LOAD CAPABILITY OF INDUCTION GENERATOR AND THEIR CONTROLS

BY

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CERTIFICATE

Certified that the dissertation entitled " THE LOAD CAPABILITY OF INDUCTION GENERATOR " which is being submitted by SRI P. C. PANDA in partial fulfilment for the award of the degree of master of engineering in Electrical Machine Design of University of Roorkee is a record of the Student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or dimploma.

This is further to certify that he has worked for a period of three months and nineteen days from April 27, 1963 to August 15, 1963 for preparing dissertation for master of engineering degree.

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C_O_N_T_E_N_T_S

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NOMENCLATURE

p	Number of Pole pairs
f	Supply frequency
f_2	frequency of rotor e.m.f. and current
n	rotor speed in r.p.s.
f_r	rotational frequency r.p;
s	slip of the rotor
v_1	Terminal voltage of stator per phase
E_1	Stator induced e.m.f. per phase
E_2	e.m.f. in one equivalent rotor per phase
I_1	Stator current per phase
I_m	Magnitising current per phase
I_2	Rotor current per phase
r_1	Stator winding resistance per phase
x_1	Stator winding reactance per phase
z_1	Stator winding impedance per phase
r_2^1	Rotor equivalent resistance per phase
x_2^1	Rotor equivalent reactance per phase
z_{2s}^1	Rotor equivalent impedance per phase
x_c	Capacitive reactance per phase
R_e	Load resistance per phase
x_e	Load reactance per phase
M	Torque
P	Power
θ	Stand still impedance angle of rotor ($\tan \theta = x'_2/r'_2$)
ϕ'_2	Impedance angle of rotor ($\tan \phi_2 = sx'_2/r'_2$)
δ	Load angle

INTRODUCTION

In developing the country's water power, uptil now only those of greatest energy concentration is being considered in our country. That is those where large volume and a considerable load of water is available within a short distance. This has led to the present type of hydro-electric generating station, that we see around us now. Due to the vast amount of energy controlled by these modern stations the Auxilliary and controlling devices in these stations have become so numerous as to make the station a very complex structure, requiring high operating skill and involving high cost of installation.

At the same time, not only are all these devices necessary for the safe operation of the station but we hope that with the materialisation of national or zonal grid systems, additional devices like automatic recording apparatus and multirecorder become necessary for safe and reliable operation.

With this type of station, it is obviously impossible in most-cases, to develop water power of small and moderate size. A generating station of 5000 H.P. will rarely and one of hundred horse power will hardly ever be economical.

On the other hand, a hundred h.p motor installation is a good economical proposition and average size of all the motor installations is probably below hundred horse power.

If we see the hydrological datas for the power projects in our country, it is startling to note, how large a part of the potential water power of the country is represented by comparatively small areas of high elevation, inspite of the relatively low rainfall of these areas. As most of these areas are at considerable distance from the ocean, most of the streams are small in volume. That is, it is the many thousands of small mountain streams and creaks, of relative small volume of flow, but high gradients, affording fair heads, which apparently make up the bulk of the country's potential water power.

Only a small part of the country's hydraulic energy is found so concentrated locally as to make its development economically feasible with the present type of generating station.

The solution of the problem of the economic development of smaller water powers, is the adoption of induction generator and it has been evolved, for develping these many thousands of small hydraulic powers, to collect the power of the mountains streams and creaks. By the adoption of induction generator, the following simplification in the generating station is made.

(1) Hydraulic turbines of simplest form, continuously operating at full load, without governors.

(2) Low-voltage induction generators direct connected to the turbines.

(3) Step-up transformers direct connected to the induction generators.

(4) High tension circuit breakers connecting the step-up transformers to the transmission line.

In smaller stations, even these may be dispensed with and replaced by disconnecting switches and fuses.

Lightening arresters on the transmission line, where the climatic or topographical location makes such necessary,

A station voltmeter, a totalling ammeter or integrating wattmeters and a frequency indicator may be added for the information of station attendant, bût are not necessary and voltage, current, output and frequency are not controlled from the induction generator station, but from the main station or determined by the available water supply.

But all these described above will be necessary when the induction generator is adopted as a single unit self excited generator, and the commercial adoption of this type of generator is yet to come.

There are on the lower courses of our streams some hydraulic powers, which are relatively small due to their low heads, and which can not be economically developed by the synchronous generator, due to the low head and correspondingly low speed. The designing characteristics of the induction generator, with regards to low speed machines, are no better - if any thing rather worse - than those of the synchronous generator, and the problem of the economical utilisation of the low head still requires solution.

The same reasoning applies also, and to the same extent, to the problem of collecting in-numbrable small-quantities of mechanical or electrical energy, which are or can be made available, whenever fuel is consumed for heating purposes. Of the hundred million quiental of coal, which are annually used for heating purposes, most is used as steam heat. Suppose, then, we generate the steam at high pressure as is done now in many cases for reasons of heating economy- and interpose between steam boiler and heating system, some simple form of high pressure steam turbine, directly connected to induction generator, and tie the latter into the general electrical distribution system. In this way the overall economy will be much better than utilising steam at low pressure and temperature.

Whenever the heating is in operation, electric power is generated as, we may say as 'by product' of the heating plant and fed into the electric system.

This paper presents a complete theory and a few experimental data on self-excited induction generator as well as the induction generator connected to infinity bus-bar. Chapter (I) deals with the basic conception of electromagnetic theory involved in generating action, when the machine is driven above synchronous speed. Attempt has been made to explain the phenomena in a simplex way.

Chapter (II) deals with the vector diagram, equivalent circuit, power, torque, load angle and voltage- Amps ratings of the induction generator.

Conception of load angle has been intsoduced in this machine by the author, just to bring a better physical insight in to the actual phenomena in the machine. It does not change at all the classical theory of the induction machine as such, but apart from anything else, it brings a closer similarity between the induction Machine and synchronous machine.

Expression for optimum volt-ampere relations and power components has been derived in this chapter. Accordingly equations of power and torque is derived in terms of torque angle and a number of performance curves have been drawn and they are quite similar to curves for synchronous mahhine.

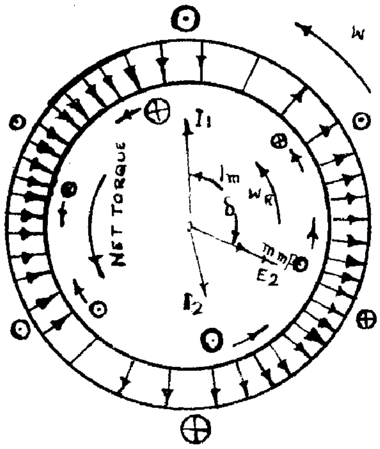
Chapter III deals with the induction generator connected to infinity bus bar. Different Methods of determining the phase rotation of the machine have been discussed exhaustively by the author with necessary equations and experimental results.

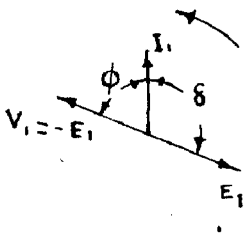
Curves of load tests, performed on a 10 H.P machine has been given in this chapter, along with the oscillagraphic record of in-rush current at different speed. Discussions on over voltage, runaway speed, speed detectors and low voltage, have been given from the practical stand points. An interesting speed detector which is in use in Japan has been described here in details.

At the end of this chapter author deals with the stability of the machine in relation to its water wheel prime mover and as well as its own stability with reference to its load angle vs torque curve. Electro-dynamic equation has been discussed as in case of synchronous machine. Critical power and correspondingly load angle for different values of

$\frac{r_2}{x_2}$ have been derived from Torque angle and load curves by equal area criteria method and in this connection of stability of machine, the conception of load angle makes the approach to the problem more simple and has brought much similarity with the synchronous machine. At the end of this chapter the idea of stability co-efficient which was originated by steinmetz has been extended and mathematical expression of the co-efficients with primary as well as without primary impedance have been derived and discussed.

In chapter IV the theory of self excited generator by static capacitor along with the experimental results have been given and all the results speak very much in favour of the use of self excited generator as independent unit. Author also has performed certain test on self excited induction generator by synchronous condenser and it vives similar characteristic like the self-excited generator by static capacitor.





(b)

FIG-2

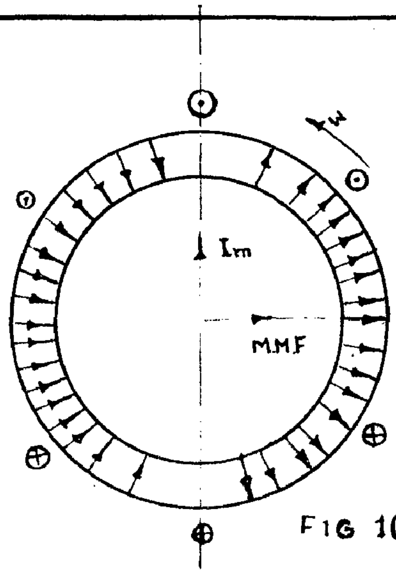
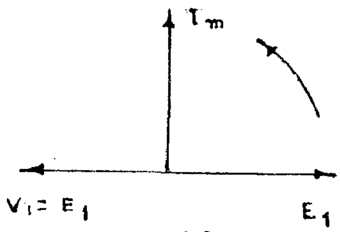


FIG 1(a)



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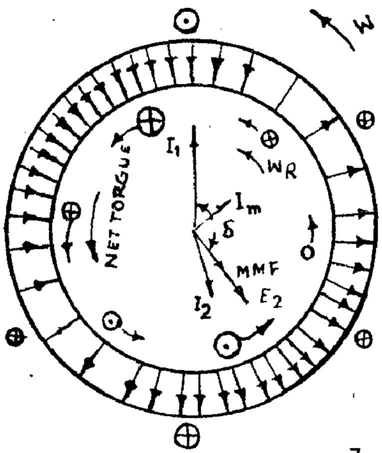


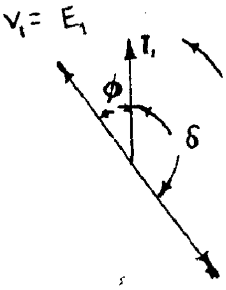
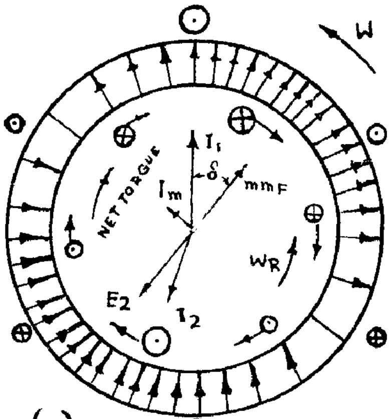


FIG-3 (b)



(a)

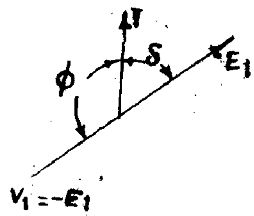


FIG-4

CHAPTER - I

THEORY :-

In actual induction machine, with elaborate winding each phase current flows in coils, which are distributed over several slots and the system produces a travelling current sheet, which approximates very closely to sinusoidal distribution. This current sheet in turn produces a space distribution of magneto-motive force which lags behind the current by a space angle of 90^{o} (Electrical).

The rotational speed of the current sheet and m.m.f waves is given by $\frac{f}{p}$. If the rotor circuit of an induction machine is opened, the conditions are analogous to a transformer whose secondary is open circuited. (Fig. (1) gives the conditions for the instant in time, when the red phase current is maximum. The current and m.m.f waves can be represented by single space vectors lying along the axes of maximum current and m.m.f

If the stator resistance and leakage reactance are neglected in the first instance, the rotating flux will attain a value, such that the back e.m.f (E_1) it generates in the stator winding is exactly equal to the applied e.m.f (V_1). The current I_m, which flows is that required to set up such a flux. Fig. 1(b) shows the time relationships corresponding to the red phase only and the sets of vectors corresponding to other phases, have the same flow, and are displaced by $\pm$ 120^{o} from that of red phase. The e.m.f induced in the rotor conductors are in space phase with the flux producing them, so that, if the rotor circuits are closed and the rotor is held at stand still, a wave of rotor current is produced, which travels at the same speed as the stator wave. The space position of this wave is decided by the rotor impedance.

At stand still, the rotor reactance is in general, greater than the resistance and the current wave lags on the voltage by large angle. The machine behaviour is then, similar to that of a transformer, whose secondary is short circuited and the stator current adjust itself, so that the net M.M.F produced by the two current waves is again sufficient to provide the same flux and therefore the same back E.M.F, as was present on open circuit.

In Fig 2(a) which illustrate the space conditions in squirrel cage machine at standstill, tangential arrows are drawn to indicate force on each bar. The force on any bar is given by the product of the flux at that point and the current in the bar. If the flux and current are sinusoidally distributed in space, the net force on the rotor, by analogy with the power in a single phase circuit is given by

$\frac{1}{2} I_2 \phi \cos \theta$ where I_2 and ϕ are maximum amplitudes of flux and current waves and θ is the space angle between them.

If the rotor is now allowed to rotate at some velocity below the synchronous speed (the speed of the stator magnetic field) the relative velocity between the rotor and the flux wave is reduced. It is convenient to express rotor speed in terms of a quantity known as the fractional slip (s)

defined as $s = \frac{\omega - \omega_r}{\omega}$

where $\omega = \frac{f}{p}$ and ω_r = rotor speed.

The frequency of rotor currents for any value of (s) is thus equal to 'sf' and the speed of the magnetic field produced by rotor current with respect to rotor is $s\omega$. The speed of the rotor current wave in space is then $s\omega + \omega r = \omega$

Thus it is seen that at any slip the two current patterns are revolving at the same speed and the space conditions at speeds below synchronism are similar to those for stabdstill except that the rotor reactance is reduced to sx_2 where x_2 is the standstill reactance and the rotor induced voltage is reduced to SE_2 where E_2 is the stand still induced e.m.f.

Hence the current changes in magnitude and its space position swings, closes to that of induced e.m.f with decrease of slip. Fig . (3) corresponds to a speed just below synchronism. When the rotor is revolving at exactly synchronous speed, the rotor induced e.m.f is zero, hence torque is zero.

If the machine speed is above the synchronous speed, then the relative velocity (the slip velocity) is reversed and hence the induced e.m.f in the rotor is reversed. The rotor current sheet must always lag behind the induced e.m.f in time, because the rotor is inductive, but since the direction of relative motion has reversed, the space lag of rotor current, when the machine is motoring, becomes, a space lead when the machine is generating. The rotor currents are such as to produce negative torque, so that power must be supplied to the shaft to enable the rotor speed to be maintained. The power flow from the supply to the machine, when the speed is below synchronism is given by $V_1 I_1 \cos \phi$. Examination of vector diagram Fig 4.(b) shows that the quantity $V_1 I_1 \cos \phi$ becomes negative when the speed is above synchronism. The power flow in this case is from the machine shaft to the supply and the machine becomes generator. The conditions for the generating phase are shown in Fig. (4).

The point of greatest importance, which arises from the consideration of space diagrams, is that the rotor current never has a component in the direction of the reactive magnetising current, even when the machine is generating and the magnetising relactive KVA must come from supply. Same conditions apply when the load on generator is partly reactive. All reactive KVA must be supplied from electrical side.

TOR DIAGRAM OF INDUCTION MOTOR

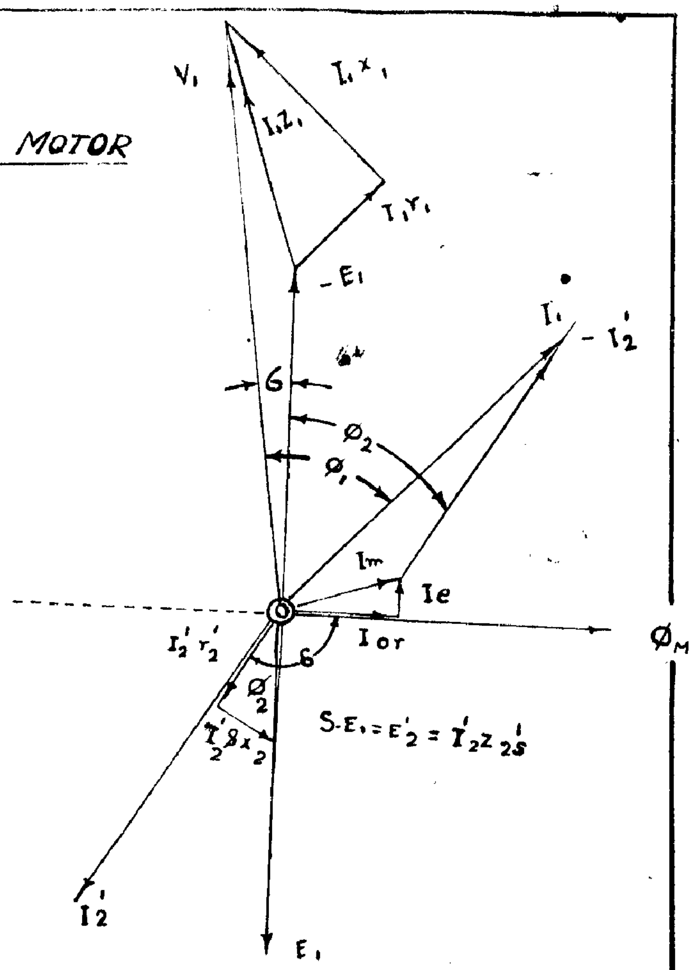
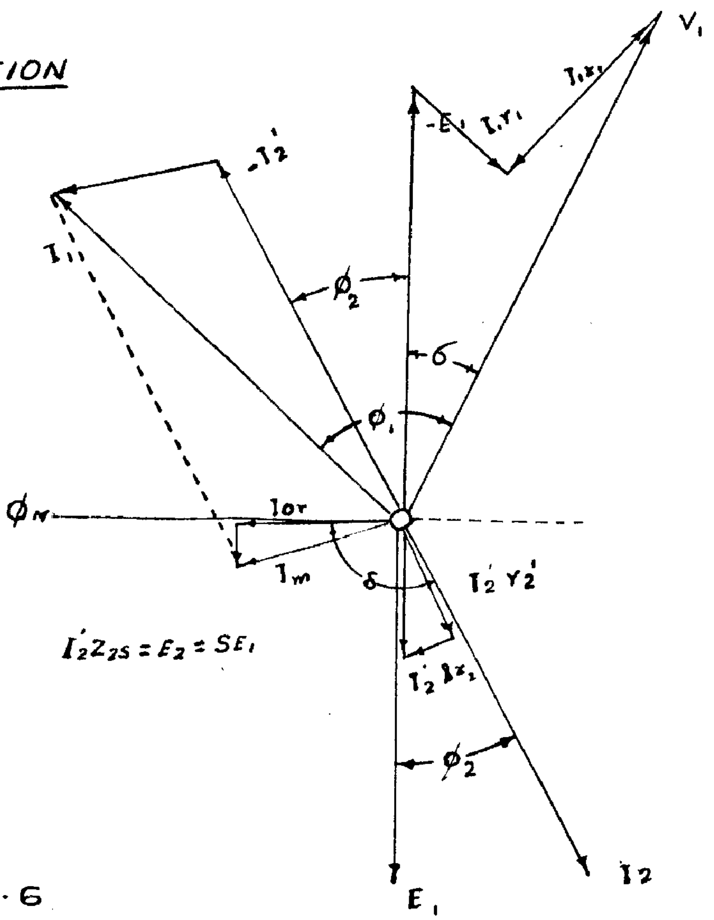


FIG-5

CTOR DIAGRAM OF INDUCTION GENERATOR



FIG·6

CHAPTER - II

VECTOR DIAGRAM AND EQUIVALENT CIRCUIT

VECTOR DIAGRAM :

Line induction motor, the air gap flux in an induction generator, is assumed to remain constant with constant voltage and to be unchanged by the variation in the speed of the rotor Hence, when running as a generator, the machine must be supplied with its usual magnetising current. I_m. The reversal of the voltage due to generator action makes this magnetising current lead the out put voltage. This current can not come from the induction generator itself and must come from a synchronous generator. Hence the induction generator must always be operated in parallel with an ordinary alternator to supply a common load, the removal of the alternator from the line reduces the excitation of the induction machine to zero and its generator action ceases.

Fig. 5 and Fig. 6 show the vector diagrams of induction motor and induction generator respectively. The p.f. angle between the induced voltage and current is fixed by the constants of the rotor and by slip.

