) was experimentally found to be 3.5

So rotor resistance per phase refered to stator = 0.585 ohms

The no load and short circuit test were performed on the machine and circle diagram for asynchronous motor was drawn corresponding to the data obtained in the above two tests. The following results were obtained.

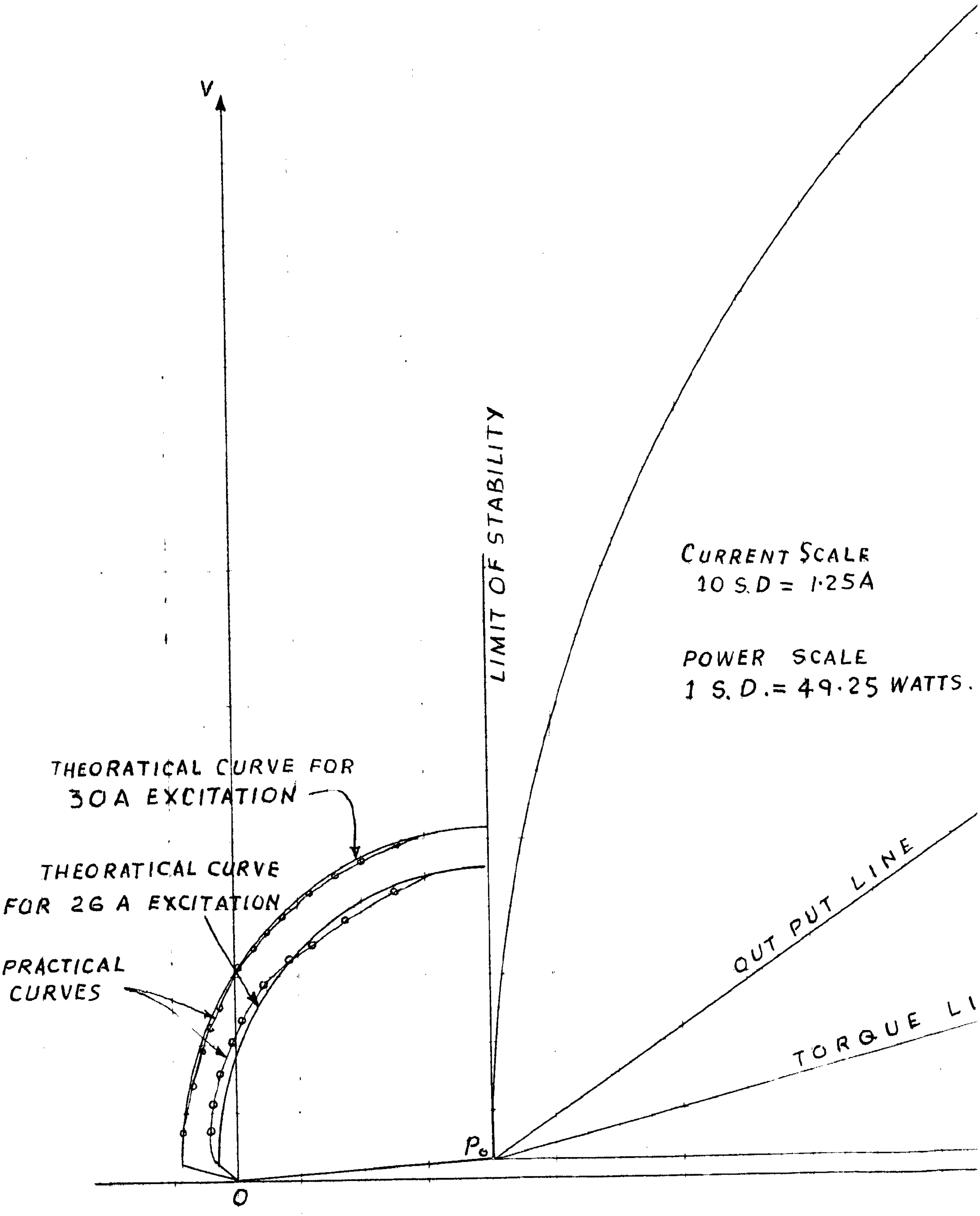
Stator Current at full load = 11.25A.
P.F. of the stator current = 0.82 lagging
Rotor current at full load = 9.15 A.
P.F. of Rotor current = 0.985 lagging
Slip at full load = 0.0635
Full load torque = 3.43 synchronous Kw
Maximum pull out torque = 8.44 Synchronous Kw
Pull out torque/Full load torque = 2.46

CIRCLE DIAGRAM OF ASYNCHRONOUS MOTOR



POWER SCALE
1. S.D = 97·8 WATTS.

CURRENT SCALE
10 S.D = 2·5 A



VERIFICATION OF CURRENT LOCUS OF S.A.M.

Efficiency at full load = 88%

The d.c. excitation for running the motor as synchronous motor was calculated as follows:

Rotor Current = 9.15 A (Stator ~~turns~~ terms)

= 9.15 x 3.5 (Rotor ~~terms~~ terms)

= 32 A.

Equivalent d.c. excitation = $32 \times \sqrt{2}$ = 45.2 A.

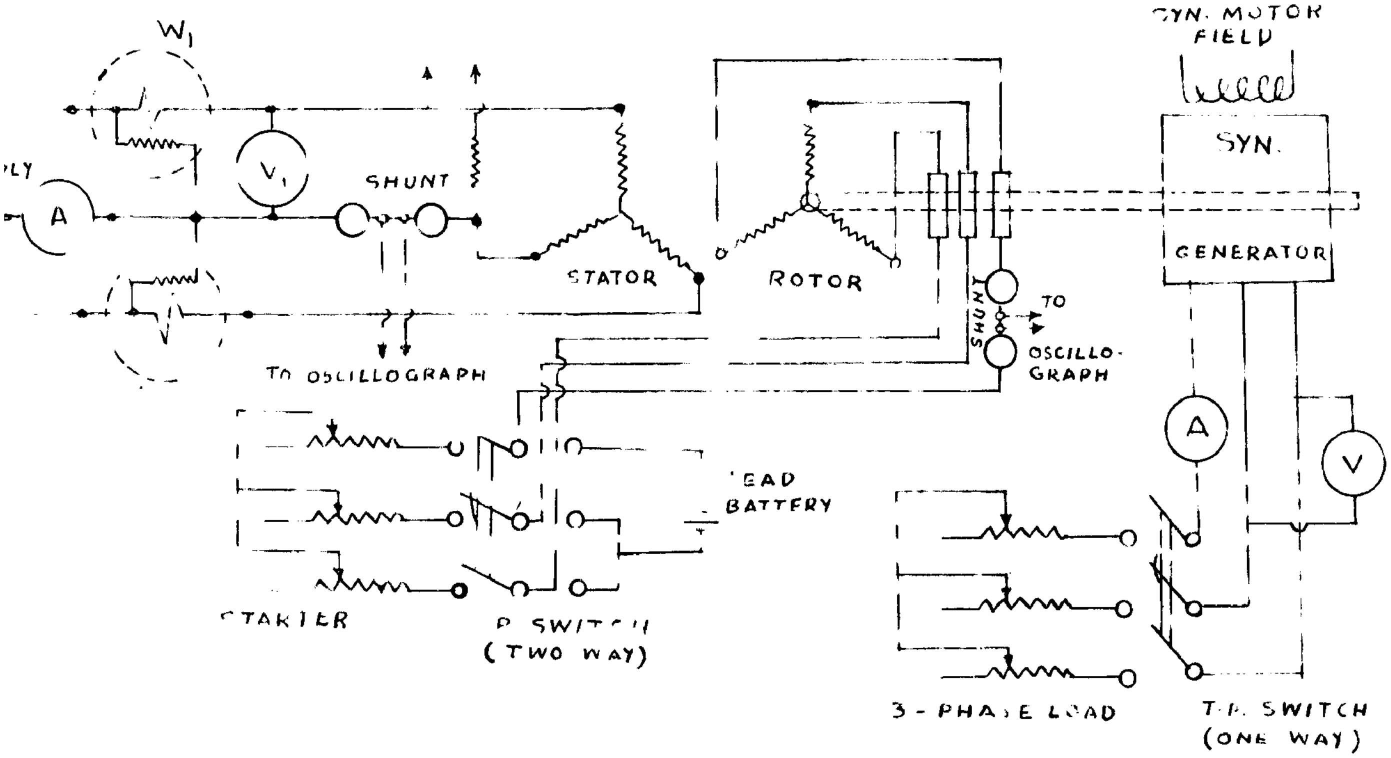
So in order to have same rotor m.m.f with d.c. excitation, rotor current should be 45.2A.