Referring to the vector diagram of the induction generator it can be seen that the p.f. angle between the induced voltage and current is fixed by the constants of the rotor and by the slip, and

$$\cos \phi_2 = \frac{r_2'}{\sqrt{r_2'^2 + s^2 x_2'^2}}$$

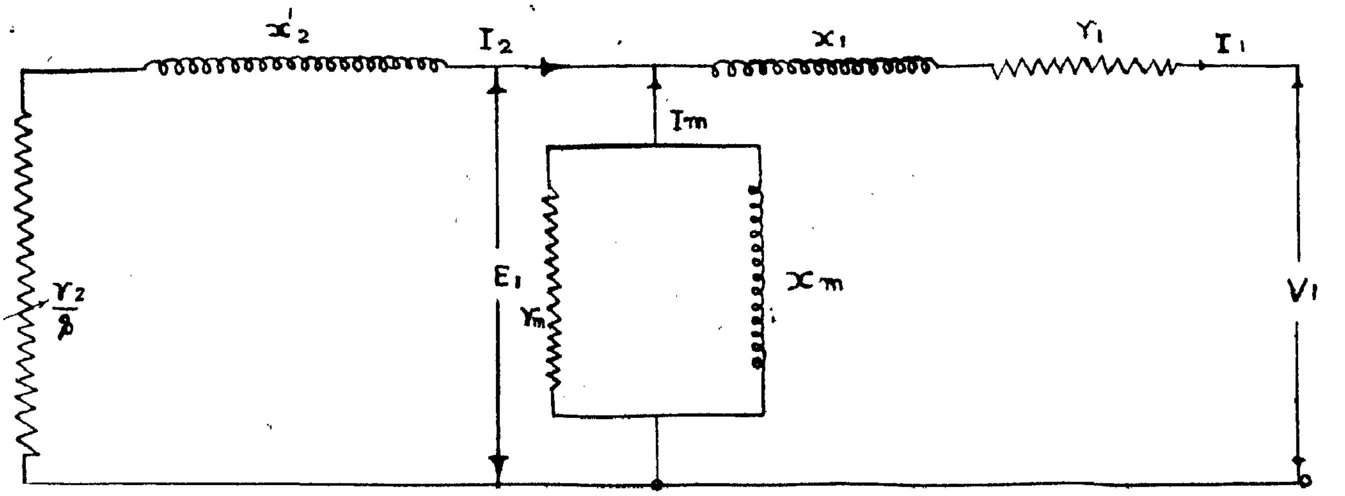


FIG: 7

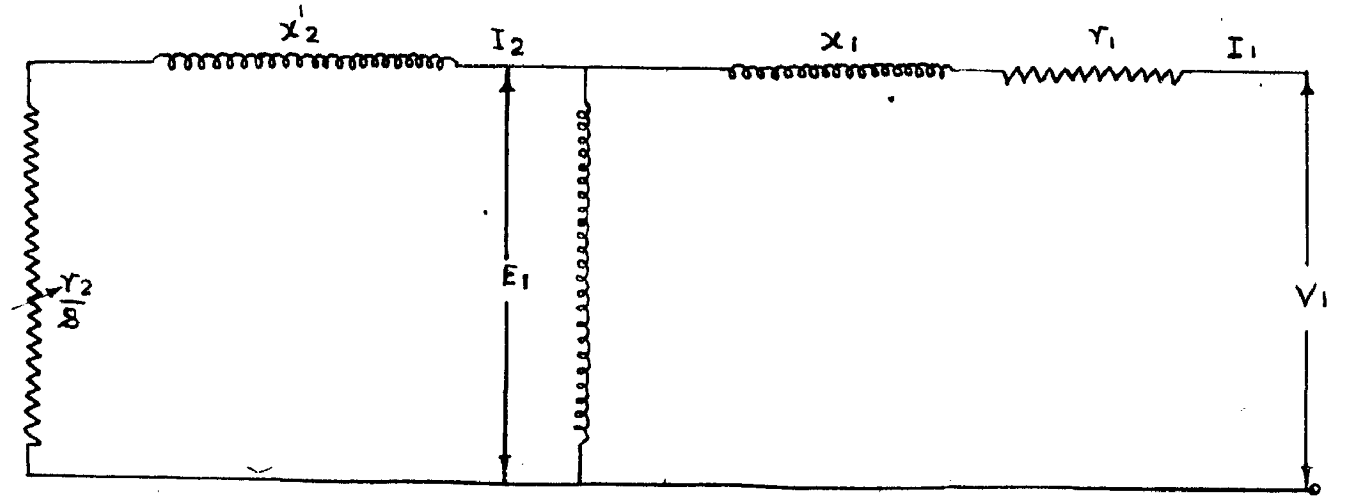


FIG: 8

The angle ($\phi_1 - \delta$) is fixed by the relative values of the no load current and load component. The angle 'δ' is fixed by the primary impedance drops. The resulting power factor angle ϕ_1 between the line current and the terminal voltage is thus fixed by the machine constants rather than load. It is seen from the vector diagram that the generator can supply a load with leading current only; its power factor will vary slightly with load, but the current will always lead. If it is connected to a load which requires a lagging current, it is necessary that the synchronous machine, connected in parallel with the induction generator, operate at a low-lagging power factor to neutralize the induction generator lead.

EQUIVALENT CIRCUIT:

Fig. (7) gives the equivalent circuit for induction generator. A simplified equivalent circuit is given in Fig. 8, where, the magnetising loss component resistance, has been neglected to simplify the analytical treatment.

TORQUE AND POWER

For a given main flux and (approximately) stator voltage the rotor e.m.f E_2' and Current I_2' are settled by the slip, while the phase angle ϕ_2 is a function of r_2' and sX_2'. The rotor power P_2 is then also a function of the slip and so is the torque.

$$M = M = k_t E_1 I_2' \cos\phi_2$$

Where M = torque. $I_2' = \frac{E_2'}{Z_{2s}'} = \frac{sE_1}{\sqrt{r_2'^2 + s^2 x_2'^2}}$ for one phase

$$\cos \phi_2 = \frac{r_2'}{\sqrt{r_2'^2 + s^2 x_2'^2}}$$

the $M = K_t \dfrac{s E_1^2 r_2'}{r_2'^2 + s^2 x_2'^2}$

This is also a general expression and valid for actual conditions. If the mutual flux is constant, however, so will E_1 be constant. The torque may be written in terms of the ratio

$$\alpha = \frac{r_2'}{x_2'} = \frac{r_2}{x_2}$$

So $M = \dfrac{R_t E_1^2}{x_2'} \dfrac{s\alpha}{s^2+\alpha^2} = K_t \dfrac{s\alpha}{s^2+\alpha^2}$ (1)

Where $K_t = \dfrac{R_t E_1^2}{x_2'}$

For constant flux and a given arrangement of rotor winding K_t is constant.

MAXIMUM TORQUE TO BE SUPPLIED BY PRIME MOVER

Eq. (1) for the torque supplied to induction generator by the prime mover, will show a maximum value for any given ratio $\alpha = \dfrac{r_2}{x_2}$

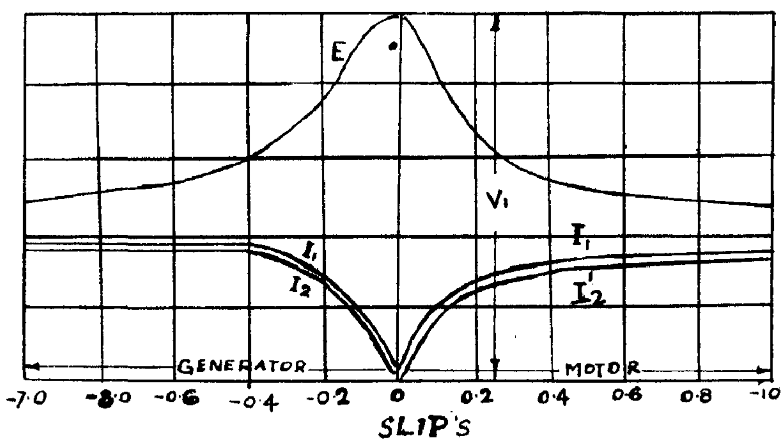
Writing $\dfrac{dM}{ds} = 0$

Giving $\alpha(s^2+\alpha^2) = 2s^2\alpha$ $\quad s^2 = \alpha^2$ or $s = \pm\alpha = \pm\dfrac{r_2}{x_2}$

So the maximum value of torque

$M_m = \pm \dfrac{1}{2} K_t$

If $s = \pm \alpha = \pm \dfrac{r_2}{X_2}$ or $r_2 = \pm sX_2$ the



VARIATION OF E.M.F AND CURRENTS WITH SLIP

FIG: 9

torque is a maximum.
The negative slip refers to a speed exceeding the synchronous and this holds good for generating action. The positive value of slip corresponds to sub-synchronous range and this holds good for induction motor action.

For value $\alpha = 0$ or $r_2 = 0$ minimum torque is zero, that is if the rotor had no resistance, it could develop no electrical power. This is obvious from the vector diagram of the induction generator in Fig. (6) for such a case I_2' would always lead by 90^0 to E_2 and would have no power component along E_2

MECHANICAL POWER :

The torque equation above may be multiplied by

$$\omega_r = 2\pi n_1 (1-s)$$

to give

$$P_m = \frac{K_t s \alpha (1-s)}{s^2+\alpha^2} \quad \ldots (2)$$

The mechanical power has got the maximum value when

$$\frac{dP_m}{ds} = 0$$

Differentiating 'P_m'

or
$$(s^2+\alpha^2)(1-2s) - 2s^2(1-s) = 0$$

or
$$s = -\alpha^2 \pm \alpha\sqrt{1+\alpha^2} \quad \ldots (3)$$

The positive sign before the root referring to motoring action and the negative to generating conditions.

Inserting the value of slip for induction generator conditions, the maximum value of mechanical power required from the prime mover is ;

$$P_{mg} = \frac{1}{2} K_t \left(\sqrt{1+\lambda^2} + \lambda\right) = \frac{1}{2} K_t \left(\frac{Z_2 + r_2}{x_2}\right)$$

where $Z_2 = \sqrt{r_2^2 + x_2^2}$ at $s = 1$

where as maximum mechanical power for motoring action is

$$P_{mm} = \frac{1}{2} K_t \left(\frac{Z_2 - r_2}{r_2}\right) \qquad \text{So} \qquad \frac{P_{mg}}{P_{mm}} = \frac{Z_2 + r_2}{Z_2 - r_2}$$

It is seen that for large rotor resistances the mechanical power produced for motoring action is severaly limited.

Where as in case of induction generator it is seen that higher the rotor resistance the greater is the mechanical power required from the prime mover for a particular value of electrical output. From the above equations for maximum torque and maximum power, it is seen that both of them do not occur at the same slip. The maximum power condition, for induction genenator occurs at higher slip, where as for induction motor it occurs at low slip.

INDUCTION GENERATOR WITH PRIMARY IMPEDANCE:

All the above treatments for torque and power have been made with the assumption that the air gap flux remains constant irrespective of load, which is not true in actual practice. However, the general shapes of the characteristic curves of the induction generator are not altered to any important deg degree, when the assumption of constant flux is dropped in favour of the more natural one of constant applied voltage atleast not within the usual limit of load. To take into account more exactly the variations of flux, it is desirable to employ the equivalent circuit, and to make the analysis from that. Incidentally, the equivalent circuit will show that a close approximation to the actual conditions is obtained, if the stator leakage reactance is assumed added to the rotor, and similarly for the stator resistance which is howe ever independent of slip. The general equivalent circuit in Fig. (7) will furnish a complete vector explanation of the machine.

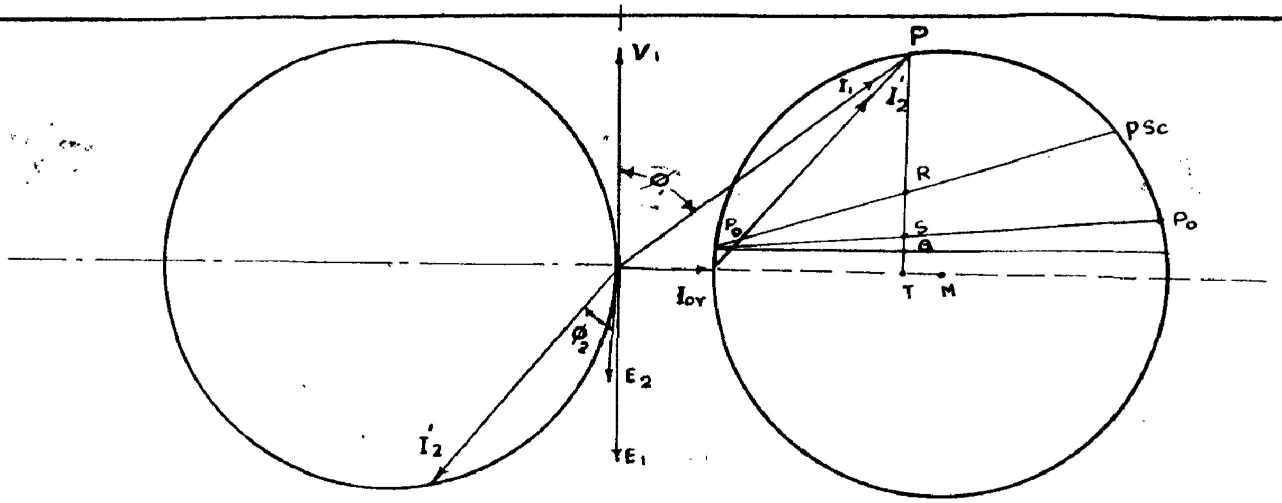
Using for simplicity the complex operational rotation, the stator impedance is $Z_1 = r_1 + jx_1$ The rotor impedance $Z'_{2s} = r'_2/s + jx'_2$ The admittance of the magnetising circuit is $y_m = \frac{1}{r_m} - \frac{j}{x_m} = g_m - jb_m$

The rotor current is $I'_2 = \frac{E_1}{Z'_{2s}}$ and the magnetising current $I_m = E_1 Y_m$. The stator current is the vector sum of these or $I_1 = E_1 \left(\frac{1}{Z'_{2s}} + y_m \right)$

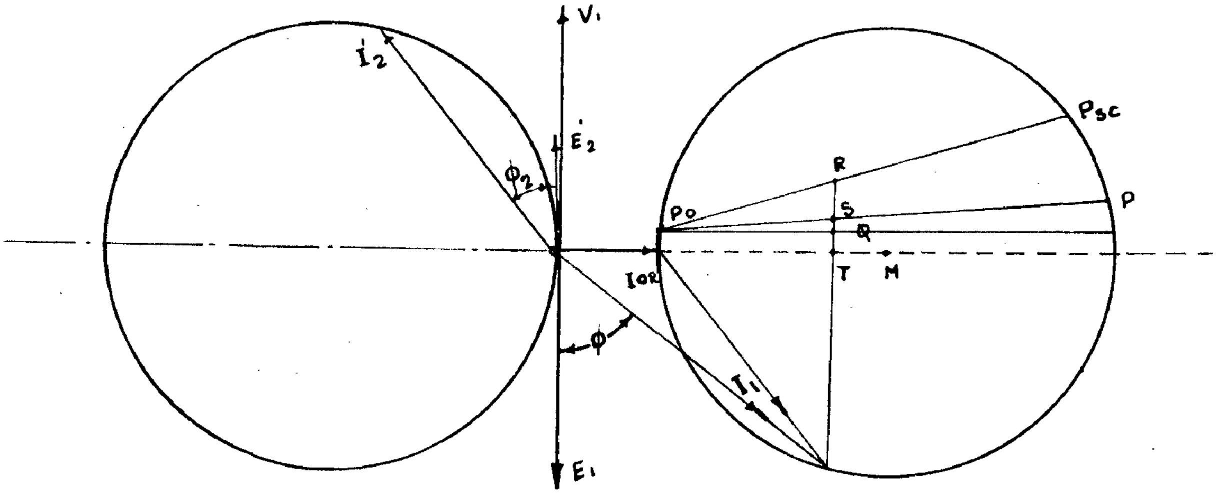
The terminal voltage is

$$V_1 = E_1 + I_1 Z_1 = E_1 \left(1 + \frac{Z_1}{Z'_{2s}} + y_m Z_1\right)$$

The complex number $Z_1 Y_m$ is a small fraction very nearly a small positive scalar value (since it is the product of two complex numbers each with a large phase angle, one positive and one negative) putting therefore $(1 + z_1 y_m) = c_1$



SUB-SYNCHRONOUS INDUCTION MOTOR FIG: 10(a)



SUPER-SYNCHRONOUS INDUCTION GENERATOR FIG: 10(b) a plain number slightly greater than unity then

$$V_1 = E_1 (c_1 + \frac{Z_1}{Z'_{2s}})$$

From which
$$E_1 = \frac{V_1 Z'_{2s}}{Z_1 + c_1 Z'_{2s}} = \frac{V_1 (r'_2/s + jx'_2)}{(r_1 + jx_1) + c_1 (r'_2/s + jx'_2)}$$

$$E_1 = \frac{V_1 \sqrt{(r'_2/s)^2 + x'^2_2}}{\sqrt{(r_1 + c_1 r'_2/s)^2 + (x_1 + c_1 x'_2)^2}}$$

At synchronous speed $s = 0$ and $E_1 = \frac{V_1}{C_1}$ so that C_1 is the ratio $\frac{V_1}{E_1}$ when the rotor is driven at synchronous speed.

The rotor current is
$$I'_2 = \frac{E_1}{Z'_{2s}} = \frac{V_1}{Z_1 + c_1 Z'_{2s}}$$

$$= \frac{V_1}{(r_1 + jx_1) + c_1 (r'_2/s + jx'_2)}$$

Scalar value is

$$I'_2 = \frac{V_1}{\sqrt{(r_1 + c_1 r'_2/s)^2 + (x_1 + c_1 x'_2)^2}} \qquad (1)$$

curves typical of the variation of E_1, I_1 and I'_2 with slip are given in Fig. (9) for generating and motoring action. At synchronous speed, $s = 0$, E_1 is very nearly equal to V_1 it may be within 2 or 3 percent. It rapidly falls with increase of slip in either direction. The current I'_2 is zero at synchronous speed, increases rapidly with small values of slip and thereafter tends to a constant value. The stator current I_1 is the magnetising current at synchronous speed, but soon reaches values very close to those of I'_2, since I_m is comparatively small. The mutual flux ϕ_m is proportional to E_1. The torque in synchronous watts is given directly by (1 - s) M for induction generator from the prime mover and output from rotor to the stator is given by $M = F_2 = \frac{I_2^{1} r_2^{1}}{s}$ per phase putting in the scalar value of I_2^1 from(1) $M = \frac{V_1^2 \, r_2'/s}{(r_1 + c_1 r_2'/s)^2 + (x_1 + c_1 x_2')^2}$

The fraction $sM = F_2$ is the true I^2R loss of the rotor. The slip for maximum torque is obtained by differentiating the above equation for M and equating to zero $\frac{DM}{ds} = 0$ yielding

$$s = \pm \frac{c_1 r_2'}{\sqrt{r_1^2 + [x_1 + c_1 x_2')^2}} \simeq \pm \frac{r_2'}{\sqrt{r_1^2 + (x_1 + x_2')^2}}$$

putting $C_1 = 1$

The above value of slip does not greatly differ from $\frac{r_2'}{(x_1 + x_2')}$

The maximum value of torque is obtained by inserting the critical value of 's' in eq. (11) in the expression M

So $$M_m = \frac{V_1^2}{2c_1 \{\sqrt{[r_1^2 + (x_1 + c_1 x_2')^2]} \pm r_1\}} \quad (12)$$

+ve sign of the expression for motoring action and -ve sign for generating action. It is seen that maximum torque is independent of rotor resistance.

For motoring operation, the maximum torque is larger for lower values of r_1, x_1 and x_2'. The rotor resistance does affect the speed at which maximum torque occurs.

For generator action the maximum torque is seen to be independent of r_2. But an increase of stator resistances, now increases the maximum torque M_m

$$\frac{M_{mg}}{M_{mm}} = \frac{\sqrt{r_1^2+X_1^2}+r_1}{\sqrt{r_1^2+X_1^2}-r_1} \simeq \frac{X_1+r_1}{X_1-r_1}$$

where $X_1 = x_1 + C_1X'_2$

and this relation holds good so long as r_1^2 is sufficiently less than x_1^2

If $X_1 = 7r_1$ then $\frac{M_m\text{ (generator)}}{M_m\text{ (motor)}} = \frac{8}{6} = 1.33$

If the primary resistance is large, the maximum torque running as generator will be very high indeed.

The power at the slip which gives maximum torque for induction generator is

$$P_{mt}(\text{generator}) = \frac{V_1^2\left[\sqrt{r_1^2+(x_1+c_1x_2')^2}+c_1r_2'\right]}{2c_1\left\{\sqrt{r_1^2+(x_1+c_1x_2')^2}-r_1\right\}\left\{\sqrt{r_1^2+(x_1+c_1x_2')^2}\right\}}$$

This is not the maximum power. The maximum power occurs at slip

$$s = \frac{-c_1r_2'}{r_1^2+2r_1r_2'c_1+(x_1+c_1x_2')^2}\left[\sqrt{r_1^2+2c_1r_1r_2'+(x_1+c_1x_2')^2-c_1^2r_2'^2}-c_1r_2'\right]$$

and this slip is smaller than the slip at which maximum torque occurs.

RELATION BETWEEN POWER AND VARS FOR AN INDUCTION GENERATOR

Referring to the equivalent circuit - Fig.(8), the power and vars output of an induction generator can be derived in the following manner -

$P_g + jQ_g = V_1^2 / -Z$ (1)

V_1 = terminal voltage

Z^* = conjugate of the independence seen looking into the induction generator.