The current locus for synchronous motor operation of S.A.M for d.c. excitation of 30A and 26 A were drawn theoratically Since current diagram of S.A.M. is all in alternating quantities, so the corresponding A.C. equivalents of 30A and 26A direct current are $\frac{30}{3.5 \times \sqrt{2}}$ = 6.05A (Stator terms) and 5.25A respectively. With P_0 as centre, circles were drawn with excitations 6.05 A and 5.25 A respectively. The S.A.M. was coupled to a synchronous generator which could be loaded. These theoretical curves of current locus have been verified experimentally.

SET UP
OF THE EXPERIMENT.

Oscillographic records of rotor current, stator current were simultaneously recorded on a six channel magnetic Oscillograph for the machine pulling into synchronism and going out of synchronism on synchronous overload.

Following is the electrical circuit used for the experiment.



The pictorial view of the above arrangement is shown in the facing photograph.

Shunts of 100A and 7.5 A were used to record rotor current and stator current. In order do record the voltage variations of stator, a high resistance was used in series with the voltage vibrator. The machine was run as an asynchronous motor. The starting resistance was cut step by step. The switch was put on the D.C. side and the machine pulled into step. Then it was put on sudden synchronous overload It pulled out of synchronism and started running as asynchronous motor. The exposure time for the recording film was so adjusted so as to include asynchronous run, pulling into step, the synchronous run and the effect of synchronous overload. The records are shown on the facing photographs. The following conclusions have been drawn :

1. The curves no.1 show the variation of rotor current. When the machine is working as asynchronous motor, the rotor current is sinusoidal and varying with slip frequency. The broken part of the curve shows the operation of switching on direct current. The rotor current shall now be sum of induced alternating current and forced direct current. The induced alternating current shall die down to zero as the machine accelerates from subsynchronous to synchronous speed. At synchronous speed, rotor shall carry only direct current sent by the exciter into it. When the machine is put on synchronous overload, the machine will alternately be motoring and generating. During the time, it is motoring, the value of rotor current will increase and during the time it is generating the value of rotor current will decrease.

2. The curves no.2 show the variation of stator current. It has the supply frequency. When the machine is running as asynchronous motor, it has constant value. Also when it is running synchronised, it has constant value. During the synchronous overload, when the machine works as motoring, the value of stator current increases and

OSCILLOGRAPH NO. 1.

OSCILLOGRAPH NO. 2.

OSCILOGRAPHS SHOWING
VARIATION OF ROTOR CURRENT,
STATOR CURRENT & STATOR VOLTAGE.

during the time it works as generating, the value of stator current decreases because in this case, the machine tries to pump current into supply. It is observed that when rotor current increases, stator current also increases and when rotor current decreases stator current also decreases.

3. The curves no. 3 show [illegible] voltage applied to the stator. It does not vary.

5.2. PERFORMANCE CHARACTERISTICS :

The performance characteristic curves for the experimental motor have been drawn from current diagram for

(1) Full load rotor excitation.

(2) 66.4 percent of full load rotor excitation.

These curves show how the power-factor, stator current and reactive KVA vary with load.

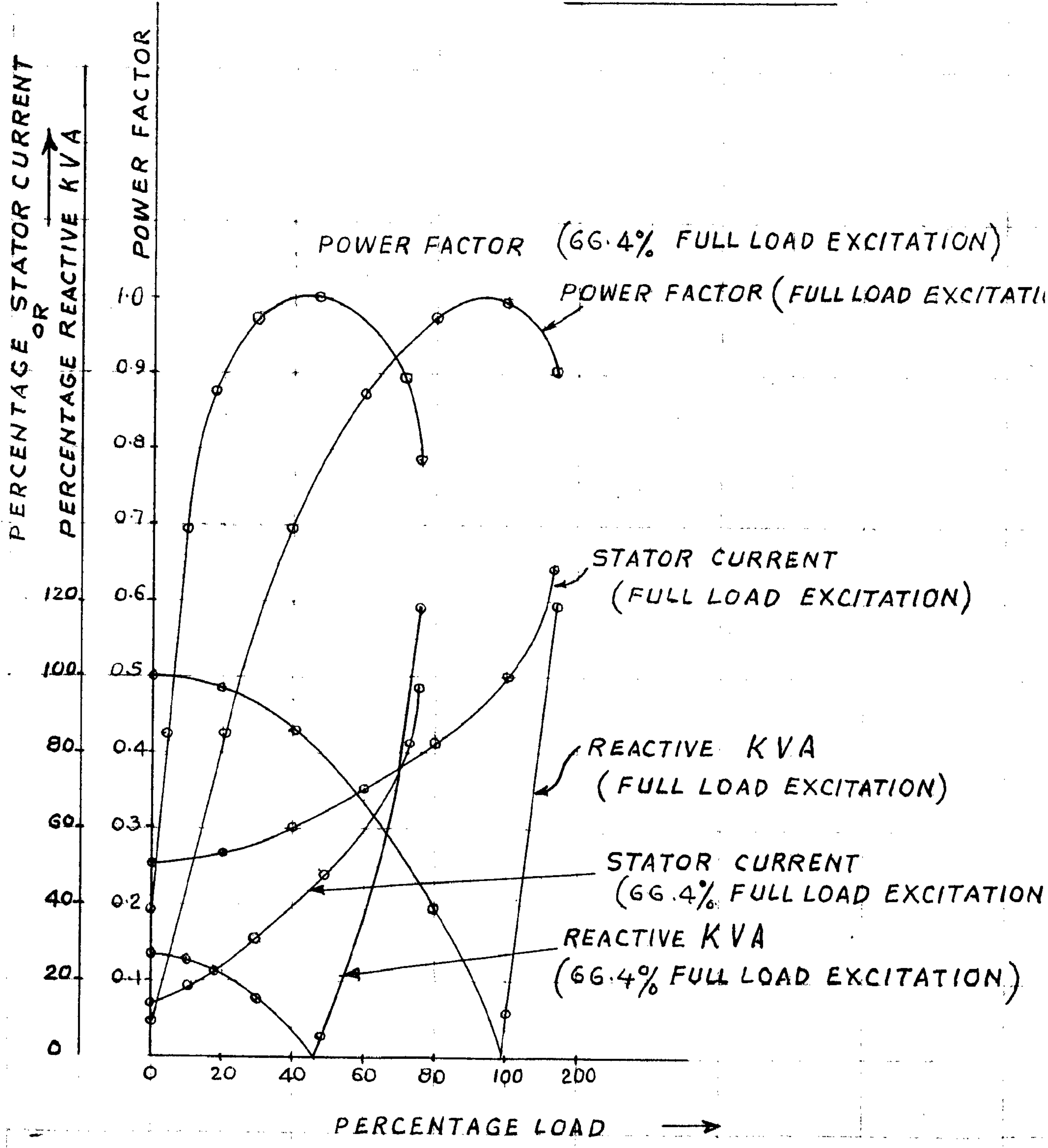
5.3. SYNCHRONOUS OVERLOADS

The S.A.M. is inherently incapable of the temporary overloads at synchronous speed. In asynchronous motor, the overload capacity is practically independent of the magnetising current, the rotor m.m.f varying automatically with load up to its maximum value called the pull out torque. In S.A.M., this property is unfortunately absent because the rotor m.m.f is fixed. By having more of excitation (and hence more of stator current), the available power of the machine can be increased. But the values of stator and rotor currents are limited by copper space available and the permissible heating. The nature of load where S.A.M. is used (e.g. pumps or fan loads) an overload of 10 to 20 percent is improbable and in such cases an overload capacity of 15 percent for the machine will be sufficient.

5.4. IMPROVEMENT OF POWER FACTOR :

A low power factor will increase the first cost of the machine in addition to its running cost. If the power factor of the machine is increased, the useful energy available is increased without increasing the electrical proportions of machine and in certain cases these can be reduced. Also

FIG. 5.2. PERFORMANCE CHARACTERISTIC OF S.A.M.



the running cost of the machine is decreased.