$-Z = R_g + jx_g$ and $-Z^* = R_g \; j \; x_g$.

then $$R_g + j\,x_g = -r - j\,x_1 - \frac{(r_2'/s + jx_2')\,jx_m}{r_2'/s + j(x_2' + x_m)} \qquad (2)$$

For this treatment r_m is neglected.

$$P_g + jQ_g = V_1^2 / R_g - j\,x_g$$

adding and subtracting $j\frac{x_m^2}{2(x_2' + x_m)}$ to the right of the equation (2) and on simplification it gives

$$R_g + j\,x_g = -r_1 - j\left[x_1 + x_m - \frac{x_m^2}{2(x_2' + x_m)}\right]$$

$$- \frac{j\,x_m^2}{2(x_2' + x_m)}\left[\frac{r_2'/s - j(x_2' + x_m)}{r_2'/s + j(x_2' + x_m)}\right] \qquad (3)$$

Let $$x' = x_1 + \frac{x_m x_2'}{x_m + x_2'}, \qquad \frac{x_m^2}{x_2' + x_m} = x_m + x_1 - x'$$

Substituting these in equation (3)

$$R_g + j\,x_g = -r_1 - j\frac{(x_1 + x_m + x')}{2} - j\frac{x_m + x_1 - x'}{2}\left[\frac{r_2'/s - j(x_2' + x_m)}{r_2'/s + j(x_2' + x_m)}\right] \qquad (4)$$

$$\text{Or} \quad (R_g+r_1) + \left[X_g + \frac{(x_1+x_m-x')}{2}\right] = -j\frac{(x_1+x_m-x')}{2}\left[\frac{r_2'/s - j(x_2'+x_m)}{r_2'/s + j(x_2'+x_m)}\right] \qquad (5)$$

Taking magnitude of both the side of the equation and combining the results and eliminating 's' the following equation is obtained -

$$(R_g + r_1)^2 + (X_g + x_1 + x_m)\,(x_g + x') = 0 \qquad (6)$$

$$R_g = \frac{P_g V_1^2}{P_g^2+Q_g^2} \qquad \text{and} \qquad X_g = \frac{Q_g V_1^2}{P_g^2+Q_g^2}$$

Substituting these values in equation (6) it becomes

$$\left(\frac{P_g V_1^2}{P_g^2+Q_g^2} + r_1\right)^2 + \left(\frac{Q_g V_1^2}{P_g^2+Q_g^2} + x_m + x_1\right)\left(\frac{Q_g V_1^2}{P_g^2+Q_g^2} + x'\right) = 0 \qquad (7)$$

expanding and rearranging this equation we get

$$\left[P_g + \frac{V_1^2 r_1}{r_1^2+(x_m+x_1)x'}\right]^2 + \left[Q_g + \frac{V_1^2(x_m+x_1+x')}{2(r_1^2+[x_m+x_1]x'}\right]^2 = \frac{V_1^4(x_m+x_1-x')^2}{4\left[r_1^2+(x_m+x_1)x'\right]} \qquad (8)$$

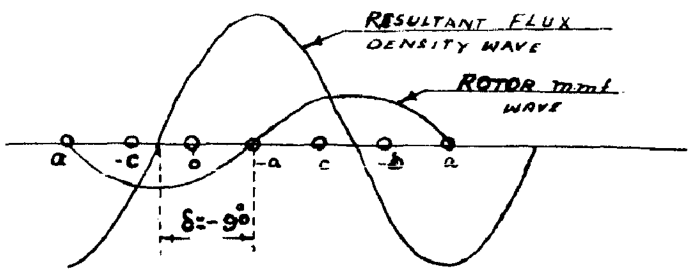
The equation (8) is an equation to circle with centre at

$$P_g = \frac{-V_1^2 r_1}{r_1^2+(x_m+x_1)x'} \qquad Q_g = -\frac{V_1^2(x_m+x_1+x')}{2\left[r_1^2+(x_m+x_1)x'\right]}$$

$$\text{Radius of the circle } k_g = \frac{V_1^2(x_m+x_1-x')}{2\left[r_1^2+(x_m+x_1)x'\right]}$$

Thus for a given terminal voltage there is a fixed relation between real and reactive power . Equation to the

FIG11(a)



1500 RPM FLUX WAVE WITH RESPECT TO STATER
1600 R.P.M ROTOR WITH RESPECT TO STATER
100 R.P.M FLUX WAVE WITH RESPECT TO ROTOR
100 R.P.M ROTOR mmf WITH RESPECT TO ROTOR
1500 R.P.M ROTOR mmf WITH RESPECT TO STATER
⟵ DIRECTION OF ELECTRO-MAGNETIC ROTOR TORGUE

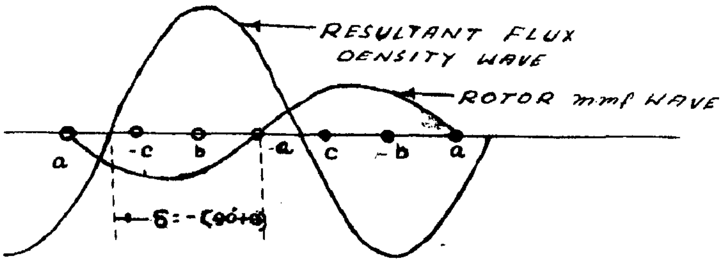


FIG-11(b) DEVELOPED ROTOR WINDING OF INDUCTION GENERATOR WITH FLUX DENSITY AND mmf WAVES IN THEIR RELATIVE POSITIONS FOR (a) ZERO AND (b) NONZERO ROTOR LEAKAGE REACTANCE

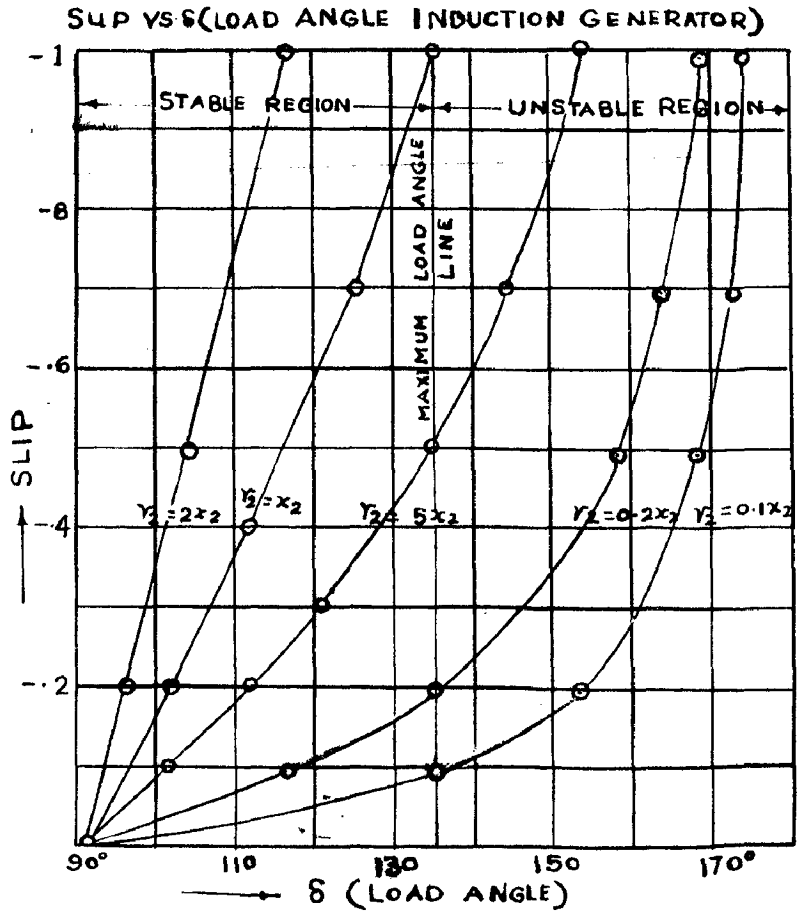


FIG-12

circle indicates that there is a definite limit to the power output of the generator. This limiting value of power will be called the power limit of the generator and is given by the following equation.

$$P_L = \frac{V_1^2 (x_m + x_1 - x' - 2r_1)}{2[r_1^2 + (x_m + x_1)x']} \qquad (9)$$

$$x' = x_1 + \frac{x_m x_2'}{x_m + x_2'}$$

If the stator resistance is neglected and the value of x^1 is substituted in equation (9)

$$P_L = \frac{V_1^2}{2\left[\frac{(x_m + x_1)(x_m + x_2')}{x_m^2}\left(x_1 + \frac{x_m x_2'}{x_m + x_2'}\right)\right]} \qquad (10)$$

Circle diagram of induction generator:-

Fig.(10) shows the conditions(a) for sub-synchronous speed and (b) for super synchronous speeds. In the rotor, above synchronous speed, the conditions are electrically similar to those at sub-synchronous speeds. As the speed is raised above synchrononism the slip increases negatively the rotor frequency rises from zero and the rotor e.m.f. similarly increases. From the expression of I_2^1 (rotor current) it is seen that the rotor current locus is consequently a circular arc, so that the ~~rotor~~ two semicircles for sub and super synchronous speeds respectively , meet to form a complete circle. The diagram for the stator current is then by the right-hand circles in Fig.(a) and (b). Just as for the simple circle diagram for motoring condi-

-tions, Fig. (a), P.T. represents the input, R S the rotor I^2R, SQ the stator I^2R and QT the core, friction and windage losses, and PR the output, so RS, SQ, and QT have the same significance when the machine is generating, Fig. (b). The electrical output as a generator is TP, the mechanical input in RP, the scale.

As a generator, the vector marked E_1 is the terminal voltage of the machine (Neglecting stator impedance drop), and the stator current I_1 is clearly a leading current of definite phase angle $\emptyset_1$. The output is determined by the circular locus and cannot be arranged to provide a lagging load. This feature emphasises the necessity for a.c. excitation by synchronous machinery. The plain induction generator cannot operate alone, and when working on a system in parallel with synchronous machine, it increases the amount of lagging reactive kilovars that the latter has to provide.

Conception of load angle in induction generator:

In all electrical machines, the torque is produced by interaction of magnetic fields of the stator and rotor currents. Quantitatively, it indicates that under the assumed sinusoidal conditions, the torque is proportional to the product of air gap flux density the m.m.f. of the rotor and the sine of the angle 'δ' between their axes in space. This angle is commonly called the torque angle for motor and load angle for generator.

It has been discussed subsequently in this chapter of that the reversibility of electro-mechanical energy conversion, as well as of the basic similarity of phenomena in generators

LOAD ANGLE - VS - PERCENT OF MAXIMUM TORQUE OF INDUCTION GENERATOR (NEGLECTING PRIMARY IMPDANCE)

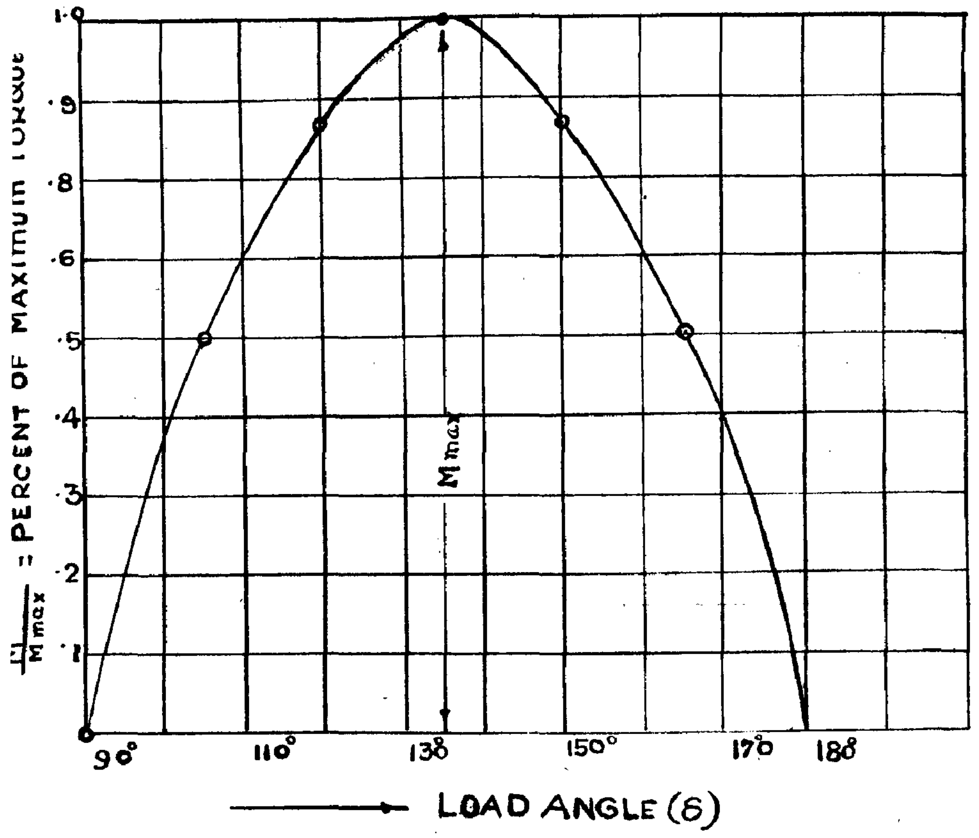


FIG = 13

and motors, is avoidable in polyphase induction machine. For the conception of 'load angle' the induction generator action may be examined by means of fig.(11). Relative directions of motion are indicated by the arrows inserted between parts (a) and (b) of fig.(11). The numerical values of speed are shown for the particular case of a 4-pole, 50 c/s machine, whose rotor is driven mechanically at 1600 rpm. In fig.(11)(a) the air gap flux density wave is shown in the position of maximum instantaneous voltage in phase 'a' but the induced rotor voltage directions in fig.(a) and fig.(b) are opposite because of the oppositely directed relative motions of air gap flux and rotor conductors. With negligible rotor reactance, the phase (a) current and consequently the rotor m.m.f. wave is displaced by 90° from the flux density wave of phase 'a'. In the generator, the rotor m.m.f. wave is of polarity opposite to that in the motor because of the opposite induced voltage. The load angle 'δ' is therefore -90° as shown in fig. (a). The electromagnetic rotor torque is directed towards the left in Figure (11-b).

When rotor leakage reactance, is appreciable, the rotor m.m.f. wave will not take its place at an angle of 90° the flux density wave of phase 'a' until the flux wave has travelled $(90 + \phi_2)$ degrees farther down the gap relative to rotor. This travel is towards the left in Figure (11-b).

The load angle is now $\delta = +(90^{\circ} + \phi_2)$

For a generator then, the electromagnetic torque on the rotor is in the direction opposite to the rotation of the

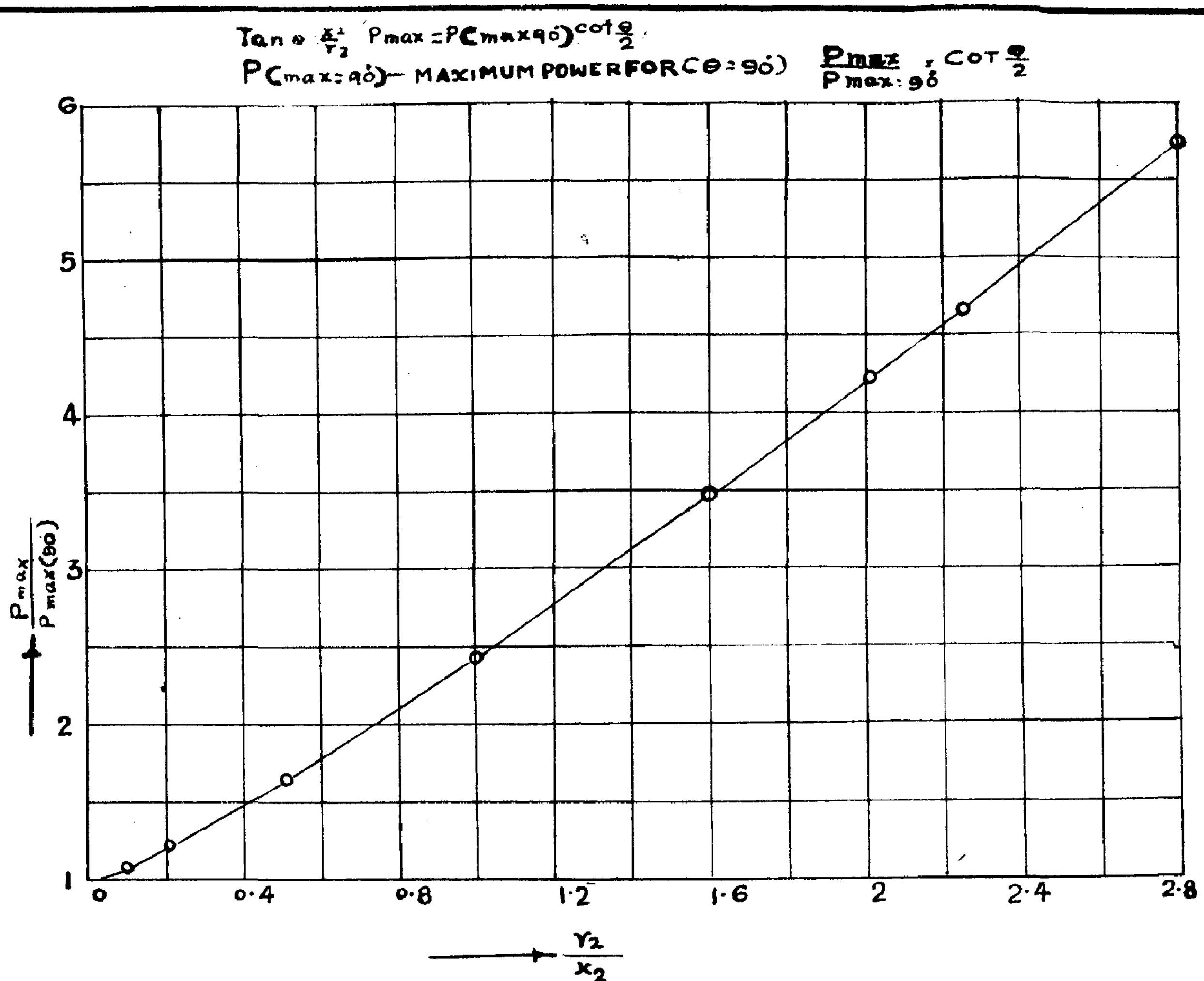

Tan θ = X1/Y2 Pmax = P(max 90°) cot θ/2
P(max 90°) — MAXIMUM POWER FOR (θ = 90°) Pmax / Pmax 90° = COT θ/2
6
5
4
3
2
1
0
0·4
0·8
1·2
1·6
2
2·4
2·8
Pmax / Pmax(90)
r2 / x2

FIG = 13 (a)

flux wave in space. It is a steady torque because rotor and stator fields are stationary relative to each other.

EXPRESSION FOR LOAD ANGLE FOR DIFFERENT CONDITIONS OF POWER AND TORQUE:

Maximum torque condition:

$S = -r_2/x_2 \quad \tan s = -\tan(90^\circ + \phi_2) = \cot \phi_2$

$\cot \phi_2 = r_2/sx_2$. (From vector diagram)

$\tan s = -1$ or $\delta = 135^\circ \quad \tan \delta = -r_2/sx_2$

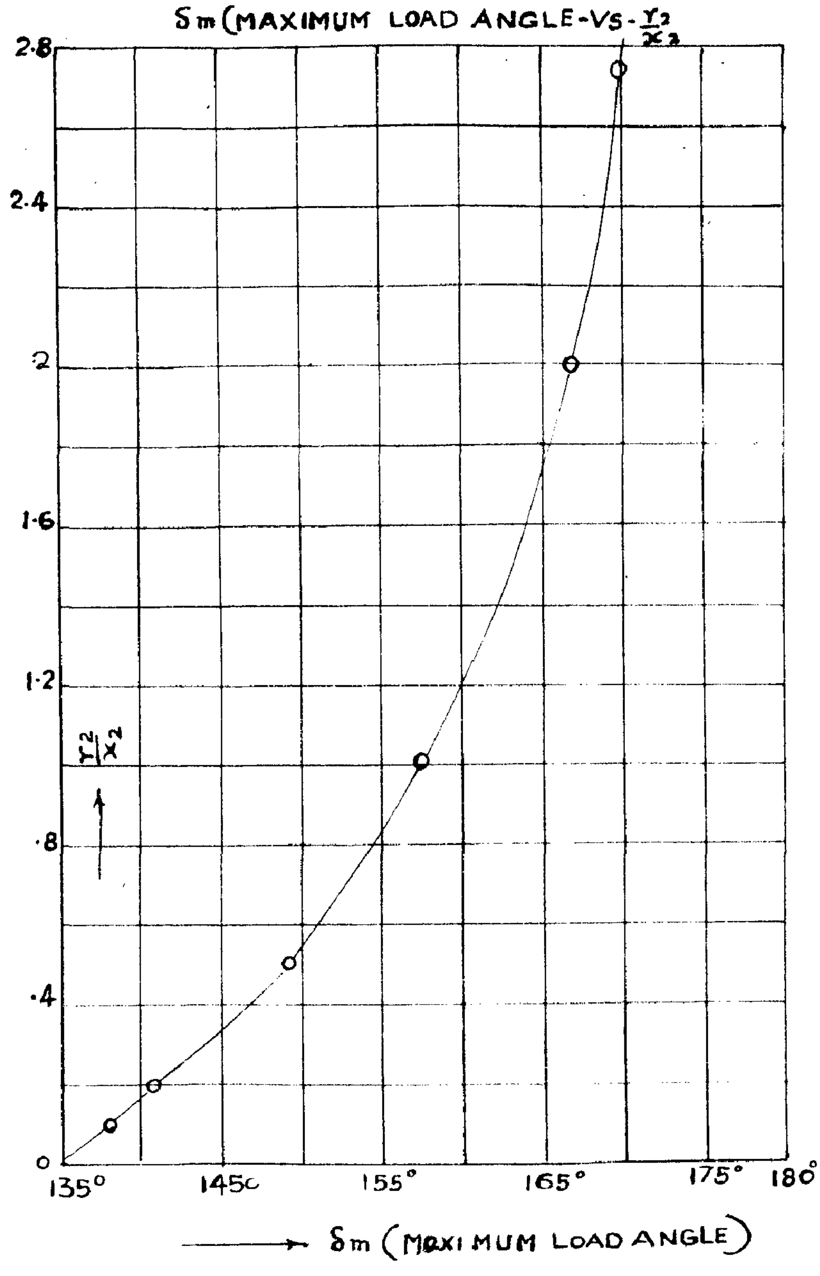
For different values of r_2/x_2 a family of curves have been plotted in fig.(12) between torque angle (δ) and slip of the induction generator. It is seen from the Fig.(12) that for all values of r_2/x_2 the maximum torque angle is 135° within the stability region of the generator.

For $r_2 = x_2$ and $r_2 = 2x_2$ the machine operates stably for all values of slips (from synchronous speed to twice the synchronous speed). It can be shown that

$$M \text{ (Torque from Prime-mover to generator)} = -\frac{K_t s E_1^2 r_2'}{r_2'^2 + s^2 x_2'^2}$$

$$= M_{(max)} \sin 2\delta$$

where δ falls within the range of 90° to 180° . $M/M_{max} = \sin 2\delta$. For different values of (δ) between 90° to 180° M/(Max) is plotted in fig.(13). This curve is similar to the torque angle and torque or load curve of the synchronous machine. In the above expression of torque, primary impedance is ignored.



δm (MAXIMUM LOAD ANGLE - VS - Y2/X2
2.8
2.4
2
1.6
1.2
.8
.4
0
Y2/X2
135°
145°
155°
165°
175°
180°
δm (MAXIMUM LOAD ANGLE)

FIG-13(b)

EXPRESSION OF MECHANICAL POWER, SUPPLIED TO GENERATOR, IN TERMS OF LOAD ANGLE

P_g = Mechanical power supplied to generator = $-\frac{s\alpha K_t(1+s)}{s^2+\alpha^2}$

$\alpha = r_2/x_2 = \cot\theta$. s = slip. $K_t = E_1{}^2N/x_2'$

where θ = Impedance angle of the rotor at stand-still.

Substituting the value of s and α in terms of δ and θ.

$$P_g = -\frac{K_t}{2}\left[\frac{\cos(2\delta+\theta)}{\sin\theta} + \cot\theta\right] \qquad (1)$$

Value of $\cot\theta$ is positive.

So the maximum value of P_g will occur when $\cos(2\delta+\theta) = 1$

Or $(2\delta_m+\theta) = 2\pi$. Or $\delta_m = (\pi-\theta/2)$. So $P_{g(max)}$

$$\text{Or } P_g/P_{g(max)} = \frac{\cos(2\delta+\theta)+\cos\theta}{1+\cos\theta} \qquad (2)$$

The relation-ship between maximum power angle and different values of r_2/x_2 is shown in fig. (13-b).

equation (2) can also be expressed in terms of δ and δ_m substituting $\theta = 2\pi - 2\delta_m$

$$\frac{P_g}{P_{g(max)}} = \frac{\cos 2(\delta_m-\delta) + \cos 2\delta_m}{1+\cos 2\delta_m}.$$

and $P_g(max) = -\frac{K_t}{2}\cot\theta/2 = K_t\cot\delta_m$.

$\theta = 90°$ $P_{max(90°)} = -K_p/2$ $P_{max(90°)}$ $\cot\theta/2$

Fig.(13-a) and fig.(13-b) gives relation between r_2/x_2 and $P_{max}/P_{max(90°)}$ r_2/x_2 and δ_m respectively.

CHAPTER III

INDUCTION GENERATOR CONNECTED TO INFINITY BUS BAR

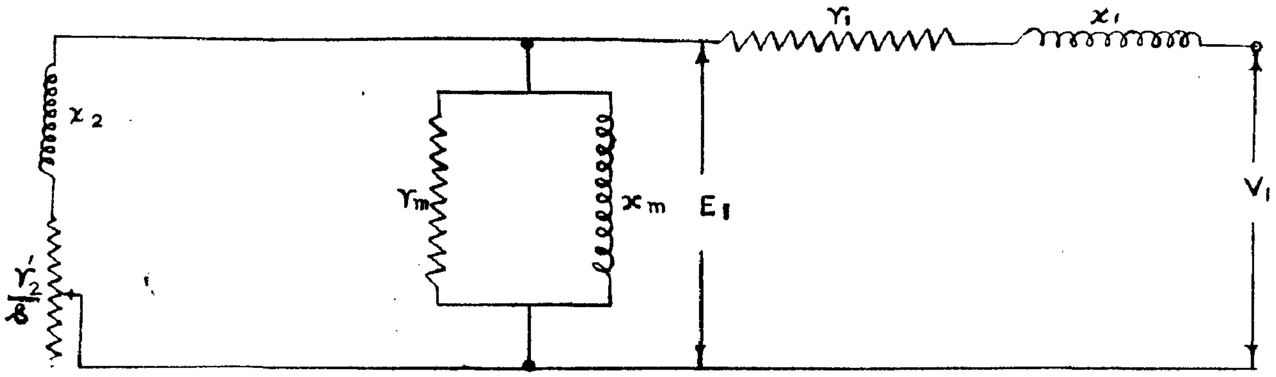
(1) STARTING OF INDUCTION GENERATOR:

It is possible to make a line start of an induction generator as a squirrel cage induction generator. In general, starting current of an induction motor is 5 to 6 times of its rated current and is liable to cause disturbance in the system. If the generator is made to accelerate to a speed close to synchronism and is thrown to power supply , the starting current can be made smaller. At a speed colse to synchronous speed , however the stator current and the torque undergo a sudden change. If the speed rises, above a point of the maximum torque (point 'A' on torque curve*) there is a danger of run away. Then a precise speed detector is called for. This behaviour of the set attending runaway speed will be discussed later, in generator details.

CHECKING OF PHASE ROTATIONS

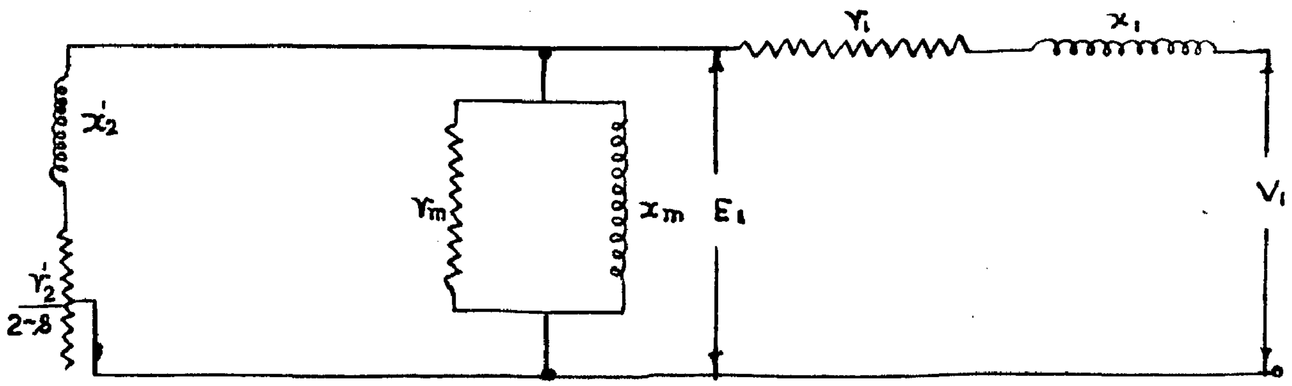
The phase rotation of the synchronous machines is measured against that of the electrical system to which they are to be connected. This requires excitation. The voltage of the machine is to be built up to normal voltage and measurement and indication is to be taken by direct or through voltage transformers, depending upon the machine voltage.

* In fig. 22.



EQUIVALENT CIRCUIT OF INDUCTION GENERATOR
WITH +VE-SEQUENCE VOLTAGE

FIG: 14



EQUIVALET CIRCUIT OF INDUCTION GENERATOR
WITH -VE SEQUENCE VOLTAGE

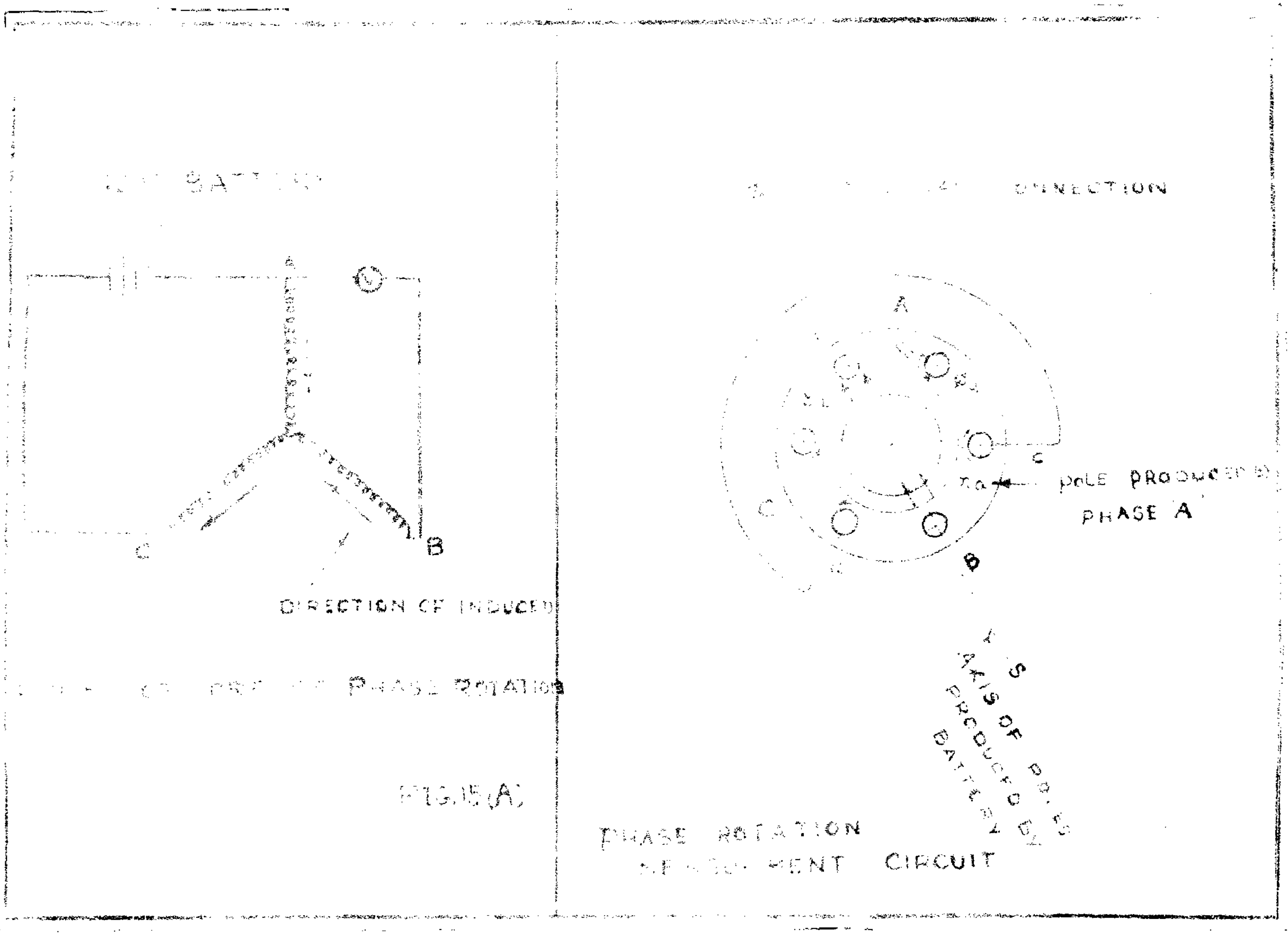
FIG 15

In an induction generator, no voltage exists in the windings until the stator is switched on to the bus bar.

First Method

If a synchronous generator is connected to the induction generator, free of all connections to the main electrical net works on any other 3-phase a/c low voltage source (even from the network with a step down transformer) and side by side stator current is measured, the phase rotation can be determined. Both the machine can run at synchronous speed. If the phase rotation of the induction generator is correct or in other words, if the direction of rotation magnetic field produced in the induction generator by the current supplied from the synchronous machine has the same direction of rotation as the induction generator rotor, the current at any voltage will not exceed the normal value. Under this condition the voltage supplied by the synchronous machine can be called as positive sequence voltage. When two terminals of the voltage supply is interchanged, keeping the direction of rotation of induction generator unchanged, the rotating magnetic field produced in the machine will have opposite direction. Under this condition, the voltage supplied to the machine is called as negative sequence voltage. If the rotation is wrong or in other words, with the negative sequence voltage, higher current will appear before the full voltage is applied.

The equivalent circuits for induction generator with positive sequence as well as negative sequence voltage are a



A
B
C
DIRECTION OF INDUCED
PHASE ROTATION
DIRECTION
POLE PRODUCED BY
PHASE A
AXIS OF POLES
PRODUCED BY
BATTERY
S
PHASE ROTATION
CIRCUIT

FIG.15(A)

shown in fig.(14) and in fig.(15). The current into the stator of the generator. Under both conditions is given by the following expression.

$Y_m = \frac{1}{r_m} - \frac{j}{x_m} = -\frac{j}{x_m}$ (Neglecting loss component)

$I_1 = E_1(1/Z'_{2s} + Y_m)$, $V_1 = E_1(1 + Z_1/Z'_{2s} + Z_1 Y_m) \simeq E_1(1 + Z_1/Z'_{2s})$

Since $1 + z_1 y_m = 1$ $z_1 y_m$ being very small

$$I_1 = V_1 \frac{1 + Z'_{2s} Y_m}{Z'_{2s} + Z_1} \qquad \frac{V_1[1 + (r'_2/s + jx'_2)y_m]}{r'_2/s + jx'_2 + r_1 + jx_1} =$$

$$= \frac{V_1\left[1 - \frac{jr'_2}{s x_m} + \frac{x'_2}{x_m}\right]}{r_1 + r'_2/s + j(x_1 + x'_2)} \quad \text{or} \quad |I| = \frac{V_1\sqrt{(r'_2/s x_m)^2 + (1 + x'_2/x_m)^2}}{(r_1 + r'_2/s)^2 + x^2}$$

$$x_1 + x'_2 = x$$

With the slip = s the expression for current in equation (1) corresponds to positive sequence voltage.

$$I = V_1 \sqrt{\frac{(r'_2/s x_m)^2 + (1 + x'_2/x_m)^2}{(r_1 + r'_2/s)^2 + x^2}} \qquad (2)$$

For negative sequence voltage $s_n = (2-s)$, current at any slip is given by the expression.

$$I_n = V_1 \sqrt{\frac{\left[\frac{r'_2}{(2-s)x_m}\right]^2 + \left[1 + \frac{x'_2}{x_m}\right]^2}{\left[r_1 + \frac{r'_2}{2-s}\right]^2 + x^2}} \qquad (3)$$

__Currents at stand still__

At stand still $s = 1$

So $$I_p = V_1 \sqrt{\frac{(r'_2/x_m)^2 + (1 + x'_2/x_m)^2}{(r_1 + r'_2)^2 + x^2}} = I_n \qquad (4)$$

At stand still both the currents are same. So curves for I_p and I_n - V_s slip will start from same point.

But at any other slip the magnitude of I_n is greater than I_p and at synchrnous speed, the magnitude of currents are given by the following expression.

<u>At synchronous speed:</u>

At synchronous speed $s = 0$

$$I_p = V_1 / x_m \quad \text{(Approximately)}$$

and

$$I_n = V_1 \sqrt{\frac{\left(\frac{r_2'}{2x_m}\right)^2 + \left(1 + x_2'/x_m\right)^2}{\left(r_1 + r_2'/2\right)^2 + X^2}} \qquad (5)$$

$$= I_p \sqrt{\frac{r_2'^2/4 + (x_2' + x_m)^2}{\left(r_1 + r_2'/2\right)^2 + X^2}}$$

and the ratio I_n/I_p is(greater than unity)

This indicates, that with increase of speed from standstill to synchronous condition the difference between I_p and I_n increases. So by knowing the magnitude of currents (I_p and I_n) at any slip, preferably a slip near about synchronous speed the correct phase rotation of the machine can be determined.

Experiment verification of this result is described below.

<u>Second Method</u>

<u>Two phase connection</u> - The induction generator running at normal speed is connected to the electrical net work on two phases only. The remaining phase, is connected through a volt meter or voltage transformer and voltmeter depending upon voltage with correct phase rotation, a small voltage will

appear, but with wrong rotation a voltage slightly lower than twice the applied phase voltage will exist.

This method is useful, if no separate synchronous machine is not available for test '1' for it has the disadvantage that the connection of the stator to two phase only of the system will cause unbalanced forces in the machine winding. These will not be serious for the machines having larger numbers of pole pairs, but the method is unsuitable for higher speed machines.

Third Method

D.C. Battery Method - The following method is always possible. It requires no separate machine and no connection to electrical system.

A battery of about 12 V d.c. is connected to two stator phases, while a d.c. voltmeter is connected between the remaining phase and one of the phase connected to battery. The battery is switched on, with the machine at rest, and the direct current is phase 'A' and 'C' will produce north and south poles at the points, na, sa, nb, sb in the stator and north and south poles in the rotor. If the rotor now retates clockwise, the right hand coil of phase 'B' will be swept by a south pole in the rotor and the left hand side by a north pole. For correct phase rotation the voltage induced in phase 'B' should be as shown in figure.(15 a)

Before rotation commences, the voltmeter will give a reading because of the voltage drop in phase 'A' caused by the battery current with correct phase rotation, this voltage will

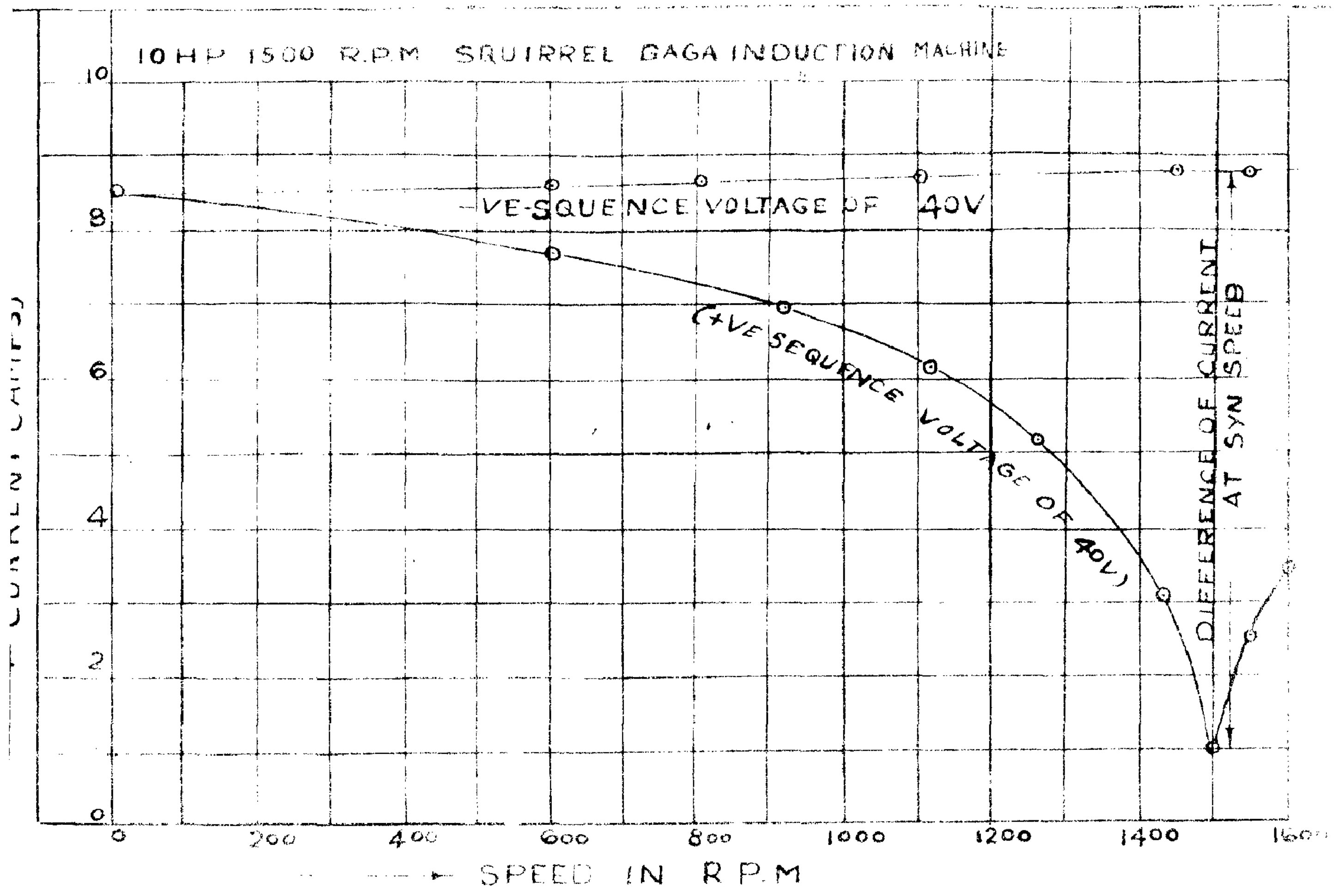

10 HP 1500 R.P.M SQUIRREL GAGA INDUCTION MACHINE
-VE SEQUENCE VOLTAGE OF 40V
(+VE SEQUENCE VOLTAGE OF 40V)
DIFFERENCE OF CURRENT AT SYN SPEED
CURRENT (AMPS)
SPEED IN R.P.M
0
2
4
6
8
10
0
200
400
600
800
1000
1200
1400
1600

FIG 16

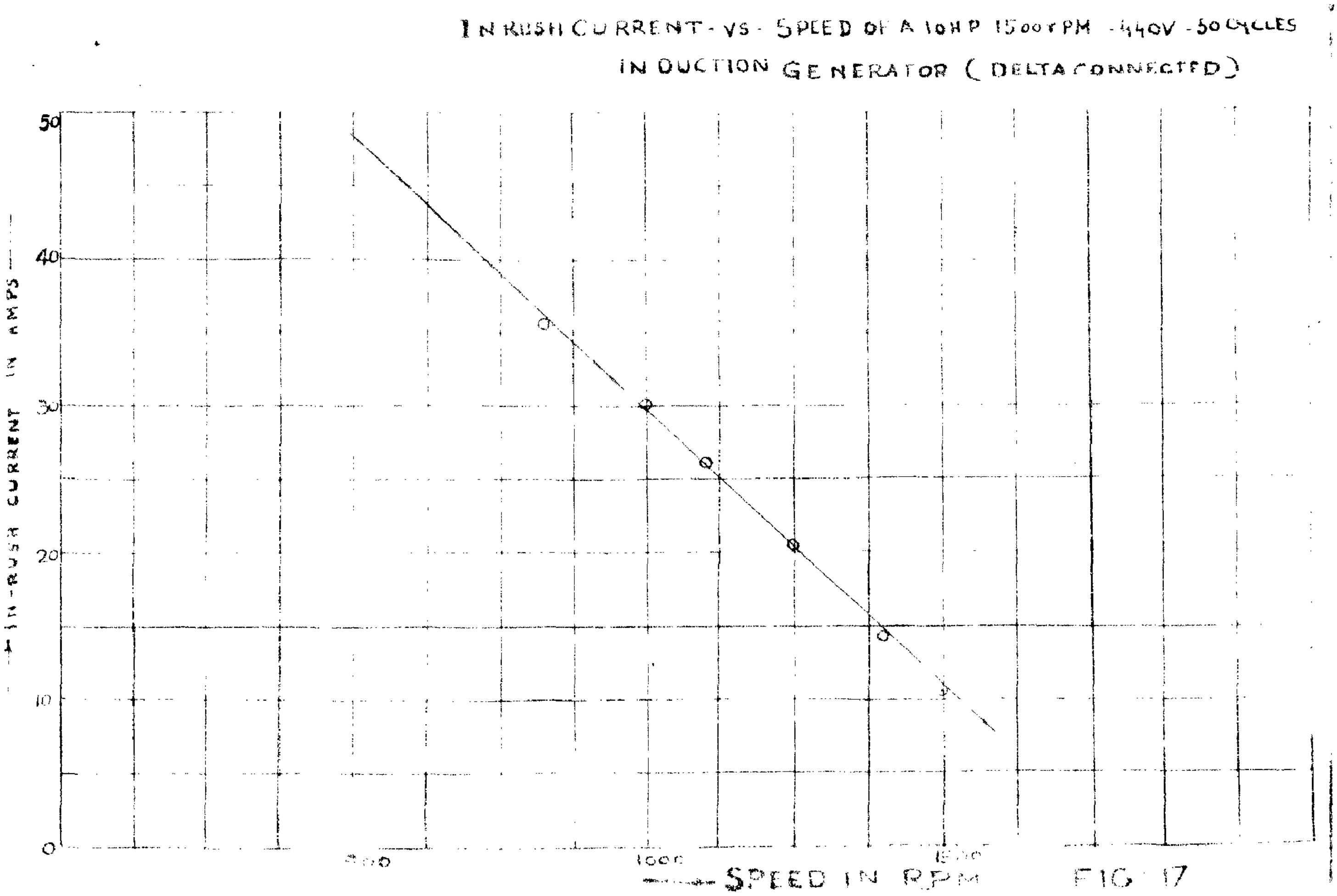

IN RUSH CURRENT - VS - SPEED OF A 10 HP 1500 rPM - 440V - 50 CYCLES INDUCTION GENERATOR (DELTA CONNECTED)
IN-RUSH CURRENT IN AMPS
SPEED IN RPM
0
10
20
30
40
50
1000

FIG 17

decrease by kick momentarily as the machine commences to rotate. Wrong phase rotation will result in an increase by kick in the voltmeter readings, and this also happens momentarily.