Curves (i) show how the power factor of the machine improves with excitation keeping the load constant.

Curves (ii) show how by varying excitation with load, the power factor is maintained constant.

5.5. AUTOMATIC VARIATION OF EXCITATION WITH LOAD:

The constant excitation corresponding to full load and unity power factor or 0.9 leading power factor has constant rotor losses for all loads. When the machine is operating at fractional loads or even no load, the power factor is quite low but the stator current and stator copper loss are unnecessarily high. This goes to decrease the efficiency of the machine. In order to reduce the stator loss, the rotor loss and the increase the efficiency, a system of variable excitation is introduced which sends excitation current to the rotor corresponding to the state of mechanical load. Such a system is shown in fig. 5.5.

The system consists of S.A.M, a three-phase rectifier and current transformers. The exciter of S.A.M has got two fields, one shunt field fed from the exciter and other field fed indirectly from the line with the help of current transformers and a 3-phase rectifier. The exciter shunt is designed to produce the output necessary to excite the motor at a required power factor and no load. When the load on the machine increases, the line current increases and consequently the current in the auxiliary field and so the excitation of exciter increases which in-

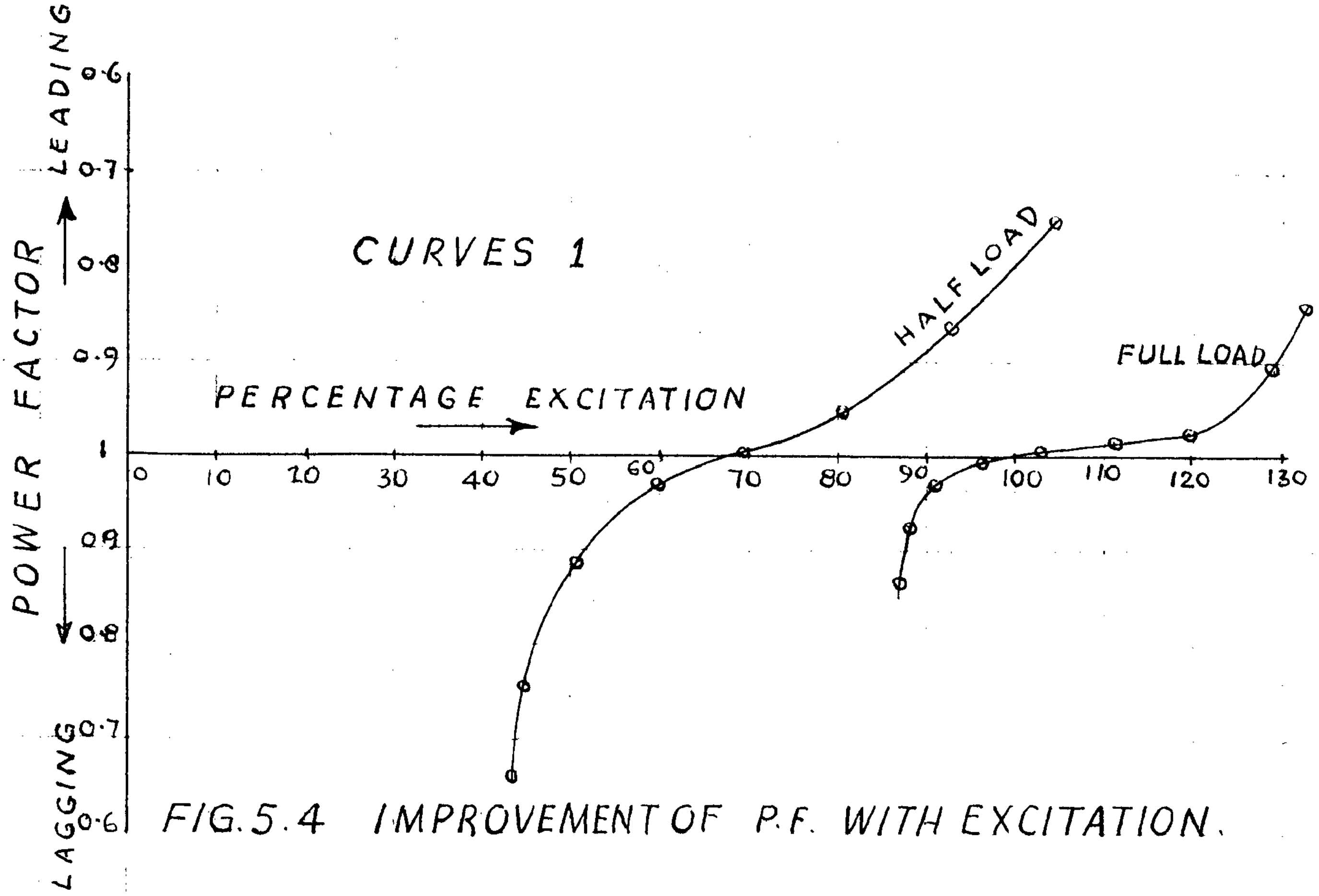


FIG. 5.4 IMPROVEMENT OF P.F. WITH EXCITATION.