Tests were performed on a 10 H.P. 1500 rpm 50 cycles squirrel cage induction motor coupled to a d.c. machine. Phase rotation of the induction machine is determined by the method I, which is described earlier in this paper. At 40 V (3 phase supply) the positive sequence as well as negative sequence currents at different speeds were taken and the relationship between speed and current is shown in Fig.(16).

It has been indicated in the beginning of this chapter that the in-rush current to the induction generator will be less in magnitude, if the machine is switched on to supply system near about the synchronous speed. To confirm this theory the test was done to get a relationship between in-rush current and speed of the set. The set was switched on at different speeds to 440 V supply and the first kick in the ammetor was being noted as in-rush current at different speed. This method of measuring the in-rush current is highly approximate, but it gives an idea about the relationship. Fig.(17) gives the relationship between the in-rush current and speed of the set, and it is approximately a straight line in sub-synchronous range and between slip .02 to 0. In super synchronous range in-rush current will increase once again.

Oscilloscopic record of the in-rush current, applied voltage and speed response of the set at three different speeds were taken which are shown in figs.(18),(19) and (20). It is seen from this test, that the sub-transient and transient current do exist for a very few cycle and will not cause any detre-

FIG.(18) AT 1300 R.P.M.

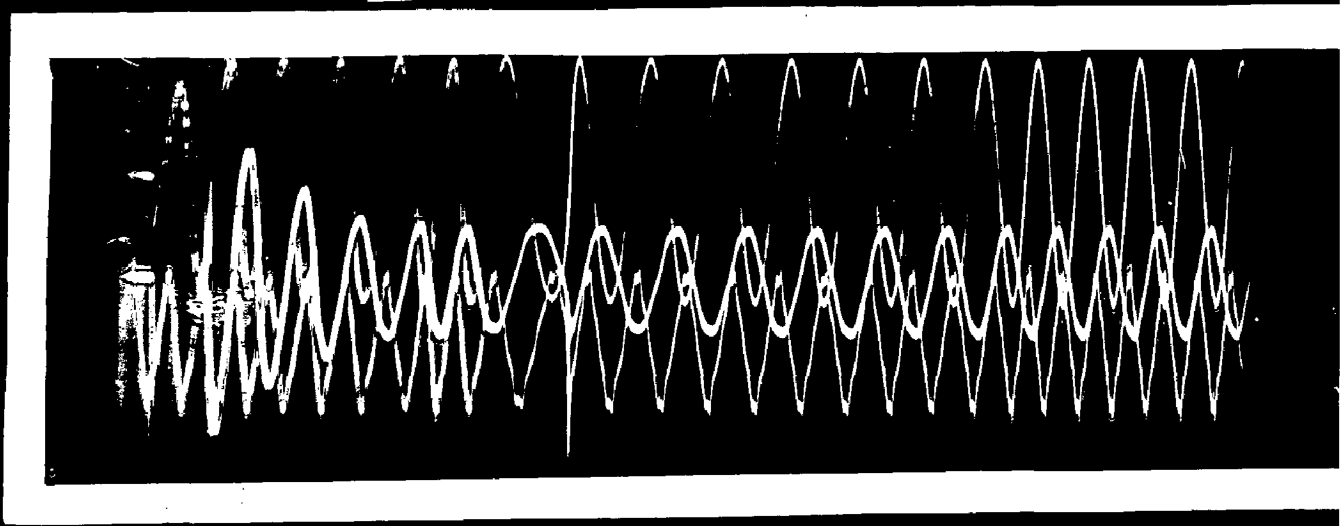


FIG.(19) AT 1350 R.P.M.

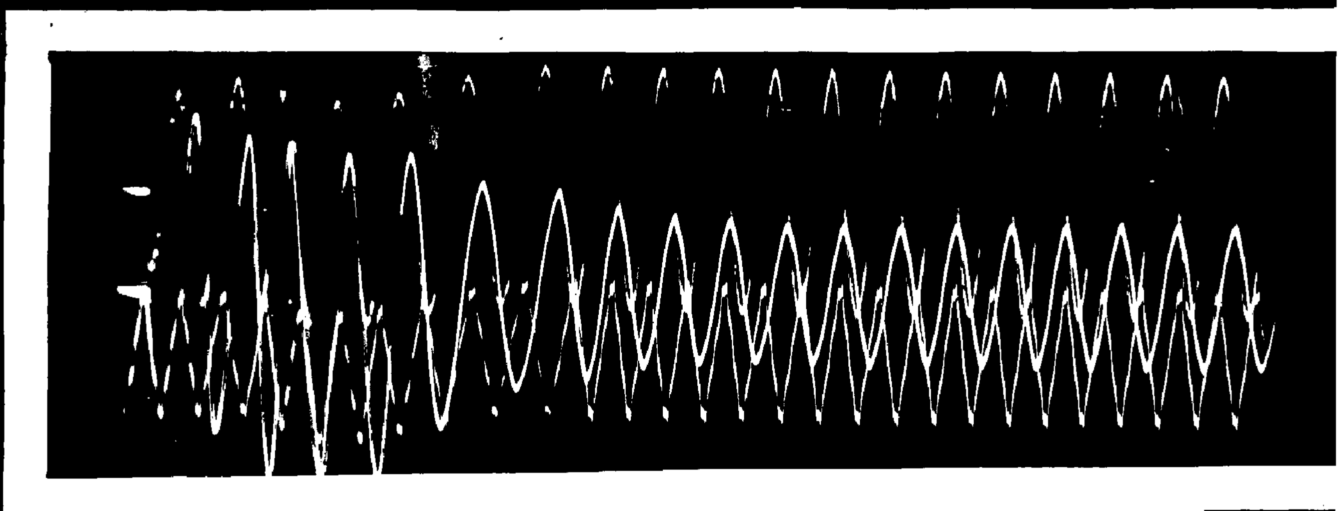


FIG.(20) AT 1440 R.P.M.

-mental effect to the machine. When the machine is switched on at a speed below the synchronous speed of the set, it experien - ces a reversal of power flow with certain amount of mechanical jerk to the moving parts. This is an undesirable feature and in author's opinion the machine can be switched on to the supply at slightly above synchronous speed, and within the stability range of the induction generator.

Load Test:

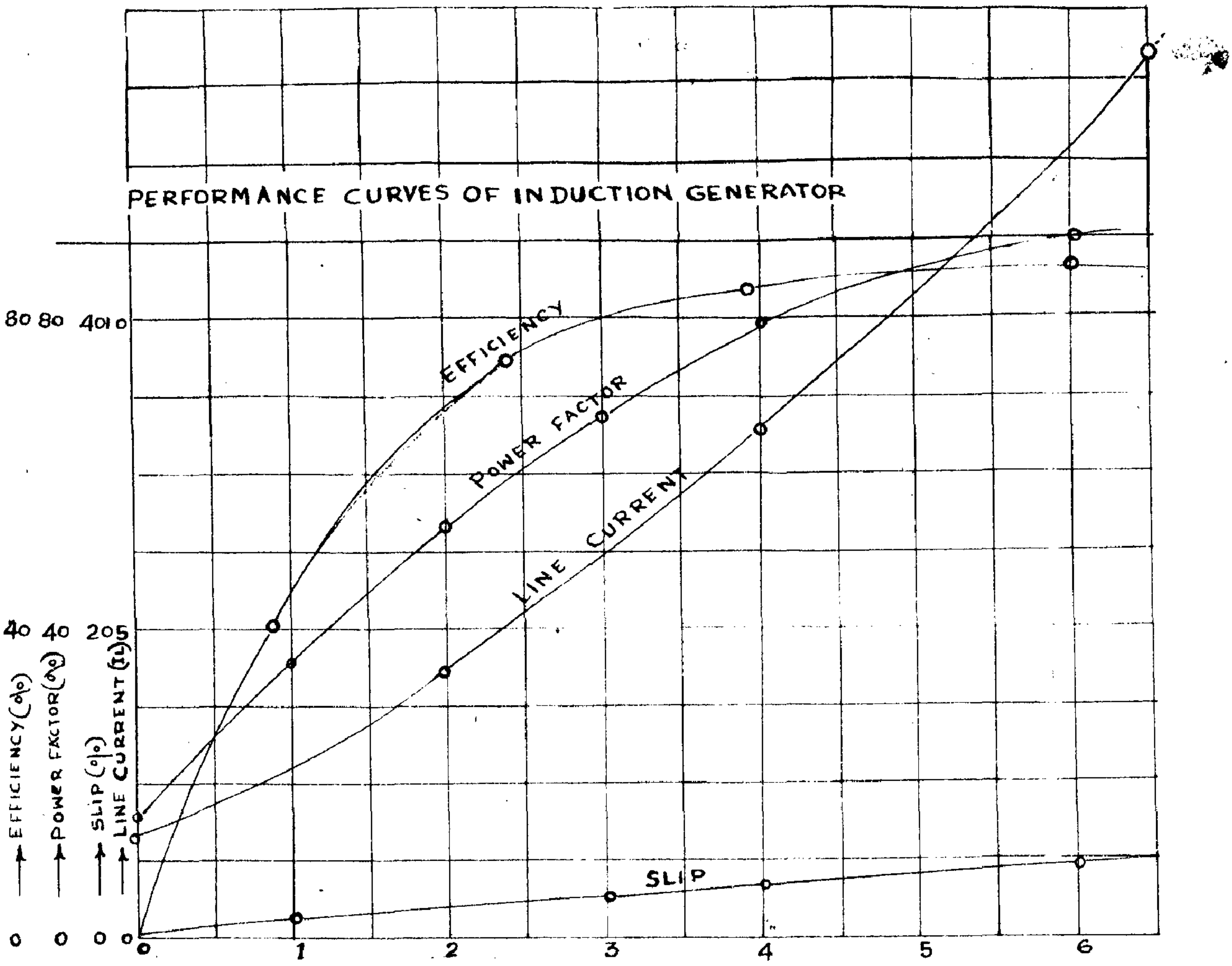
Actual load test on this 10 H.P. 1500 rpm machine was performed, with the set connected to infinity busbar. By varying the speed of the d.c. motor, induction generator was gradually loaded efficiency power factor, slip Vs-electrical output have been plotted in fig. (21).

Over Voltage:

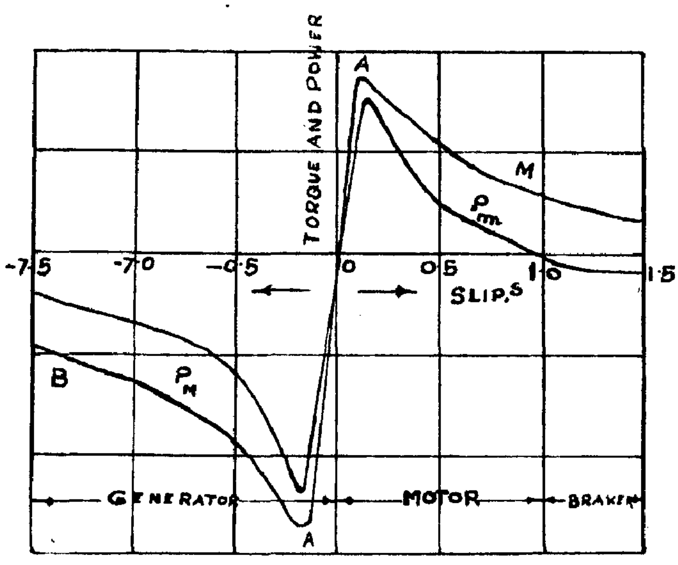
Over voltage protection should be fitted as standard to guard against self excitation which might arise due to switching operations on the electrical net works which could give rise to over voltage and this possible in most cases although in some cases they are impossible. The cost of adding over voltage relay to the main circuit breaker is quite small. The relay need only to open the circuit breaker, but if convenient, it is also usually arranged to shut down the turbine.

Low Voltage:

Low voltage protection is also a standard fitting, which is necessary for induction generator. It must have, however, a time lag and not to be very sensitive to short time voltage dips. Its principal use is to open, the main circuit breaker



FIG· 21



VARIATION OF MECHANICAL POWER AND TORQUE WITH SLIP

FIG·22

if the main net works supply fails. In this event the generator will lose its load and over speed will be the result. It may be shut down by over speed or over voltage protection, but in some cases cannot be conveniently be made to trip the switch. Restoration supply to the electrical net work will normally be from a source remote from the induction generator and is necessary to disconnect it from the supply line before restoration, otherwise it might be switched in when it is at rest. In the unlikely event of the protection failing to shut the set down, the restoration of supply with the machine at over speed might not restore it to normal load speed. Under condition of reduced voltage, stable operation at low power output and high speed is possible. The low voltaoe protection ensures that this cannot happen.

Run away speed:

From the slip and power curve of the induction generator (Fig. 22), it will be seen that the machine operates stably between OA 'A' indicates the maximum power given to the machine 6r in other words, the maximum electrical output which is to be obtained from the machine. AB is the unstable region of the powerslip curve of the generator. If the speed rises above point 'A' there is a danger of run a way, since beyond the point 'A' the generator will have the tendency to give less electrical output and consequently the extra input from the prime mover will cause the machine to accelerate and it may so happen that the machine may attain a dangerous run away speed. Such a possibility is there also when suddenly electrical load is thrown off from the machine. While loading the generator by controlling

A.C. TYPE SUPER LOW SPEED DETECTOR

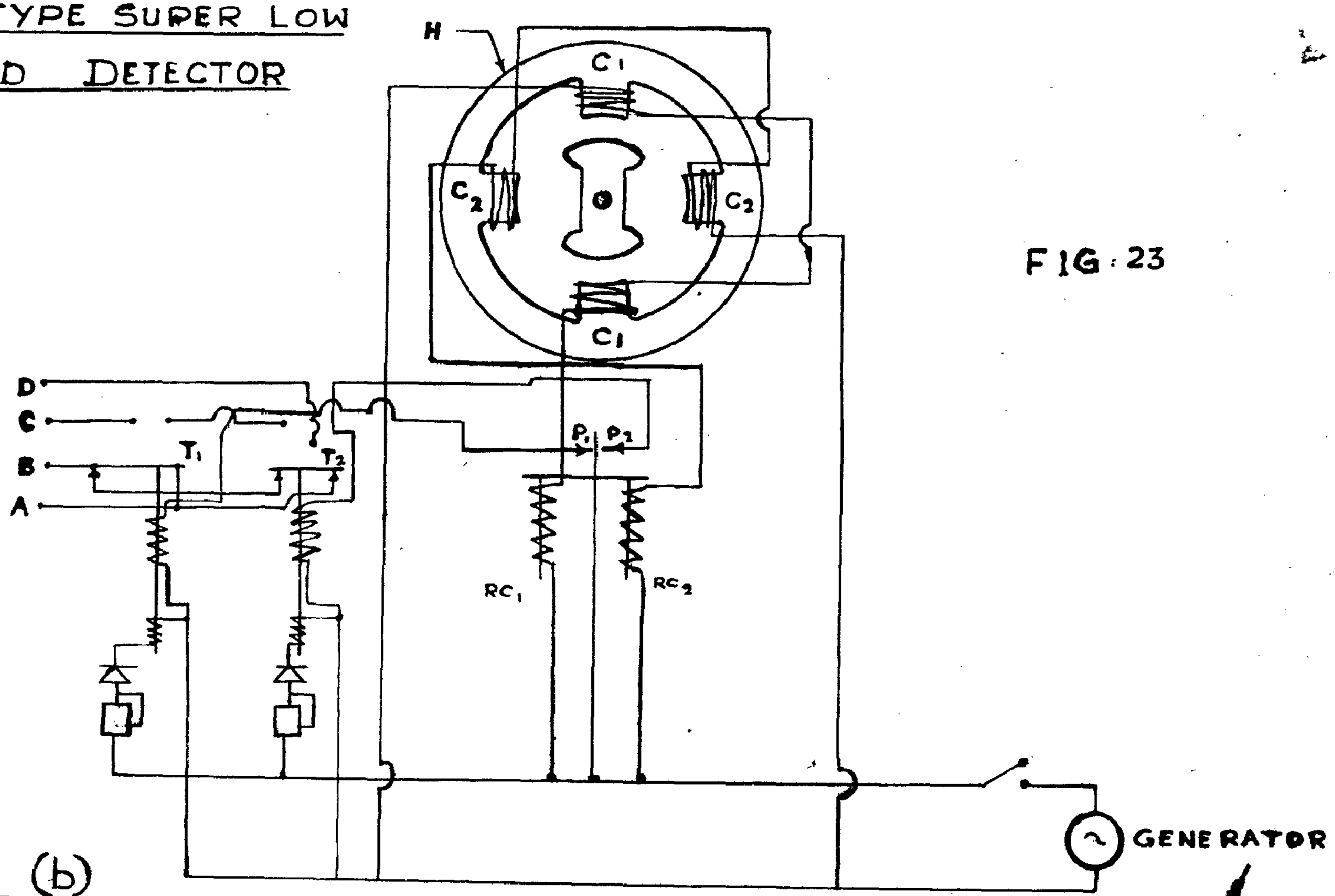


FIG: 23

(b)

the fuel or water to the prime mover, it is also required to see that the speed of the machine does not go to 'AB' region of the power slip curve. To avoid any of the possibilities already discussed, a precise speed detector is called for.

Speed detector:

A speed detector used in Japan operates in a principle of using magnetic circuit with a construction of changing magnetic reluctance with the rotation of the machine. The magnetic reluctance of the path is detected by an A.C. supply and a relay and the state of start and stop and detected indirectly. One of such type of speed detector is given below:

I = laminated rotor core.

H is the laminated stator core having salient poles being provided with coils C_1 and C_2. 'I' is driven by turbine generator shaft 'R' is a balancing relay and has coil and RC_1 and RC_2, which are connected in series to the forgoing C_1 and C_2 respectively. In the state illustrated, C_1 ha- the large impedance. Accordingly current of RC_1 being larger than that of RC_2, R closes at the left contact P_1. At a point where 90^o rotation is made from the illustrated state, contacts P_2 close. P_1 and P_2 energise coil 'M' of time relays T_1 and T_2 so as to operate them.