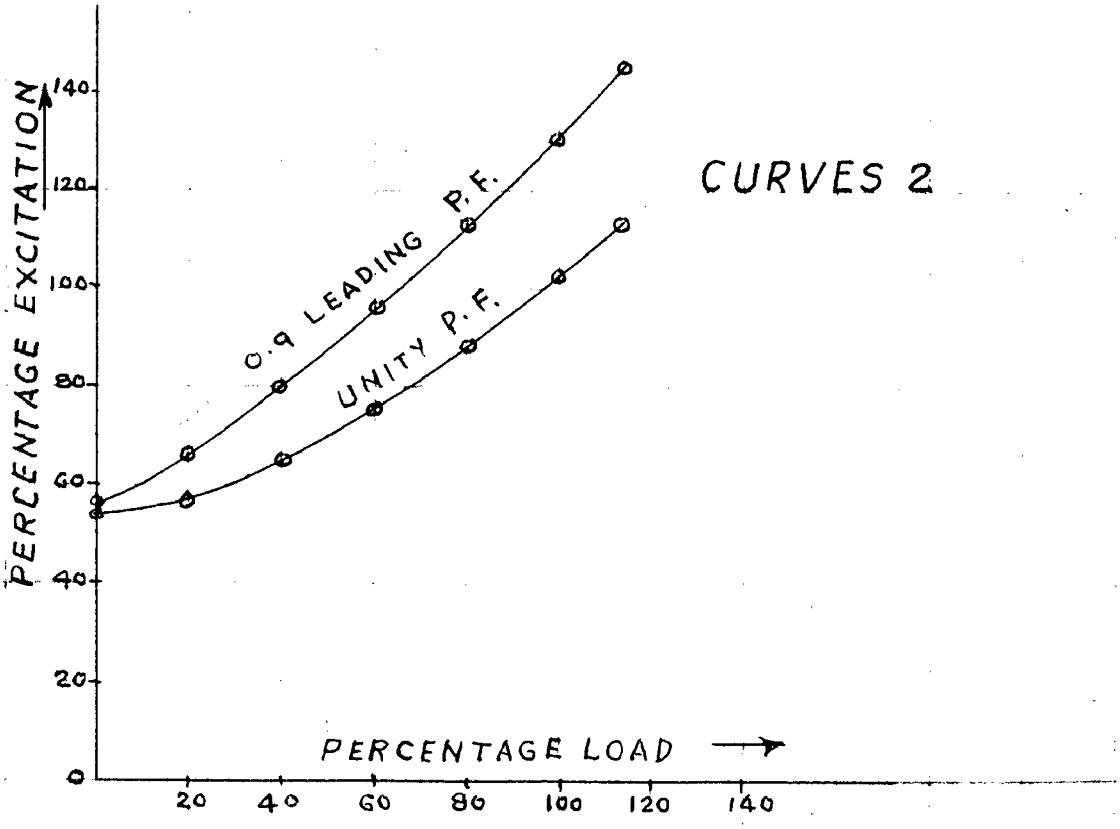
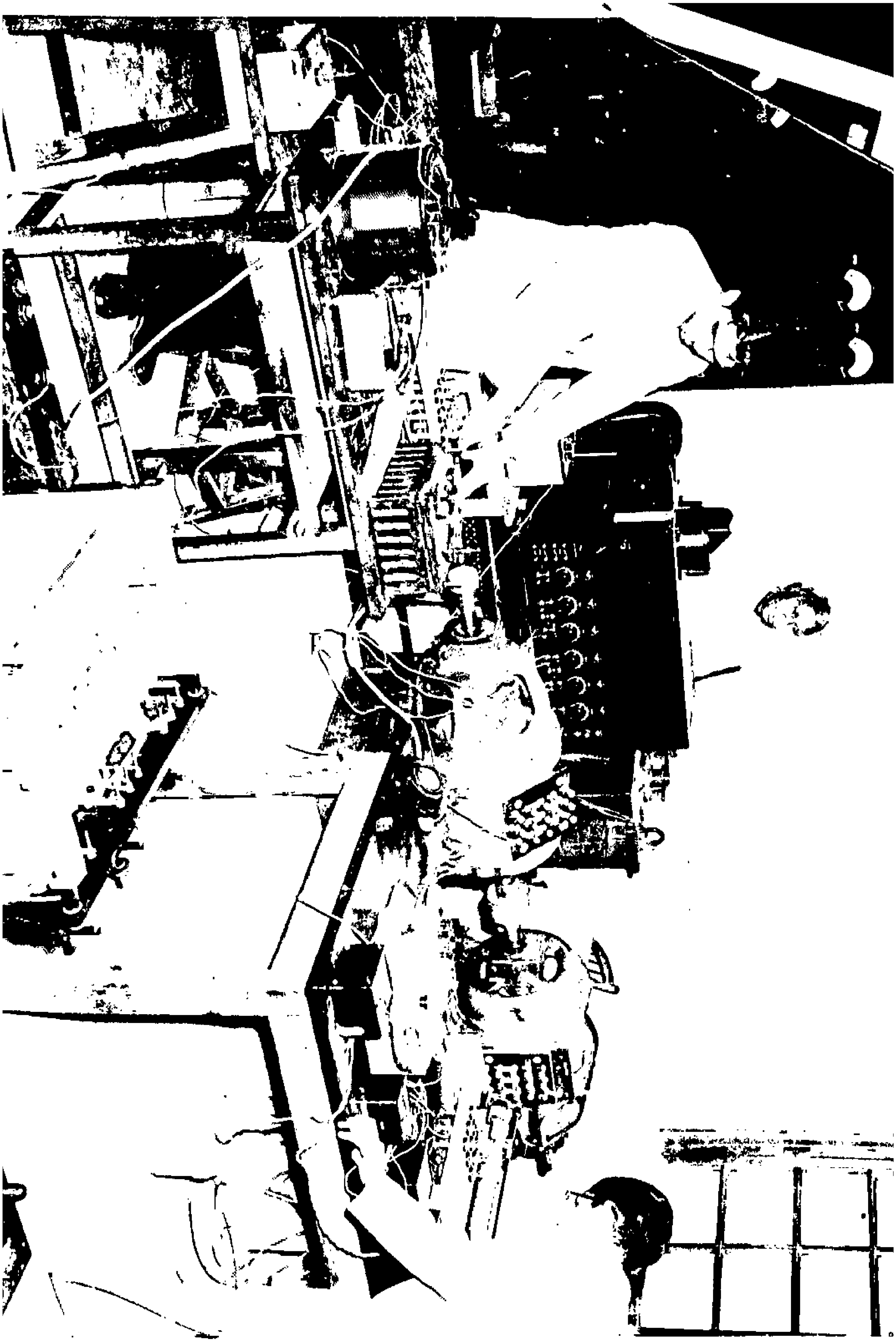


FIG. 5·4 VARIATION OF EXCITATION WITH LOAD FOR CONSTANT P.F.



increases the voltage of the exciter which can supply more excitation to meet the new load condition at required power factor (say unity or 0.9 leading).

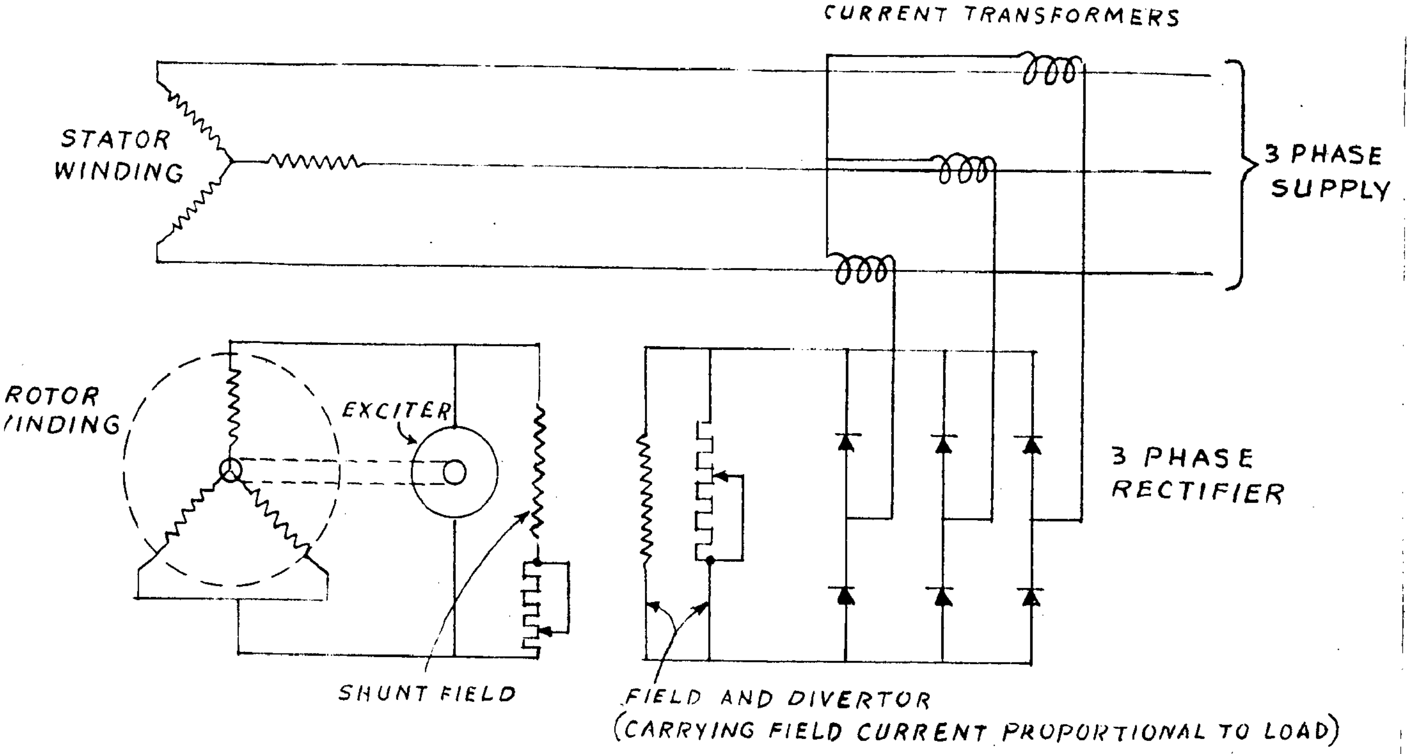


FIG. 5·5 AUTOMATIC VARIATION OF EXCITATION WITH LOAD.

High overloads are however not possible because saturation begins to affect the output of the transformers with the result that auxiliary excitation is no longer proportional to the line current and the exciter saturation will reduce the response to auxiliary excitation.

The provision of automatic variation of excitation dependent on line current also insures against the machine being pulled out of synchronism by severe voltage drops provided they are too short to increase the temperature of the machine.

5.6 EFFECT OF SYNCHRONOUS IMPEDANCE:

(a) LARGE SYNCHRONOUS IMPEDANCE:

When the synchronous impedance is large, the no load current as an asynchronous motor is quite low.

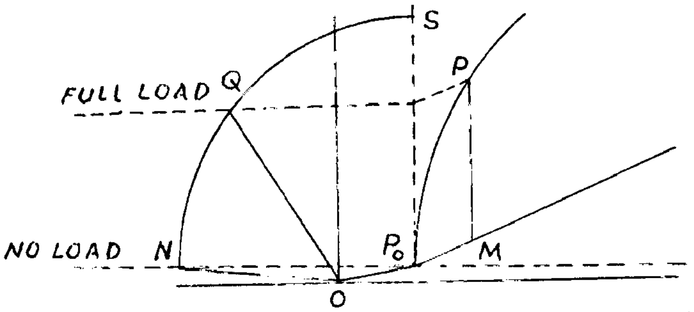


FIG. 5·61 LARGE SYNCHRONOUS IMPEDENCE.

For synchronous motor operation, it is seen that no load current is very nearly equal to full load current and power factor and efficiency are quite low except near the limit of stability. It is seen that large synchronous impedance entails a large variation of power factor with load.

(b) SMALL SYNCHRONOUS IMPEDANCE:

When the synchronous impedance is small the no load current as an asynchronous motor is quite large.

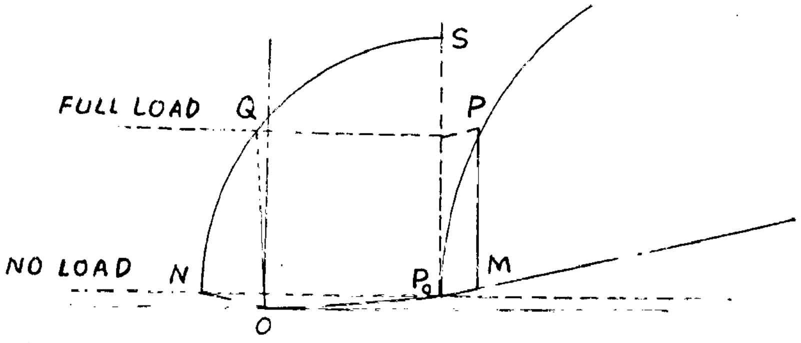


FIG. 5·62. SMALL SYNCHRONOUS IMPEDENCE.

For synchronous motor the no load current is quite less compared with full load current and the power factor and efficiency are quite high.

Hence a good asynchronous machine in which magnetising current is secured to be minimum makes a poor S.A.M. when its rotor is excited with direct current. Clearly to restrict excessive loading reactive kilo-volt-amperes a small synchronous impedance is to be prefered.

5.7. AIR GAP IN SYNCHRONISED ASYNCHRONOUS MACHINE :

Because of the conflicting requirements of asynchronous motor and synchronous motor, that is to say, for increased torque and improved power factor in an asynchronous motor, the air gap is to be as small as possible and for increased maximum output and stability in a synchronous machine, the air gap is to be quite large. In order to have a compromise between the requirements of synchronous motor and asynchronous motor, the air gap in S.A.M. is made approximately 100 percent greater than in plain asynchronous motor.

5.8. PRACTICAL CIRCLE DIAGRAM OF SYNCHRONISED ASYNCHRONOUS MACHINE.

In the last section, the method of obtaining the power

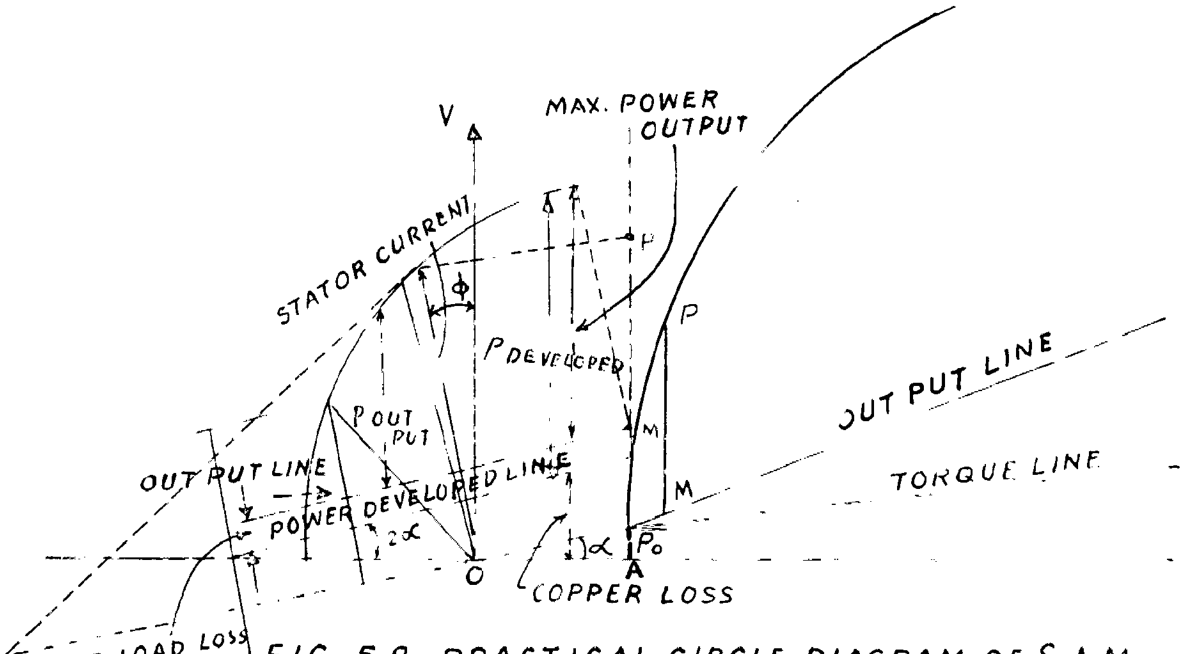


FIG. 5.8 PRACTICAL CIRCLE DIAGRAM OF S.A.M.

developed is given. If constant loss equal to the asynchronous motor no load loss P_0A is substracted from the power developed a very practical circle diagram giving the output directly is obtained. The diagram is shown in fig. 5.8