As shown in Fig.(23-b) relays T_1 and T_2 have a short ring G, a neutralised coil 'N' and a main coil 'M'. Having a far greater magnetomotive force than coil 'N' the coils 'M' immediately attracts a moveable core when the current is passed in it. Coil 'N' and this circuit is kept chargised ordinarily. In a

TIME DELAY RELAY

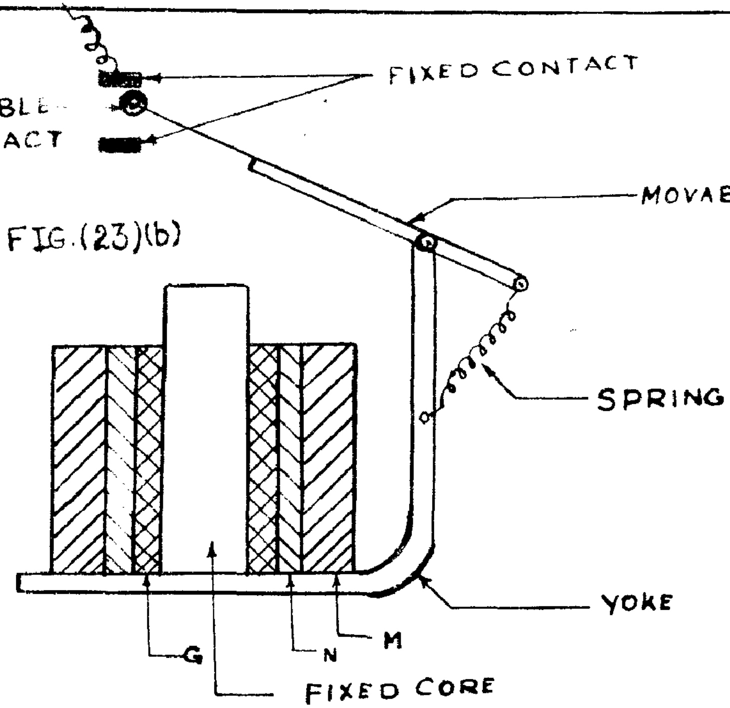


FIG.(23)(b)

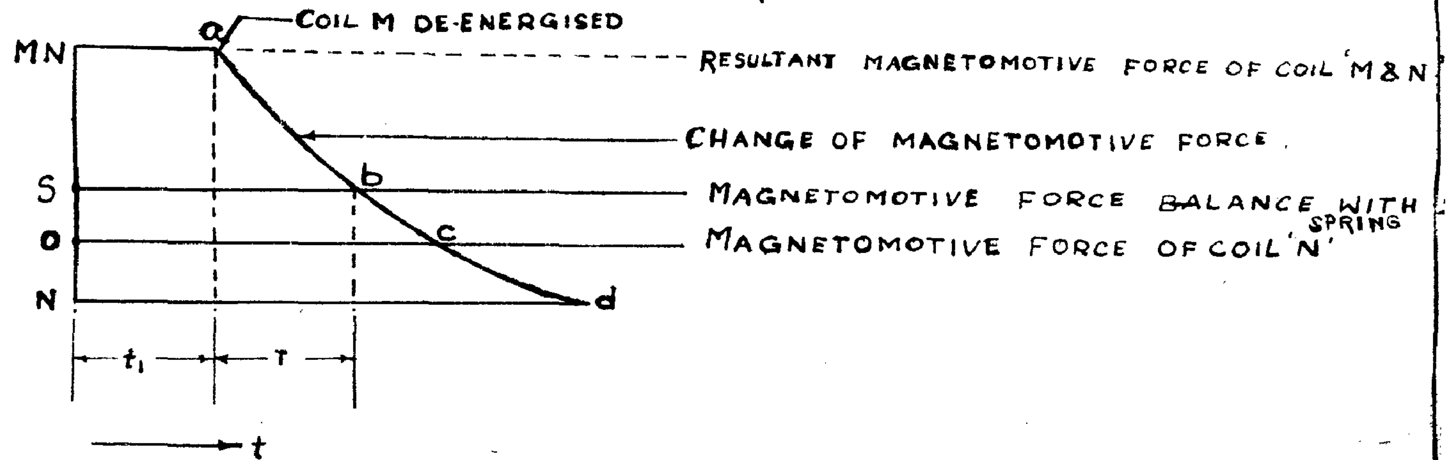


FIG23(C)

CHARACTERICTICS OF TIME DELAY RELAY

state where both coils 'M' and 'N' are being energised, resultant magnetomotive force O - MN is produced as shown in Fig.(c) to attract the moveable core. If M coil is de-energised at a time t_1, short circuit transient current flows through 'G', so as to counter-act the demagnetisation and magnetomotive force changes as shown in a, b, c, and d, without decreasing immediately. Hence if O S be a magnetomotive force needed for attracting the moveable core against a spring force, then the moveable force is detacted from the fixed core, when magnetomotive force becomes OS. Then operating state is continuous after the demagnetisation of coil 'M' as far as a point 'b' where OS intersects a curve of magnetomotive force charge for a 'T' seconds.

In the state illustrated, T_1, is operative and T_2 inoperative, and until turning 45^o in this state the operating state continues for the foregoing reasons even though T is de-energised. Next after turning beyond 45^o, P_2 is closed and T_2 becmes in an operating condition. At the turning of more than 135^o, T_2 also becomes de-energised. This means that, while rotating is in low speed, both T_1 and T_2 can never be in operating state. Above a certain speed, however both become operative. Then through combined use of the contacts of T_1 and T_2 start or stop of rotating body can be detected indirectly.

As it is clear from above mentioned, it is feasible to detect a speed when a time in which time possessed by t_1 and T_2 passes, becomes equal to a time in which I passed over an insensible angle of 'R'.

This insenible angle is about 30° and the following relation holds good between time 'T' of T_1 and T_2 and a number of rotation per minute 'N' of shaft 'I' to be detected

$N = 60/12T$ rpm.

Then it is assumed that T = 5 and it is possible to detect a number of rotation above 1 rpm at starting and below 1 rpm. at stopping. This start and stop confirming device is utilised for many kinds of automatic control as well as for a slow starting system. Though relay 'R' was explained as a balancing relay from the convenience of explanation of operation, a magnetic amplifier is in use instead of relay 'R' in both the power system.

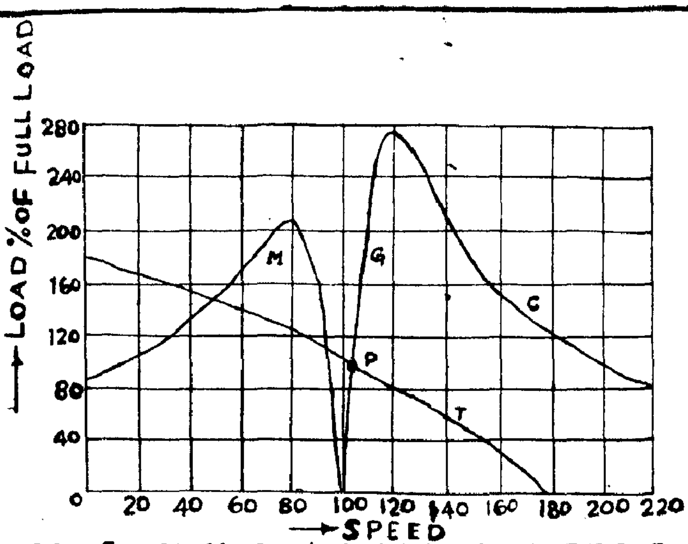


FIG. 24 SMALL H. E. INDUCTION GENERATOR PLANT
CONSTANT TERMINAL VOLTAGE

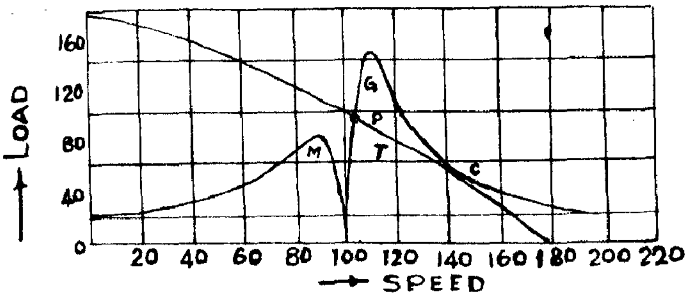


FIG. 25 SMALL H E INDUCTION GENERATOR PLANT
CONSTANT VOLTAGE IN SYNCHRONOUS STATION

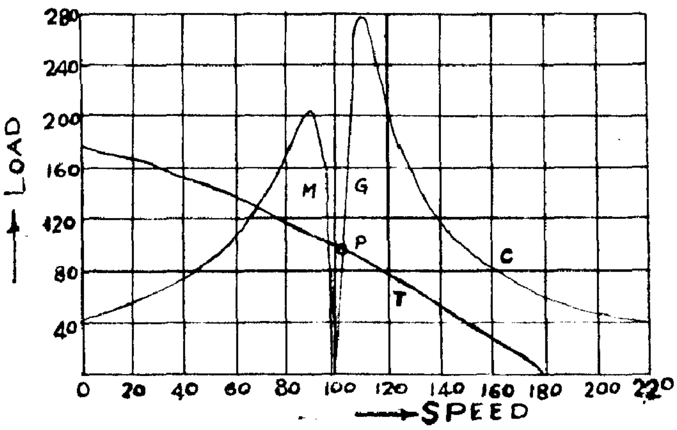


FIG 26 LARGE H. E INDUCTION GENERATOR PLANT
CONSTANT TERMINAL VOLTAGE

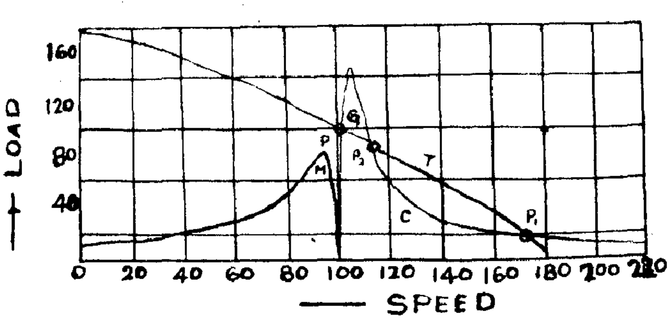


FIG 27 LARGE Hy. E. INDUCTION GENERATOR PLANT
CONSTANT VOLTAGE IN SYNCHRONOUS MAIN STATION

INSTABILITY CONDITIONS OF INDUCTION GENERATOR:

In fig.(24) the torque consumed by the induction machine at all turbine speeds above full load(P) is much higher than the torque of the turbine. However the induction generator torque curve has got a shape of rectangular hyperbola marked by 'C' and if the induction generator should be such as to bring the generator torque curve at 'C' below the turbine toque curve 'T' the speed, when once increased beyond the range 'C' would not spontaneously drop back to normal.

While in fig.(24)'C' is much higher than 'T', Fig.(24) represents the theoretical, but not real case of constant terminal voltage at the induction machine. The voltage however is kept constant at the controlling synchronous main station, and this must vary with the load in the induction generator station. Assigning an extreme case of 10 percent resistance and 20 percent reactance in the line from the induction machine station to the next synchronoism station, we get the modified torque curve shown in fig.(25). As seen at Full load 'P' there is practically no change about 4 per cent slip above synchronism. The maximum torque of generator G and motor M and the torque at the concave part of the induction generator curve 'C' have greatly decreased. However 'C' is still above 'T' that is even under these extreme assumption, the induction generator would pull the turbine down from its racing speed of 180 to the normal full load speed of 104 though the margin has become narrow.

Assuming however an induction machine with much less slip, with only half the rotor resistance of fig.24 and 25, at constant terminal voltage this gives the curve shown in fig. 26. The full load (P) is at speed 102 or 2 per cent above synchronism and while the curve branch 'C' much lower, the conditions are still perfectly stable. Assuming however, with this type of low resistance rotor, a higher line impedance 10 per cent resistance and 20 per cent reactance as in fig. 25, we get the condition in fig. 27. The range 'C' drops below T and the induction generator torque curve C intersects, the turbine torque curves at three points P, P_1, P_2 of these three theoretical running speeds, P = 102, P_1 = 109 and P_2 = 113. 5, two cv. stable, P and P_2 while the third one P_1 is unstable and from P_1 the speed must either decrease, reaching stability at the normal full load point 'P' or the machine speed up to P_2.

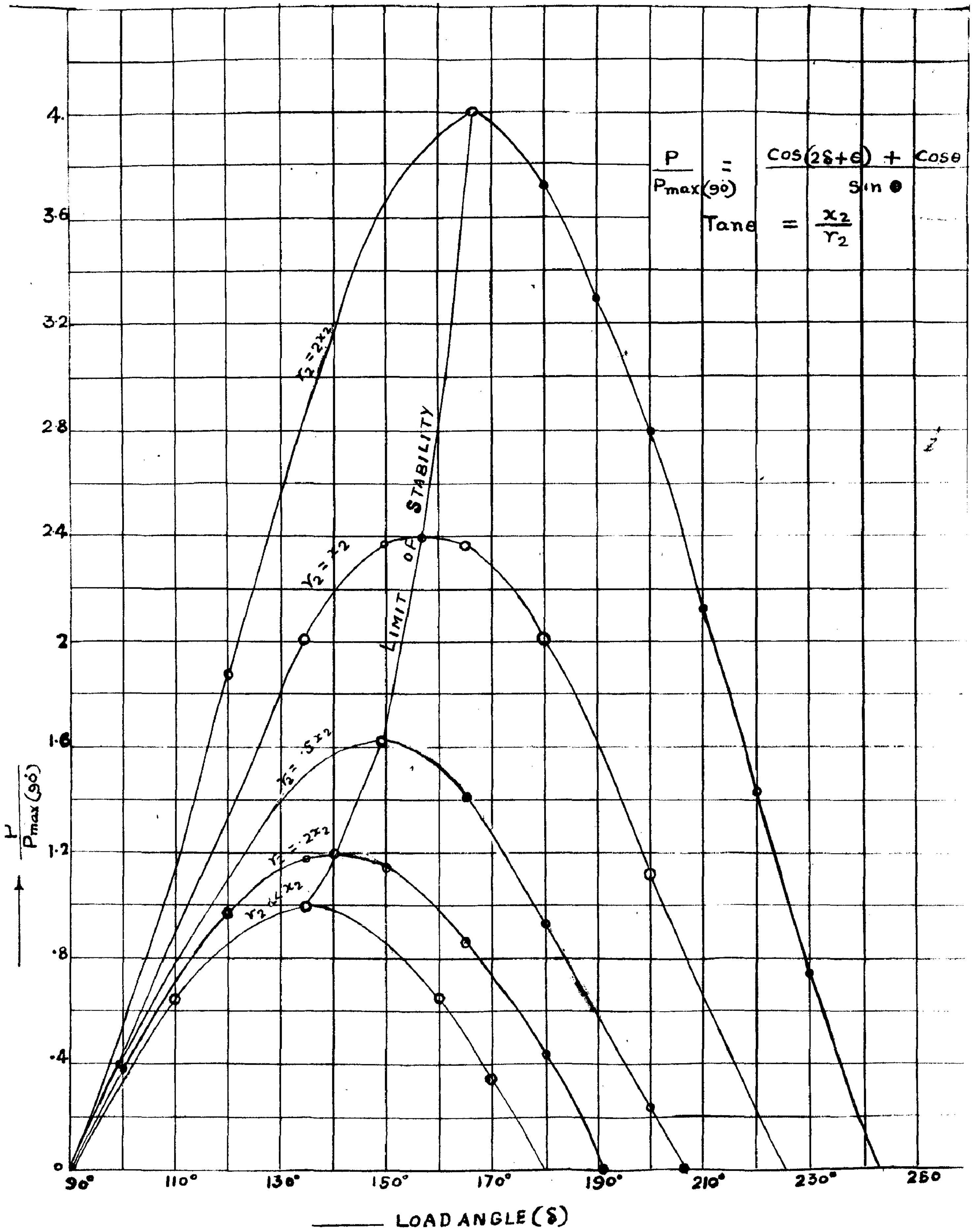
If with the conditions represented in fig. 27, the turbine should by an opening of the circuit for instance have speeded up to its free running speed 180, closing the circuit does not bring the speed back to normal, P but the machines slow down only to speed P_2, when stability is reached at very little output and very large lagging currents in the induction generator.

To restore normal condition, there would require shutting off the water, at least sufficiently to drop the turbine torque curve T below C and then getting the machines slow down to synchronism . They would not go below synchronism even with the water gates entirely closed, as the induction machine as a motor of curve 'M' holds the speed.

A solution in the case of (fig. 27) would be the use of simple excess speed governor, which cuts off the water at 5 to

10 per cent above synchronism. However the possibility of difficulty due to the " dropping out of the induction generator" as we may put it in analogy to the dropping out of the induction motor, is rather less real than it appears theoretically in smaller stations such as would be operated without attendance, as automatic stations; the torque curve of the induction generator, as a small machine, would be of the character of fig. 24 or 25 and there are not liable to this difficulty. The low resistance type of induction machines, as represented in fig. 26 and 27 may be expected only with the larger machines used in larger stations. In those some attendant would be present to close the water gates in case of the circuit breaker operating or a simple and cheap excess speed cut off would be installed at the turbines, keeping them within 10 per cent of synchronism, and within this range, no dropping out of the out of the induction generator can occur.

It is desirable however to realise this speed range of possible instability of the induction generator, so as to avoid it in the design of induction generators and stations.



4.
3.6
3.2
2.8
2.4
2
1.6
1.2
.8
.4
0
P / Pmax(90°)
90°
110°
130°
150°
170°
190°
210°
230°
250
LOAD ANGLE (δ)
P / Pmax(90°) = (cos(2δ+θ) + cos θ) / sin θ
Tan θ = x2 / r2
r2 = 2x2
r2 = x2
r2 = .5x2
r2 = .2x2
r2 << x2
LIMIT OF STABILITY

FIG: 28

DISCUSSION ON STABILITY OF GENERATOR WITH REFERENCE TO POWER AND TORQUE ANGLE DIAGRAM

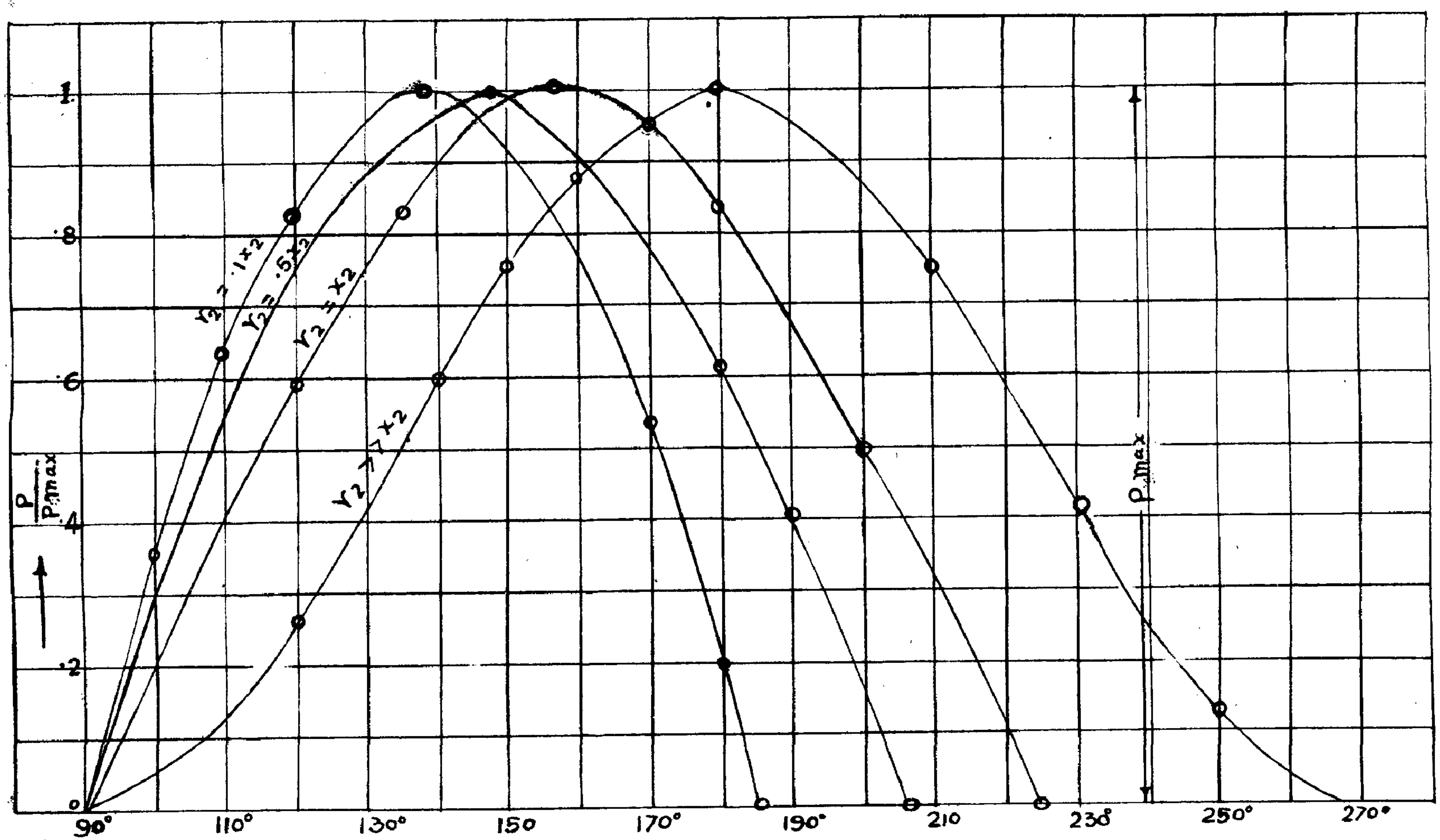
POWER.

Load angle characteristics, which has been drawn in Fig.(28) for induction generator for various value of r_2/x_2 one exactly similar to that of synchronous machine. The problem of electro-dynamic oscillation, steady state. Stability and transient stability of this generator, through not so acute, can also be studied with similar line of reasoning, to a fair degree of accmracy, as in case of synchronous generator.

A generator working on infinite, bus-bars will become a motor, if the prime mover is replaced by mechanical load. The power angle (δ) plys an important part in the operation of induction machine as in case of synchronous machine. Changes in load change its magnitude and when a machine alters from generator to motor action 'δ' reverses and when 'δ' is caused to increase excessively, the machine becomes unstable.

ELECTRO-DYNAMIC OSCILLATION

Important dynamic problems also arise in induction machine, because successful operation of the machine demands equality of the mechanical speed of the rotor mmf. and the air gap flux produced by the stator field, and because synchronising forces tending to maintain this equality are brought into play when the constancy of speed between rotor mmf. and stator air gap flux is disturbed. If the instantaneous speed of the induction machine is changed (by mechanical load on motor or electrical load on generator), the torque angle or load angle changes. In either case as long as the torque angle did not



→ TORQUE ANGLE (δ) FIG: 29

exceed the maximum value, the result would be excess of power in-put over power output and it would accelerate the rotating mass tending to restore equilibrium conditions. For example, if a large load is suddenly applied to the shaft of an induction motor, the motor must slow doen at least momentarily in order that the torque angle may assume the increased value necessary to supply the added load. In fact until new angle is reached, an appreciable portion of the energy furnished to the load comes from stored energy in the rotating mass as it slows doen. When the newly required value of angle is first reached, the equilibrium is not yet attained, for the mechanical speed is then below, the speed demanded actually by the load. In case of induction machine the condition is not so severe as in case of synchronous machine. In any case the ensuing processes involve a series of oscillation about the final position before equilibrium is ultimately restored. Similar phenomena exists in case of induction generator, when a part of electrical load is thrown off from the machine with consequent rise in speed above the expected speed or when the load is increased on the machine.

Equation to power input to induction generator is

$$P = \frac{P_{max}\left[\cos(2\delta + \theta) + \operatorname{Cos}\theta\right]}{1 + \cos\theta}$$

when θ is the stand still impedance angle of the rotor and δ = load angle of the machine.

A change in load causes an alteration in load angle 'δ'. Suppose the machine to be working on a load Pa Fig.(30)

with angle 'δa' and the load is suddenly increased to P_b with the equilibrium angle 'δb). The acceleration of the rotor from δa to δb occupies a time interval during which it gains an increment of kinetic energy. As a result its speed of rotation rises above the expected speed for the new load, it passes through the new equilibrium angle δb and reaches a more advanced position δc which may lie beyond δm where $\delta m = \pi - \frac{\theta}{2}$ and it is the angle for the maximum power input to generator. In this region a retarding torque is developed on account of the excess of output over mechanical input and a retardation will ensuse. Oscillation continues until damping has dissipated the oscillation energy.

Exact description of such events can be given only in terms of the associated electro-mechanical differential equation and decisions on restoration of equilibrium can be based on solution of the equation. This type of oscillations or hunting with the accompanying power and current pulsations may be particulrly troublesome in induction motors driving loads whose torque requirements vary cyclically at a fairly rapid frequency.

THE BASIC ELECTRO-MECHANICAL EQUATIONS

As in all other types of machines the electromechanical equation for an induction machine follows from recognition of the three classes of torque acting on the rotating members; an inertia torque, an electro-magnetic torque 'T_e' resulting from energy conversion and a mechanical shaft torque T_{sh} representing input from the prime mover or output to turn the load. In writing the equtaion, it is most convenient to specify the angular position of the shaft at any instant as the electrical angle n rotor mmf. and stator air gap flux in space. This converted to mechanical angle, has its existence in nd is a measurable quantity by stroboscopic method.

Since the inertia torque is given by the product of the moment of inertia and angular acceleration, it becomes

$$Ti = J\ 1/p\ \ \pi/180\ \ d^2\delta/\ dt^2\ \ \text{newton - M.} \quad (1)$$

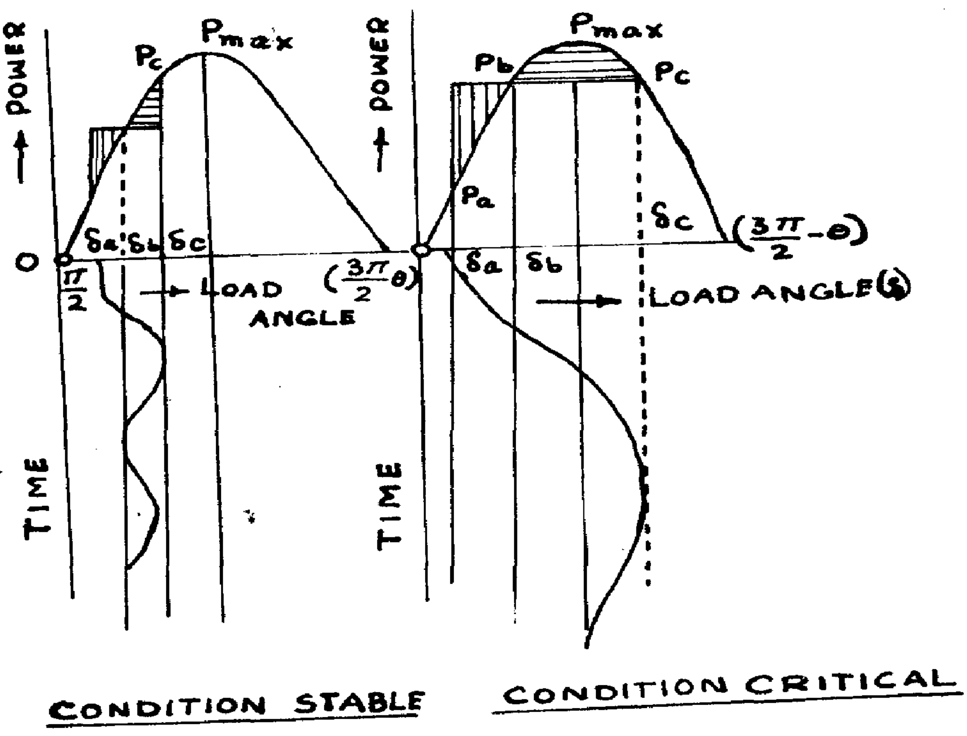
where p is the pair of poles and the factor $\pi/180$ p converts electrical degrees to mechanical radians.

The electro-mechanical equation for the machine is

$$J\ 1/p\ \ \pi/180\ \ d^2\delta/dt^2 + Te = Tsh. \quad (2)$$

The above equation is written specifically for a generator. The same equation may be applied to motor action by following an appropriate sign convention. Machine losses do not appear explicitly in the above equation. Appropriate account of losses may be taken in evaluating the torque in terms of 'Te' and Tsh, but most commonly are ignored entirely.

The inertia torque (Ti) in the above equation requires certain amount of explanation. Unlike synchronous motor, the rotor of the induction motor runs at slip speed with respect to rotating air gap flux produced by stator. But rotor mmf. when viewed from a point on the stator moves with synchronous speed in space and there exist a definite angle (mechanical) between this mmf. and stator air gap flux for a definite slip and load. This mechanical angle is measurable and observable, if a disc coupled to the shaft of the machine with balck and white sectors equal to the number of poles, is being illuminated by a monoch-



POWER
Pmax
Pc
δa δb δc
O
π/2
LOAD ANGLE
(3π/2 θ)
TIME
CONDITION STABLE
POWER
Pmax
Pb
Pc
Pa
δa δb
δc
(3π/2 - θ)
LOAD ANGLE (δ)
TIME
CONDITION CRITICAL

FIG: 30

matic light source, whose frequency voltage is equal to the frequency of rotations of the rotor. This can be best done by coupling an a.c. generator to the shaft of the induction machine and the light can be connected to the voltage available from this generator. Such type of stroboscopic method of measuring torque angle already exists for synchronous machine and in author's opinion the method which is suggested above can be utilised for measuring the torque angle of the induction machine. So viewing from stator side it looks as if the rotor is rotating with synchronous speed, just like synchronous machine and there does not exist any relative speed between the rotor and the mmf. produced by its winding. When the torque angle is observed optically with reference to a fixed point on the frame of the stator, it remains fixed and constant in magnitude in space for a particular load. Any oscillation experienced by the rotor due to transient load, can be observed in the field of vision by the variation of torque angle.

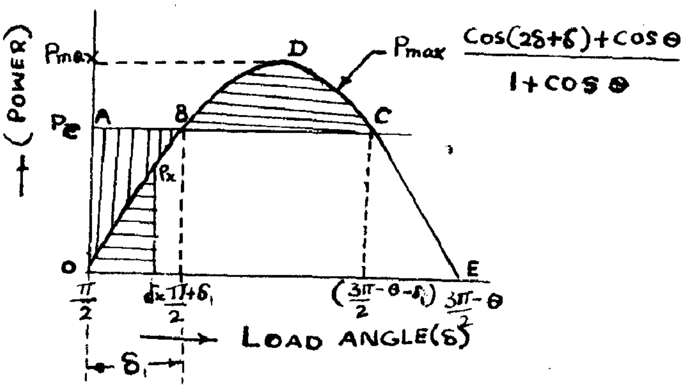
So the final electro-mechanical equation in terms of different torques becomes

$$I \; d^2\delta / dt^2 + Td \; d\delta/dt + T_{max} \sin 2\delta = Tsh \qquad (2)$$

Where Td $d\delta/dt$ is the damping rorque and Tm si 2δ is the electromagnetic torque.

Due to the presence of $T_{max} \sin 2\delta$, the above differential equation is non-linear and it is not possible to solve the equation by usual method.

When the rotor mmf. angle δ is small, advantage may be taken of the fact that the since of a small angle is closely



$\frac{\pi}{2} + \delta_1 = \delta_c$

FIG-31

equal to the angle radians and if 'δ' varies between about + 15° to -15°

$$\sin 2\delta = \pi 2\delta / 180^\circ = \pi \delta/90^\circ$$

So term T_{max} sin 2 δ is replaced by the term $T_{max} \pi \delta/90^\circ$, in the above equation. Equation (2) becomes linear and it can be solved by usual way.

$$I \; d^2\delta / dt^2 + Td \; d\delta / dt + T_{max} \pi \delta / 90 = Tsh \quad .....(3)$$

Knowing the full load speed different quantities in the above equation, the damped oscillation frequency, natural frequency natural frequency of oscillation and the transient equation of ' ' can be determined in the usual way.

DETERMINATION OF POWER LIMIT BY EQUAL AREA CRITERION

For the non-linear electro dynamic Transients associated with simple induction machine with negligible damping use may be made of graphical inter-pretation of the energy stored in the rotating mass as an aid to determining the maximum angle of swing and to settling the question of maintenance of synchronous speed between rotor mmf. and air gap flux. A single induction machine connected to large power system will be discussed here, because of the physical insight it gives to the dynamic process.

Consider specifically an induction generator which is initially unloaded. Its operating point is at the origin of curve in fig.(31). When P_x input power is suddenly increased the rotor accelerated along the sinusoid ABC and if the machine is in synchronism (rotor mmf. & air gap flux) is maintained finally comes to rest at point B with a new torque angle δx. In the region of 'C' a retarding torque is developed on account of the excess of output over input (Mechanical). The transient stability limit is reached with the value of P_x which makes first swing of the rotor terminate at an angle $\delta c = (3\pi/2 - \theta - \delta x)$ for which power deficit $(P_{max}\ \cos(2\delta + \theta) + \cos\theta / 1 + \cos\theta - P_x)$ becomes zero. For in this case there is no tendency for the rotor retardation to continue to swing it back towards the stable equilibrium position.

The criterion of transient stability limit is that the area ABC must not be greater than area BCD. The integral $\int T d\delta$ of torque with respect to angle is energy.

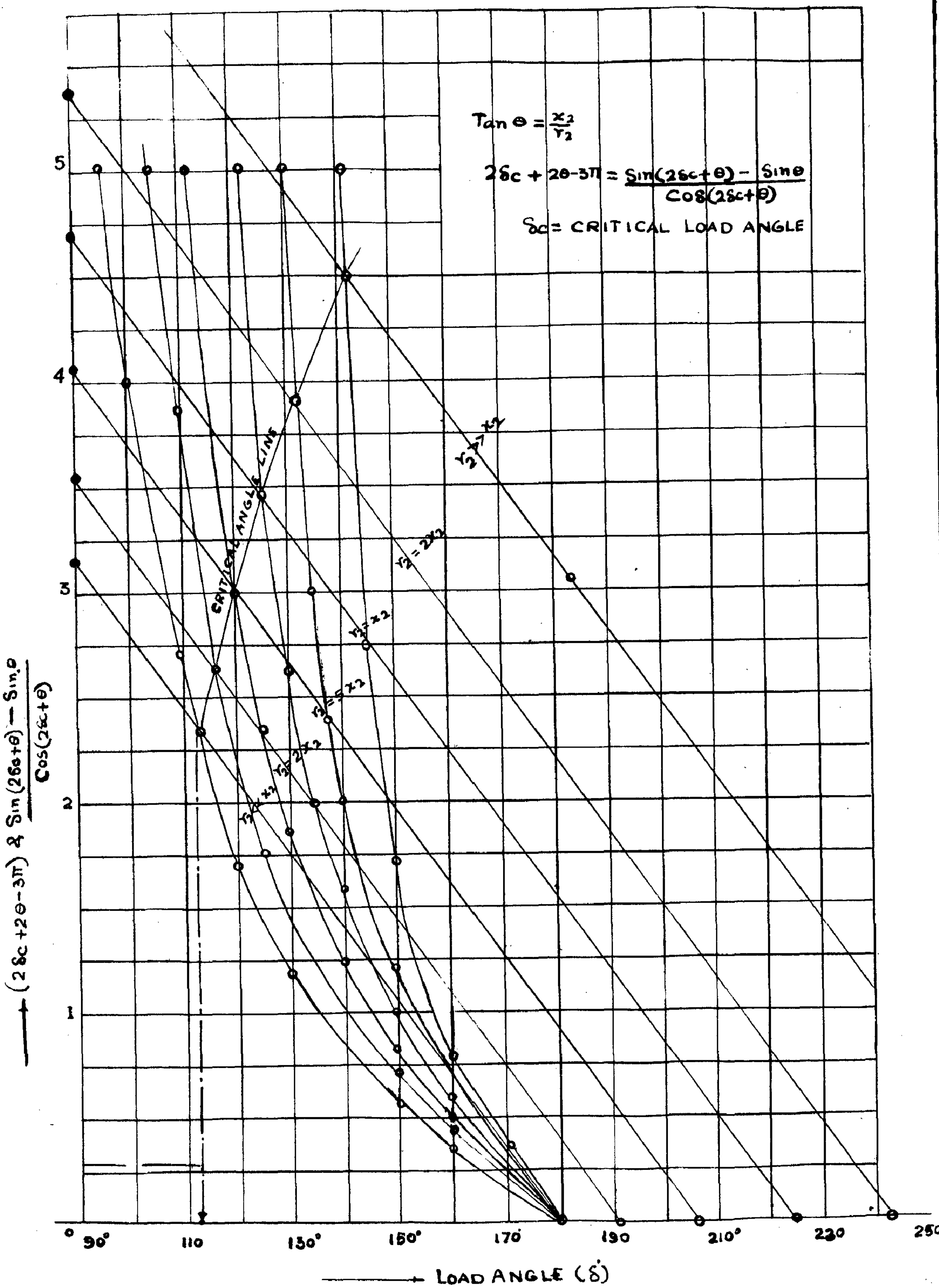
The area ABO represents the kinetic energy gained during acceleration period from O to δx while area BCD is the energy released during retardation between δx and δc. So the equality of areas BCED and OAB yields a borderline solution of instable equilibrium for which the curve 'C' is followed.

MATHEMATICAL ANALYSIS FOR CRITICAL POWER AND LOAD ANGLE

In the Fig. (31) δc is the critical load angle for suddenly applied load of P_c. Both P_c and δc are to be determined by equal area criterian.

General equation to the curve is $$P_x = P_{max} \frac{\cos(2\delta_x + \theta) + \cos\theta}{1 + \cos\theta} \quad .....(1)$$

where δx is the load angle for any power Px. Rewritting the above equation $$P_x = A \cos(2\delta_x + \theta) + B \quad ....(2)$$



Tan θ = x2/r2
2δc + 2θ − 3π = [Sin(2δc+θ) − Sinθ] / Cos(2δc+θ)
δc = CRITICAL LOAD ANGLE
CRITICAL ANGLE LINE
r2 = 2x2
r2 = x2
r2 = 5x2
r2 = 2x2
(2δc + 2θ − 3π) & [Sin(2δc+θ) − Sinθ] / Cos(2δc+θ)
LOAD ANGLE (δ)
0
1
2
3
4
5
90°
110
130°
150°
170
190
210°
230
250

FIG - 32

where $A = P_{max} / 1 + \cos\theta$ and

$B = P_{max} \cos\theta / 1 + \cos\theta$, we get the equation to area Qx

$$OAB = P_c\delta_1 - \int_{\frac{\pi}{2}+0}^{\frac{\pi}{2}+\delta_1} [A\cos(2\delta_x+\theta)+B]\,d\delta_x \quad \cdots\cdots (3)$$

$\delta c = \pi/2 + \delta_1$

So area $OAB = A/2\,(\sin(2\delta_1+\theta) - \sin\theta) + \delta_1(Pc-B)$

$$\text{Area } ACD = \int_{\frac{\pi}{2}+\delta_1}^{\frac{3\pi}{2}-(\delta_1+\theta)} [A\cos(2\delta_x+\theta)+B]\,d\delta_x - P_c[\pi-(\theta+2\delta_1)]$$

$$= A\sin(2\delta_1+\theta) + (B-P_c)[\pi-(2\delta_1+\theta)] \quad \ldots(4)$$

For critical stability Area AOB = Area ACD

$$A\sin(2\delta_1+\theta) + (B-Pc)[\pi-(2\delta_1+\theta)] = [\sin(2\delta_1+\theta)-\sin\theta] + \delta_1(Pc-B)$$

Solving this equation we get

$$Pc = A/2\,[(\sin(\theta+2\delta_1) + \sin\theta)] + B\,(\pi-\theta-\delta)\,/\,\pi-\theta-\delta_1 \quad \ldots(5)$$

From original equation to power load angle characteristics is

$$Pc = A\cos(2\delta c + \theta) + B \quad \ldots.(6)$$

$$\text{or } Pc = A\cos(\pi + 2\delta_1 + \theta) + B = B - A\cos(2\delta_1 + \theta) \quad \ldots(7)$$

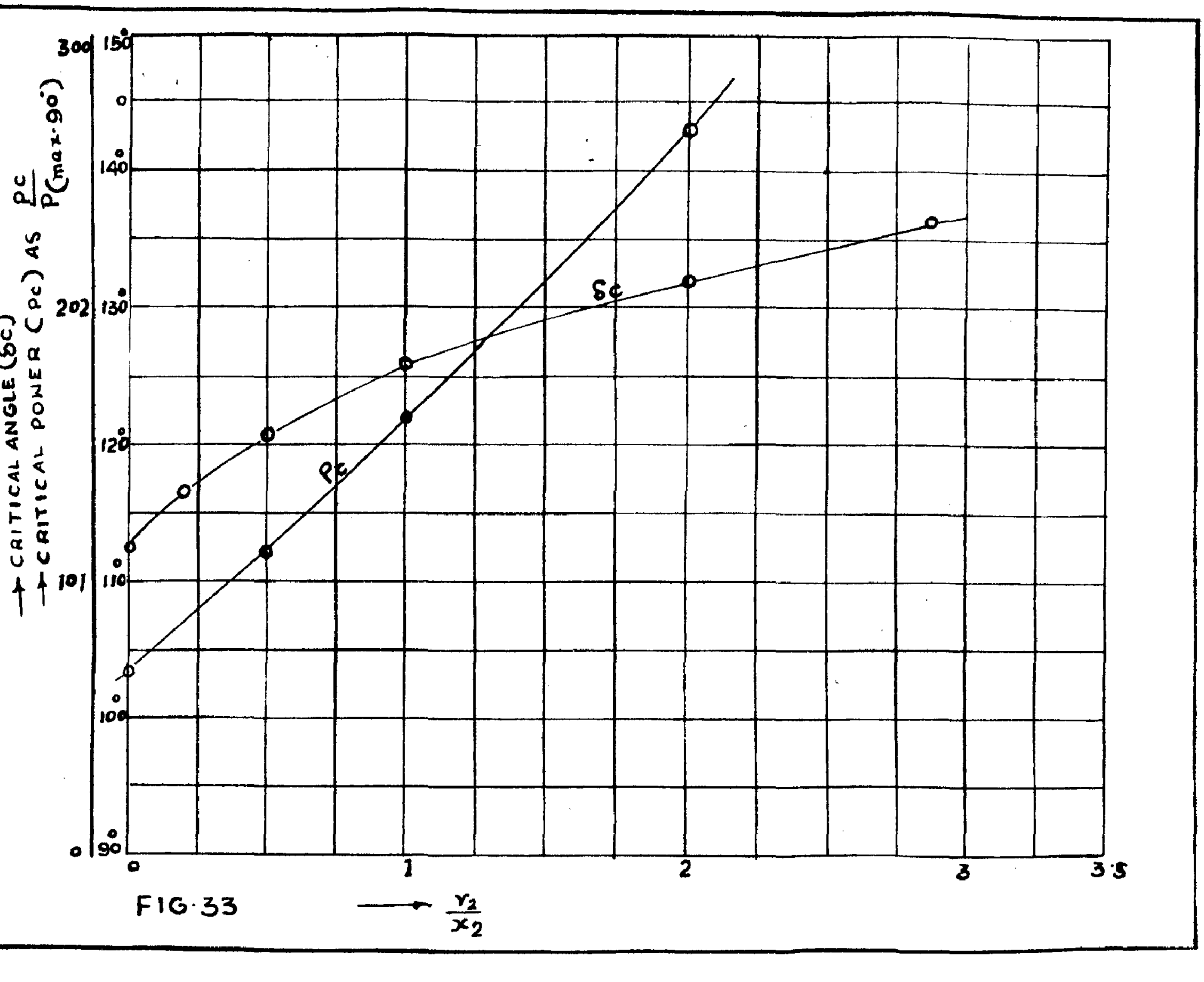
equating both the equations (7) and (8)

$$A/2\,\sin(\theta+2\delta_1) + \sin\theta\,/\,(\pi-\theta-\delta_1) = -A\cos(\theta + 2\delta_1) \ldots(8)$$

Substituting the value of $\delta_1 = \delta c - \pi/2$

$$\text{Final expression is } (2\delta c + 2\theta - 3\pi) = \sin(2\delta c+\theta) - \sin\theta\,/\,\cos(2\delta c+\theta) \quad \ldots(9)$$

For various values of θ, δc have been found out in fig.(32) by plotting both the side of the equation (9) for various values of δ.



→ CRITICAL ANGLE (δc)
→ CRITICAL POWER (Pc) AS Pc/P(max·90°)
300
202
101
0
150°
140°
130°
120°
110°
100°
90°
δc
Pc
0
1
2
3
3·5
→ Y2/X2

FIG·33

Fig.(33) gives the relationship between r_2/x_2 and δc and $Pc / P_{max(90^o)}$ where $Pc / P_{max(90^o)}$ is the optimum power which can be suddenly applied on the machine, without making it unstable.

Special case - $r2$ ~~~ x_2 $\tan\theta = \theta = 90^o$

Substituting the value of $\theta = 90^o$ in equation (9)

$2(\delta c - \pi) = \cot \delta c.$ and $Pc = P_{max} \sin 2\ \delta c.$

This equation for power is quite similar to the power equation of synchronous machine when stator resistance compared to its leakage reactance, is neglected.

For $\theta = 90^o$ or very near to that, the machine slip is very small and rotor rotates very near to synchronous speed.