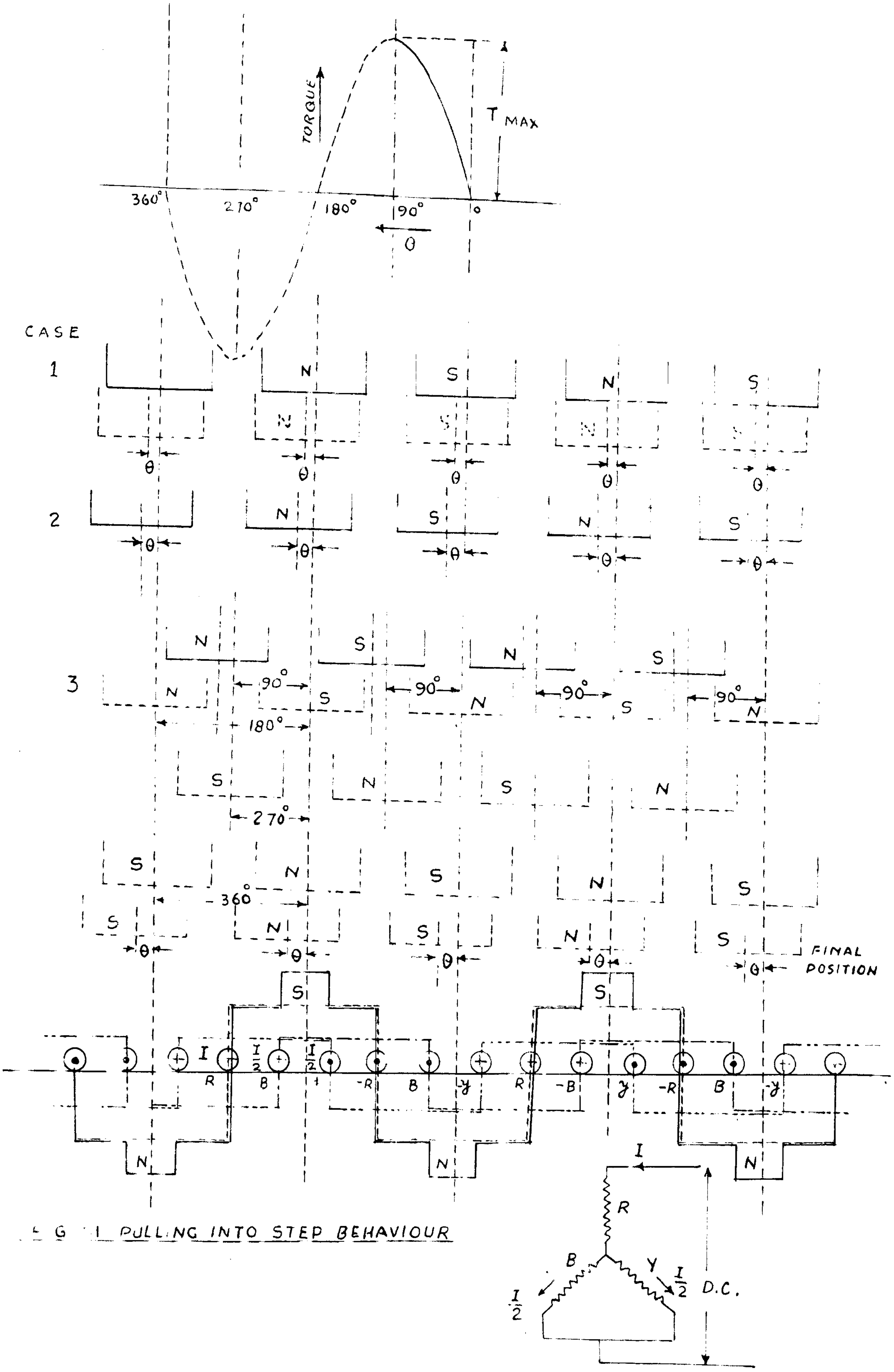


FIG. 1 PULLING INTO STEP BEHAVIOUR

SECTION - 7

DYNAMIC BEHAVIOUR

7.1. PULLING INTO STEP :

When the machine is running with rotor short-circuited, it speed is very nearly equal to synchronous speed and very low frequency currents are induced in the rotor when d.c. excitation is switched on it rises to its final value instantaneously. It is super imposed upon low frequency rotor currents. The rotor develops two torques.

(1) The asynchronous motor torque due to slip frequency currents.

(2) The synchronous motor torque due to d.c.

Before switching on d.c., the asynchronous torque was balancing the load torque and the motor was running at constant speed. After switching on, the synchronous torque developed may accelerate the rotor and the connected load. This torque depends upon the value of field current and upon the angular displacement θ between the axis of synchronously rotating a.c. poles and the axis of d.c. poles. The angular displacement varies with time in a manner determined by the following differential equation.

$$\frac{d^2\theta}{dt^2} + a.\frac{d\theta}{dt} + b\sin\theta = c. \qquad \text{(Derived in appendix)}$$

The solution of such an equation is impossible and simplifications such as $\sin\theta = 0$ in radians which are true between 30° and -30° can not be applied because θ varies even beyond these limits. However the phenomenon of pulling into step will be quite clear by means of following diagram and explaination.

Figure shows the d.c. pole formation in the winding of a rotor having one slot per pole per phase. Now the various position of stator poles with respect to rotor poles may be considered.

Case-1.

If at the instant of switching on d.c., the axis of rotor poles and the stator poles is the same (fig. 7.1), this means that the rotor does not develop any synchronous motor torque. It is only the asynchronous motor torque that is rotating the machine at asynchronous speed. However when the a.c. poles advance with respect to d.c. poles, the rotor develops synchronous motor torque depending upon the sine of angle θ . This torque developed at the rotor is in addition to the asynchronous motor torque. When the synchronous motor torque is sufficient enought to accelerate the rotor, the rotor will pull into step and shall occupy any position from 0 to θ ($\theta < 90^\circ$) depending upon load.

Case - 2.

If the excitation is switched on at any angle less than 90°, the rotor will experience synchronous torque right at the moment of switching and the machine will pull into step soon.

Case - 2

If however excitation is switched on at an angle $\theta > 90^\circ$, the motoring torque will go on falling till at $\theta = 180^\circ$, it will be zero. In this position a.c. poles oppose the d.c. poles, both being of the same polarity, the field system slips back through a pole pitch, the slip increases and the system experiences a retardation action. Due to this sudden retardation, the induction currents in the rotor increase which go to increase the asynchronous torque which pulls up the rotor. Also during this retardation, when the d.c. poles come under the next a.c. poles of opposite polarity, the rotor will experience synchronous motor torque. The increased asynchronous motor torque and the synchronous motor torque pull up the machine to synchronism. It is in very critical cases that it may require the cumulative effect of several positive half cycles to cause synchronous speed to be reached.

The necessary and sufficient condition in all the cases of pulling into step is that load torque should be less than the over load capacity of the machine as synchronous motor. If $\theta < 90^\circ$, the machine will pull into step within one swing of rotor current while for $\theta > 90^\circ$, it may pull into step within two swings of rotor current and in very critical cases with several swings of rotor current. The last situation is probable when the load torque is very nearly equal to the synchronous overload Capacity. However, the best position of switching on d.c. excitation is that which the rotor will occupy with respect to stator when synchronised.

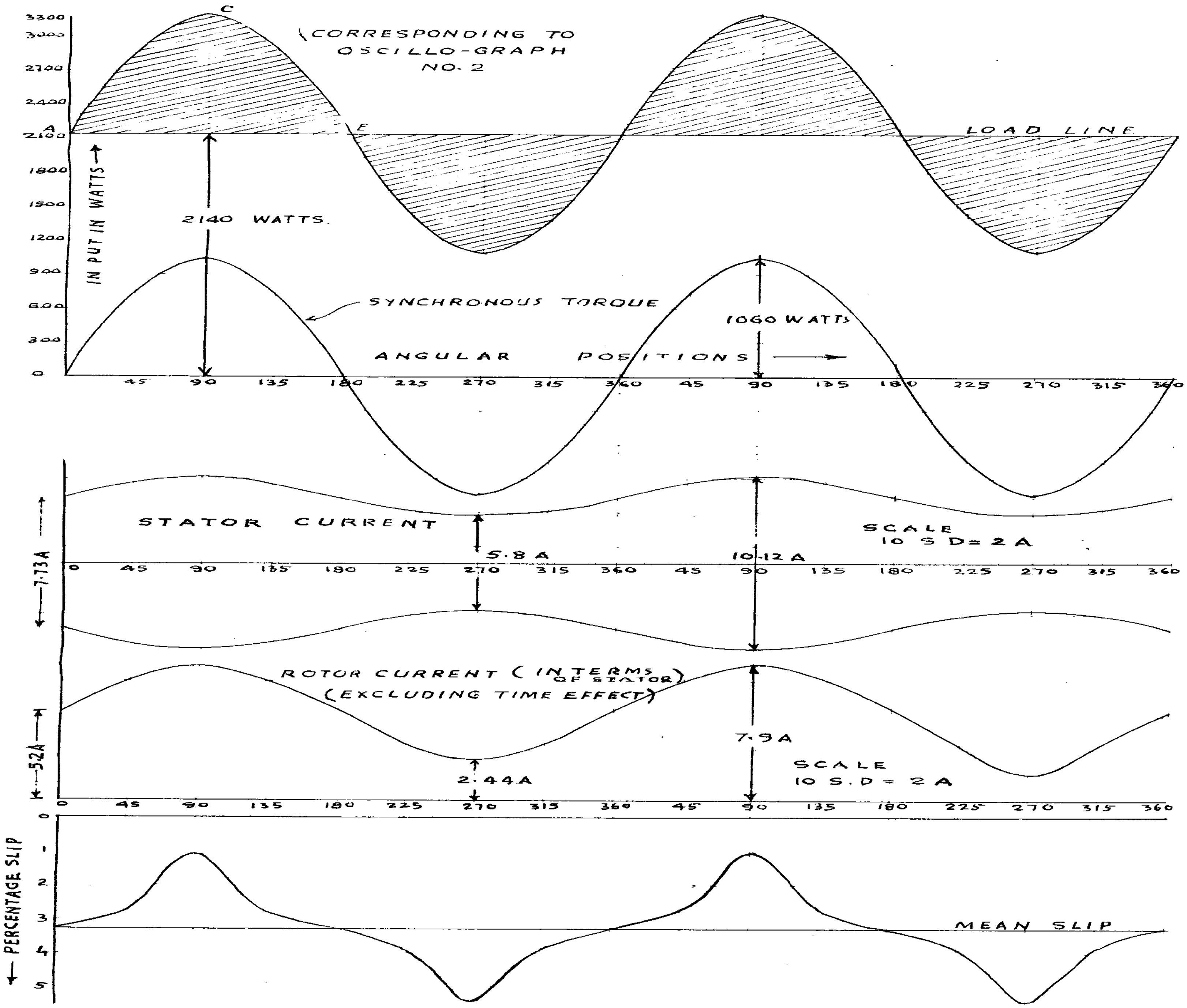


FIG. 7.2 VARIATION OF POWER IN PUT, STATOR CURRENT, ROTOR CURRENT AND SLIP ON SYNCHRONOUS OVER LOAD.

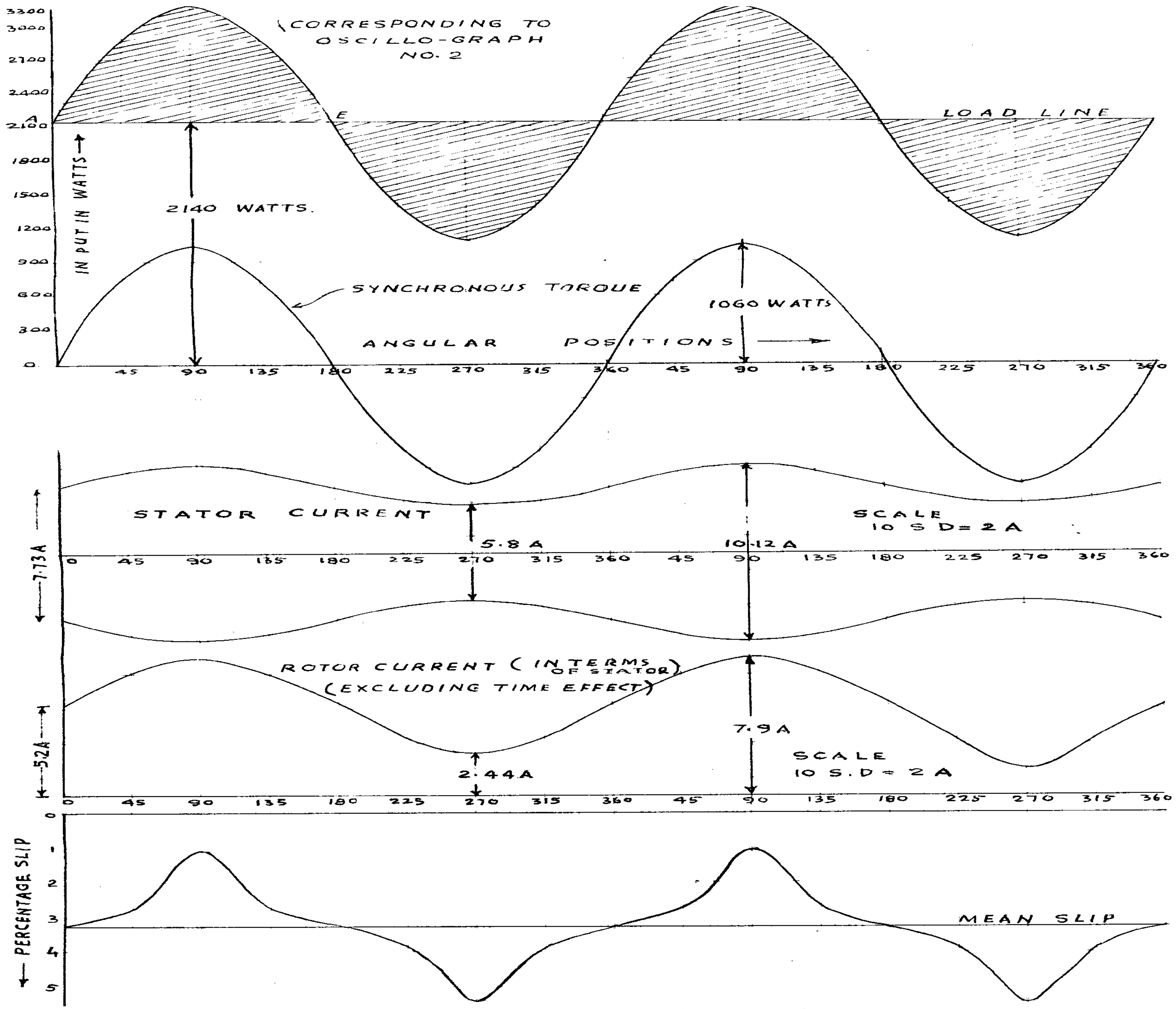


FIG. 7.2 VARIATION OF POWER IN PUT, STATOR CURRENT, ROTOR CURRENT AND SLIP ON SYNCHRONOUS OVER LOAD.

7.2. EFFECT OF SUDDEN OVERLOAD :

After the machine has come into step, if the load on the machine is increased step by step, then the relative angle between synchronously rotating a.c. and d.c. poles will go on increasing upto 90°, after which the machine will fall out of step. It will not stop but shall continue to run at subsynchronous speed because then the rotor behaves as the rotor of an ordinary three phase slip ring asynchronous motor with the only difference that now its rotor being shorted through a very low resistance of the exciter. In this state of the machine, the angle between a.c and d.c. poles will be changing cyclically from zero to 360° .

On the experimental motor, when the machine was working as synchronous motor, the power input to the machine was 1090 watts. When all of a sudden, the machine was put on an extra load of 1050 watts, the machine went out of step. The line AB shows the load line. If the losses of the motor are neglected, then AB will show the power developed or power input. The whole phenomenon may be composed like this. Let the machine be working as asynchronous motor first so that line AB shows the load line or the power developed by the motor or the power input to the machine. Now the d.c. excitation be switched on. The sine curve shows the power angle characteristics as synchronous motor corresponding to the excitation. Load line being represented by AB, there will be increase in the total torque shown by the curve ACB with the result that stator current will increase In the negative portion of power-angle curve i.e. the portion in which the machine acts as a generator, the net oscillating torque will decrease with the result that stator current and rotor current will both decrease. The hatched portion above load line produces acceleration and below load line produces retardation. The variation of power input the stator current, the rotor current and slip are given in the ~~facing graph~~ fig 7.2. They have all been derived from the circle diagram corresponding to input variations.

SECTION - 8

FIELD OF UTILISATION AND SIZE.

The S.A.M can run at unity or leading power factor. So it is practicable at places where a leading power factor with constant speed is required for example air compressors, amonia compressors, fans pumps, blowers, ore cushers and in large industrial works such as grinding mills in cement factory, line shafting in textile mills, flour mills, rubber works and paper mills.

The S.A.M. is manufactured for a range of output almost equal to Asynchronous machine. Its range varies from 50 to 6000 h.p at 11 KV. The cost of exciter, renders the use of machine below 50 h.p less popular. The real field for this machine is said to be from 100 h.p and upwards.

SECTION - 9

APPENDIX

9.1. ARMATURE -REACTION IN A.C. MACHINES :

The armature amperetums in case of a single phase windings for q slots per pole per phase is

$$A_T = \frac{\sqrt{2}\, I\, N_c}{2} \sin \omega t.$$

Where I = R.M.S. value of the current in each conductor

N_c = No. of conductors per slot.

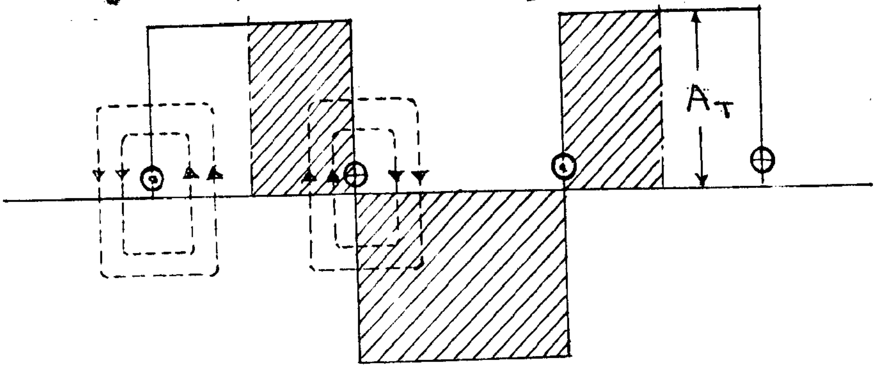


FIG. 9.1

This gives an alternating field stationary in space for which

$f(X) = f(-x)$ It is an even function so sine terms are missing.

$f(x) = -f(x + h)$ Half wave symmetry so even harmonics are absent.

Therefore $f(x) = \sum_{\nu=1}^{\infty} a_\nu \cos \frac{\nu \pi x}{\tau}.$

Where τ = Pole pitch

ν = order of the harmonic . Always odd.

$$a_\nu = \frac{1}{\tau} \int_0^{2\tau} f(x) \cos \frac{\nu \pi x}{\tau}\, dx.$$

$$\text{or}\quad a_v = \frac{1}{T}\left[\int_0^{T/2} A_T \cos\frac{v\pi x}{T}\,dx - \int_{T/2}^{3T/2} A_T \cos\frac{v\pi x}{T}\,dx + \int_{3T/2}^{2T} A_T \cos\frac{v\pi x}{T}\,dx\right].$$

$$= A_T\ \frac{4}{v\pi}\ \sin\frac{v\pi}{2}$$

$$= 0.9\, I\, N_c\ \frac{1}{v}\ \sin\frac{v\pi}{2}\ \sin\omega t\,..$$

$$A_{T_x} = f(x) = 0.9\, I\, N_c \sin\omega t\left[\cos\frac{\pi x}{T} - \frac{1}{3}\cos\frac{3\pi x}{T} + \frac{1}{5}\cos\frac{5\pi x}{T}\ ----\right]$$

In case of a 3-phase Machine with one slot per pole per phase, the Fourier Analysis of the ampere-turn wave for each phase separately is given by the following expressions.

$$A_{T_{x_I}} = 0.9\, I\, N_c \sin\omega t\left[\cos\frac{\pi x}{T} - \frac{1}{3}\cos\frac{3\pi x}{T} + \frac{1}{5}\cos\frac{5\pi x}{T}\ ---\right]$$

$$A_{T_{x_{II}}} = 0.9\, I\, N_c \sin(\omega t - 120^\circ)\left[\cos\left(\frac{\pi x}{T} - 120^\circ\right) - \frac{1}{3}\cos 3\left(\frac{\pi x}{T} - 120^\circ\right) + \frac{1}{5}\cos 5\left(\frac{\pi x}{T} - 120^\circ\right)\ ------\right]$$

$$A_{T_{x_{III}}} = 0.9\, I\, N_c \sin(\omega t - 240^\circ)\left[\cos\left(\frac{\pi x}{T} - 240^\circ\right) - \frac{1}{3}\cos 3\left(\frac{\pi x}{T} - 240^\circ\right) + \frac{1}{5}\cos 5\left(\frac{\pi x}{T} - 240^\circ\right)\ ----\right]$$

These equations represent the ampere turns due to I, II, III phase currents, each lagging by 120° in time and having a space shift on the stator of 120°

RESULTANT AMPERE TURNS OF FUNDAMENTALS:

$$\sum A_{T_{x_1}} = \frac{0.9\, I\, N_c}{2}\left[\sin\left(\omega t + \frac{\pi x}{T}\right) + \sin\left(\omega t - \frac{\pi x}{T}\right) + \sin\left(\omega t + \frac{\pi x}{T} - 120^\circ\right) + \sin\left(\omega t - \frac{\pi x}{T}\right) + \sin\left(\omega t + \frac{\pi x}{T} - 480^\circ\right) + \sin\left(\omega t - \frac{\pi x}{T}\right)\right]$$

$$= 0.9\, I\, N_c\ \frac{3}{2}\ \sin\left(\omega t - \frac{\pi x}{T}\right).$$

If there be in general m phases

$$\sum A_{T_{x_1}} = 0.9\, I\, N_c\ \frac{m}{2}\ \sin\left(\omega t - \frac{\pi x}{T}\right)$$

RESULTANT AMPERE TURNS OF THIRD HARMONICS

$$\sum A_{Tx_3} = -\frac{0.9\, I\, N_c}{2} \cdot\cdot \frac{1}{3}\Big[\sin\Big(\omega t + \frac{3\pi x}{\tau}\Big) + \sin\Big(\omega t - \frac{3\pi x}{\tau}\Big)$$
$$+ \sin\Big(\omega t + \frac{3\pi x}{\tau} - 480^\circ\Big) + \sin\Big(\omega t - \frac{3\pi x}{\tau} + 240^\circ\Big)$$
$$+ \sin\Big(\omega t + \frac{3\pi x}{\tau} - 960^\circ\Big) + \sin\Big(\omega t - \frac{3\pi x}{\tau} + 480^\circ\Big)\Big]$$

$$= 0.$$

So the third harmonic is missing.

RESULTANT AMPERE TURNS OF FIFTH HARMONICS

Proceeding as above, the ampere-turns of the fifth harmonic is

$$\sum A_{Tx_5} = 0.9\, I\, N_c \frac{m}{2}\, \frac{1}{5} \sin\Big(\omega t + \frac{5\pi x}{\tau}\Big)$$

And similarly the resultant of the 7th harmonic is

$$\sum A_{Tx_7} = -0.9\, I\, N_c \frac{m}{2} \cdot \frac{1}{7} \sin\Big(\omega t - \frac{7\pi x}{\tau}\Big)$$

So the Fourier Analysis of the three phase armature reaction ampere-turn of wave is

$$A_{T_x} = 0.9\, I\, N_c \frac{m}{2}\Big[\sin\Big(\omega t - \frac{\pi x}{\tau}\Big) + \frac{1}{5}\sin\Big(\omega t + \frac{5\pi x}{\tau}\Big) - \frac{1}{7}\sin\Big(\omega t - \frac{7\pi x}{\tau}\Big) + \cdots\Big]$$

It is seen that fifth harmonic field is rotating in a direction opposite to that of fundamental and the 7th harmonic.

For a chorded winding with q slots per pole per phase, the armature reaction ampere turn of wave modifies to

$$A_{T_x} = 0.9\, I\, N_c\, q\, \frac{m}{2}\Big[K_{dp_1} \sin\Big(\omega t - \frac{\pi x}{\tau}\Big) + \frac{K_{dp_5}}{5} \sin\Big(\omega t + \frac{5\pi x}{\tau}\Big)$$
$$- \frac{K_{dp_7}}{7} \sin\Big(\omega t - \frac{7\pi x}{\tau}\Big) \cdots\cdots\Big]$$

where K_{dp} = winding factor

= Distributor factor x Pitch factor.

DIFFERENTIAL EQUATION OF S.A.M PULLING INTO STEP AND GOING OUT OF STEP:

Let

T_m = Maximum synchronous torque in Kg-meters.

T_l = Load Torque in Kg- meter

$\rho = T_l / T_m$

$I = Wr^2/g$ in Kg meters and seconds.

p = No. of pair of poles

t = Time in seconds

W = slip at load T_l as an asynchronous motor in Mechanical radians per seconds.

pW = slip at load T_l as an asynchronous motor in Electrical radians /sec.

α = Angle of lag of centre of pole of rotor behind the synchronously rotating flux in mechanical radians.

$p\alpha = \theta$ = Angle of lag of centre of pole of rotor behind the synchronously rotating flux in electrical radians.

Load torque = $-\rho T_m$.

Synchronous torque = $T_m \sin p\alpha = T_m \sin\theta$

Asynchronous torque = $\frac{T_l}{\omega}\frac{d\alpha}{dt} = \frac{T_l}{p\omega}\frac{d\theta}{dt}$.

Acceleration = $-I\frac{d^2\alpha}{dt^2} = -\frac{I}{p}\frac{d^2\theta}{dt^2}$.

Now

$$-\rho T_m + T_m \sin\theta + \frac{T_l}{p\omega}\frac{d\theta}{dt} = -\frac{I}{p}\frac{d^2\theta}{dt^2}$$

Or $$\frac{I}{p}\frac{d^2\theta}{dt^2} + \frac{T_\ell}{pw}\frac{d\theta}{dt} + T_m \sin\theta = \rho\, T_m$$

or $$\frac{d^2\theta}{dt^2} + a\frac{d\theta}{dt} + b \sin 0 = c$$

Where ~~x~~ $a = \frac{T_\ell}{I\omega} = \frac{\rho\, T_m}{I\omega}$

$b = \frac{T_m I}{p}$

$c = \frac{\rho\, T_m\, p}{I}$

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