Stability co-efficient of induction generator

The stability coefficient of the motor as defined by Steinmetz = $1/M\ dm/di = ks$

where M = Torque of the motor and i = current.

Since both induction motor and induction generator are reversible in action, the same idea of stability coefficient can be extended to induction generator.

In case of generator M = Mechanical torque, supplied to the generator and i = current output.

If k is positive, an increase of current output caused by increased slip or increase of speed beyond synchronous speed, increases the torque 'M' to the generator. Inversely if Ks is negative generator is unstable, and this will happen only when the machine comes to unstable portion of slip torque curve and this has been explained earlier. At constant slips, the generator torque is proportional to the square of the terminal voltage V^2. If by variation of slip, caused by a fluctuation of load, the generator output current varies by di, withathe terminal voltage v constant, the torque 'M' transmitted to generator varies by the fraction Ks = 1/M dM/di. If however the variation of terminal voltage causes a variation of emf. generated, the torque supplied to the generator being proportional to v^2 changes still further by the fraction

$$Kr = 1/v^2 \; dv^2/di = 2/v \; dv/di$$

So total stability co-efficient = Ks + Kr.

since Kr is negative the voltage decreases with increasing current, the stability coefficient of the motor is reduced.

Kr = 2/v dv/di, represents the torque change due to momentary voltage change and is a characteristics of the supply system when it is connected to infinity bus bar the terminal voltage of the system is practically constant. So dv/di = 0. But in case of an induction generator which is self excited either by static capacitor or by synchronous condenser, the voltage 'v' will vary with current and the value of dv/di will depend upon the nature of the load.

<u>Expression for Ks</u> -

Let us consider an induction generator where primary impedance is neglected and this is connected to infinity bus bar. If z_1 is neglected $v_1 = E_1$ and since E_1 is constant

Kr = 2/e de/di = 0.

LOAD ANGLE (δ) - VS - STABILITY CO-EFFICIENT (Ks)

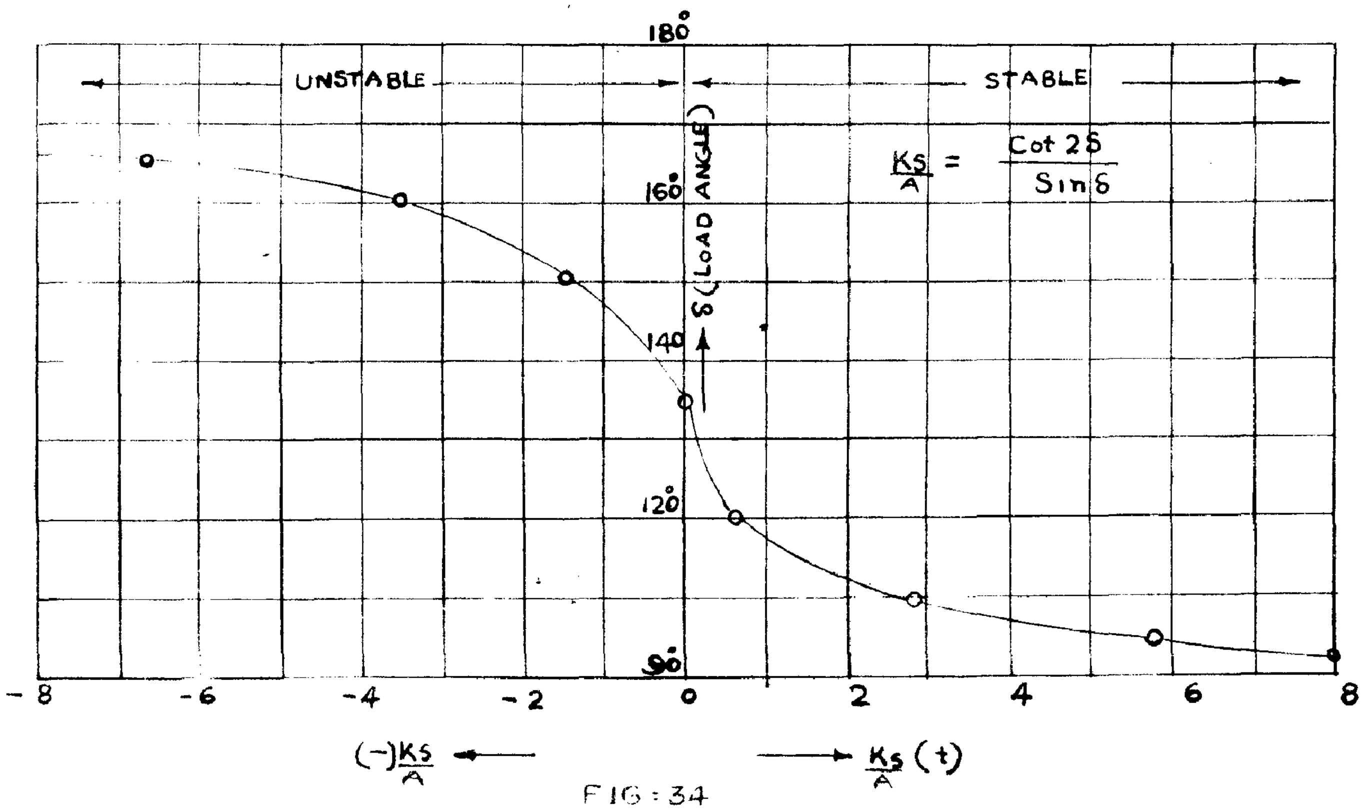


FIG: 34

$I_1 = I_2' + I_m$, I_m is practically constant since E_1 is for easier treatment assuming torque variation with I_2' only.

$K_s = 1/M \; dM / dI_2'$

$dM/dI_2' = dM/ds \cdot ds/dI_2'$ dM/ds and ds/dI_2' can be determined from the equation of M and I_2'

$$M = \frac{-Cs}{r_2'^2 + s^2 x_2'^2} \qquad C = E_1^2 r_2' K_t$$

$$\frac{dM}{ds} = \frac{-C(r_2'^2 - s^2 x_2'^2)}{(r_2'^2 + s^2 x_2'^2)} \qquad I_2' = \frac{-sE_1}{\sqrt{r_2'^2 + s^2 x_2'^2}}$$

$$\frac{dI_2'}{ds} = \frac{-E_1 r_2'^2}{(r_2'^2 + s^2 x_2'^2)^{3/2}} \qquad K_s = \frac{1}{M}\frac{dM}{dI_2'} =$$

$$= \frac{(r_2'^2 + s^2 x_2'^2)(r_2'^2 - s^2 x_2'^2)}{s E_1 r_2'^2} =$$

$= A \cot 2\delta / \sin \delta$ where A is the constant and $A + = -2x_2'/E_1$ and negative sign indicates the generating action.

δ = torque angle of the machine.

So $K_s = A \cot 2\delta / \sin \delta$ (a) for Maximum torque, $\delta = 135^\circ$. For this value of torque angle, $K_s = 0$. It is observed that for the values of torque angle between 90° to 135° the value of K_s is positive, and decreases in magnitude and becomes zero at the stability limit of the induction generator. For the torque angle between 135° to 180° , the magnitude of K_s increases with negative sign and this clearly indicates the instability of the machine in the region, which supports the conclusion drawn earlier.

Variation of K_s with load angle is shown graphically in fig.34.

Stability co-efficient (ks) with magnetising current (Im).

The above expression for 'Ks' has been derived with the assumption that torque supplied to the generator varies with rotor current I'_2.

It will be more accurate, if the variation of torque with stator current I_1 is substituted in the expression of Ks. The modified values of Ks = 1/M dM/DI$_1$

$$I_1 = E_1 \sqrt{\frac{(r'_2 / sxm)^2 + (1 + x'_2 / xm)^2}{(r'_2 / s)^2 + x'^2_2}}$$

$I_1 = I'_2 + I_m$. Where xm = magnetising reactance of the generator. The iron loss component has been neglected here.

$$I_1 = E_1 \sqrt{\frac{(r'_2 / xm)^2 + (s + sx'_2/xm)^2}{\sqrt{r'^2_2 + s^2 x'^2_2}}}$$

sx'_2/xm is quite small and can be neglected.

Substituting $r'_2/xm = a$ $r'_2 / x'_2 = d = \text{Cot}\ \theta$

where a = constant

$$I_1 = E_1/x'_2 \sqrt{\frac{a^2 + s^2}{\alpha^2 + s^2}}$$

Differentiating I_1 with respect to s

$$dI_1/ds = sE_1/x'_2\ (\alpha^2 - a^2)\ /(\alpha^2 + s^2)3/2(a^2 + s^2)^{1/2} \quad \ldots.(1)$$

Similarly,

$$dM/ds = k_t\alpha\ \ (\alpha^2 - s^2)\ /\ (\alpha^2 + s^2)^2 \quad \ldots.(2)$$

$$Ks = 1/M\ dM/dI_1 = x'_2/E_1\ \frac{(\alpha^2 - s^2)\ (\alpha^2 + s^2)^{1/2}}{s\ (\alpha^2 - a^2)}\ \left(\frac{a^2}{s^2} + 1\right)^{1/2} \quad \ldots(3)$$

Expressing the equation (3) in terms of torque angle and θ (impedance angle of rotor)

$$Ks = A \frac{\cot 2\delta}{\sin\delta} \frac{(a\cot^2\delta + \cot^2\theta)}{(\cot^2\theta - a^2)}$$

$$A = \frac{-2x_2'}{E_1}$$

Further simplification of the result can be made by substituting

$$a = \frac{x_2'}{x_m}\cot\theta = b\cot\theta \qquad b = \frac{x_2'}{x_m}$$

$$Ks = A \frac{\cot 2\delta}{\sin\delta}\left[\frac{\sqrt{b\tan\theta\tan^2\delta + 1}}{1-b^2}\right] \quad \ldots.(4)$$

The term within bracket, is always a positive quantity, what-ever may be the value of δ, since b is always a fraction. If b is neglected, the expression within the bracket is reduced to unity and the expression of Ks takes the original form which is derived earlier.

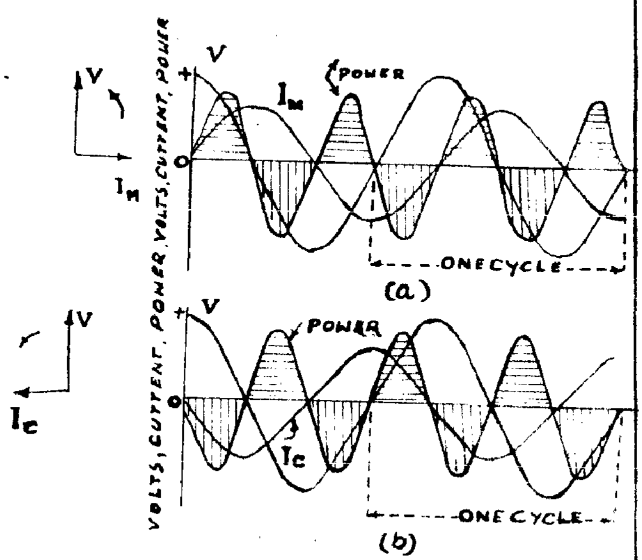


FIG 35 CURRENT AND POWER IN INDUCTIVE AND CAPACITIVE CIRCUIT

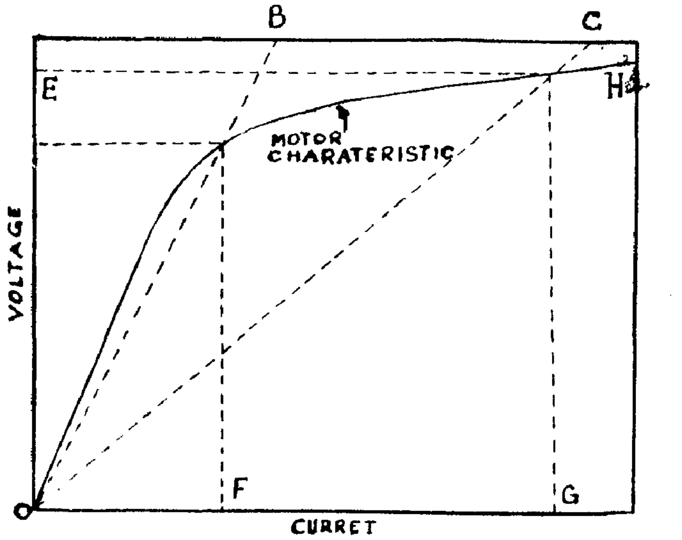
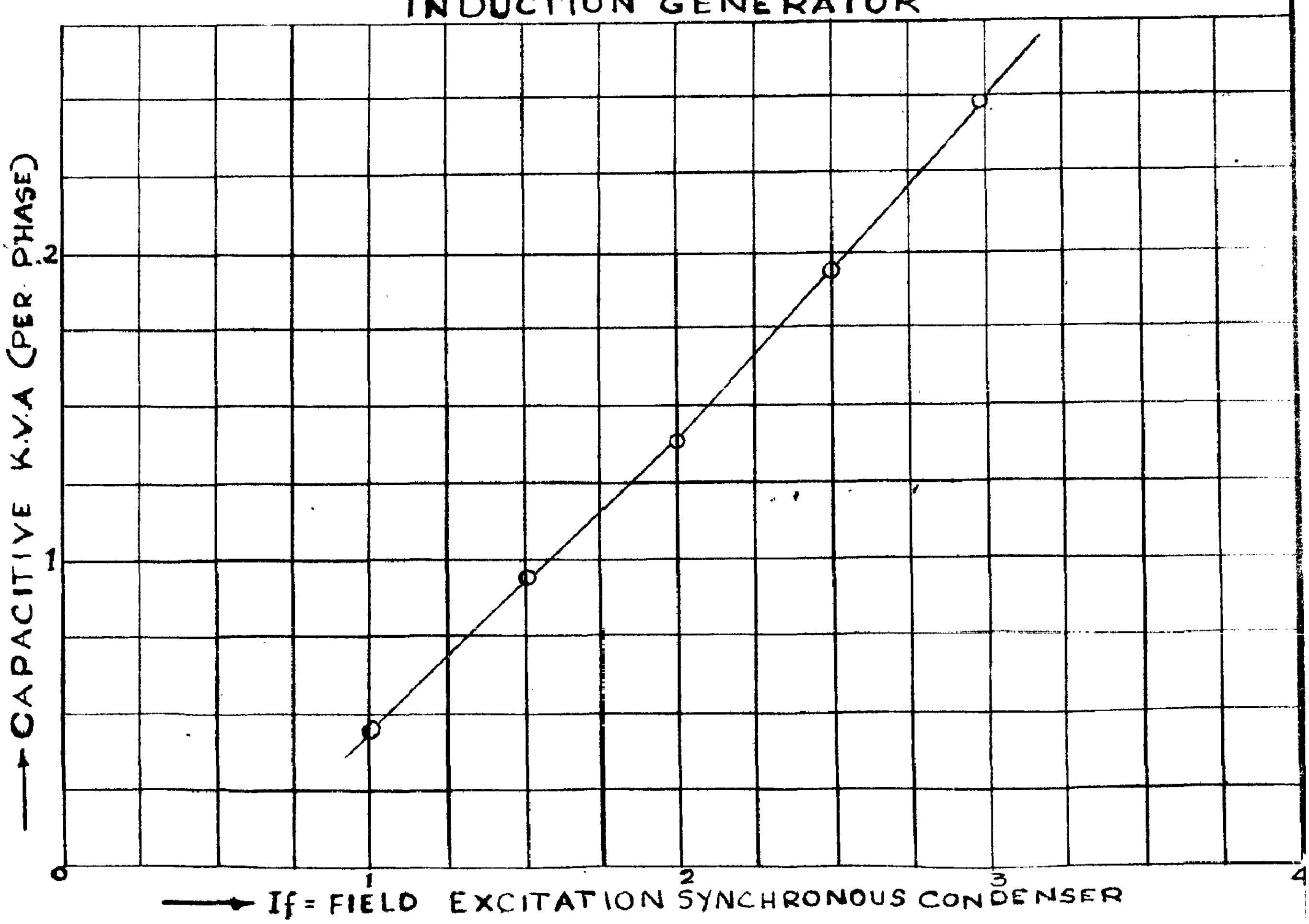


FIG. 36 MAGNETIC CHARACTERISTIC OF A INDUCTION MOTOR AND CAPACITORS

G-37

CAPACITIVE K.V.A - Vs FIELD CURRENT OF 4.4 K.V.A - 400V - 50 CYCLE SYNCHRONOUS CONDENSER USED FOR EXCITING 10 H.P INDUCTION GENERATOR



CHAPTER IV

SELF - EXCITED INDUCTION GENERATOR

Self excitation by Static capacitor

So far we have discussed the behaviour of induction generator as a component of the system with other generator connected to the system. It is possible to use induction generator as an isolated generator, if self excited. One method of doing it, is by means of capacitors, connected across the stator terminals. The magnetising current of an induction motor lags behind the voltage , as a result of which the magnetic field takes power from the supply mains during the first and third quarters of the cycle, as indicated in fig.(35) ; on the otherhand, a static capacitor takes a leading currentfrom the supply,power is taken from the supply mains to create the electrostatic field during second fourth quarter of cycle, which power is returned to the mains, during the first and third quarters. Thus a capacitor takes in current and power during the portion of a.c. cycle in which the magnetic field of the machine is returning power and vice-versa. This effect can be utilised in a self excited induction generator. The curve O.H in fig.(36) shows how the magnetising current of an induction motor varies with the voltage at the stator terminals, the machine normally, operating below the (upper) saturation part of the curve. When run at a given speed the current taken by a capacitor connected across the stator terminals will be proportional to voltage. The lines O. B. and O. C. refer to the current taken by two capacitors of different values on a given frequency neglecting losses, the voltage of a machine as an induction gene -

-rator with the smaller capacitor would be equal to O D with capacitor furrent O F with the larger capacitor on the same speed the voltage would be O S with capacitor current O G. When self excited, the induction generator can supply power at unity power factor, but if the voltage regulation (change of terminal voltage from no load to full load) is to to be reasonably low the machine must be designed so that its induction rises rapidly with the fall of terminal and voltage on load. This can be arr-anged by designing a machine with a high yoke saturation on no-load or by connecting a saturated core reactor in parallel with the capacitor or capacitors. The change of terminal voltage on changed load will then be a somewhat similar to that of a d.c. shunt dynamo. The self excited induction generator has the advan-tage that it can be used as a stand by in the event of supply failure.

<u>Build up of generator voltage</u> -

The build up voltage of the d.c. shunt generator is known to depend upon residual magnetism in the field poles of the machine and upon the resistance of the field circuit, the final build up voltage is being determined by the field circuit resis-tance. It has been discovered that the induction generator with static capacitance connected in shunt across its terminals will build up its voltage in a manner similar to the build up of D.C. shunt generator and the discussion about the capacitances supply-ing reactive KVA for excitation is given above.

Residual magnetism in the iron of magnetic circuit sets up a small alternating voltage in the stator and this voltage applied to capacitance causes a lagging magnetising current to flow in the stator winding (Machine applied leading quadrature

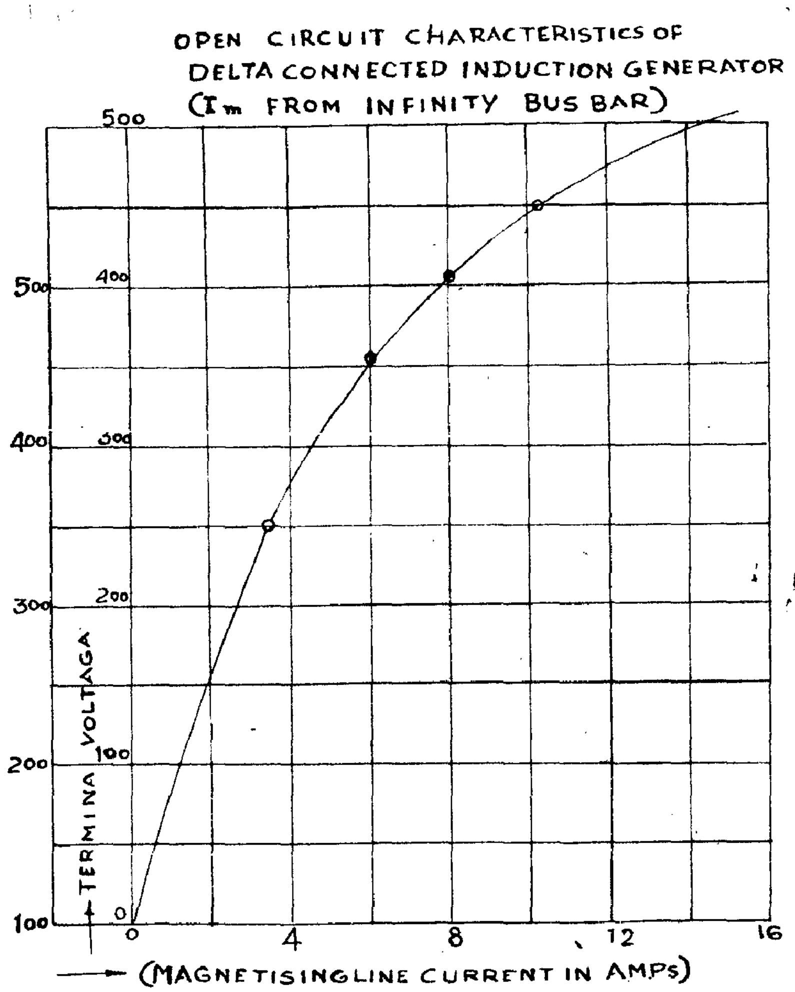

OPEN CIRCUIT CHARACTERISTICS OF
DELTA CONNECTED INDUCTION GENERATOR
(Im FROM INFINITY BUS BAR)
500
400
300
200
100
0
500
400
300
200
100
TERMINA VOLTAGA
0
4
8
12
16
(MAGNETISINGLINE CURRENT IN AMPS)

FIG 36 (a)

flow in the stator winding (Machine applied leading quadrature current to the capacitance or drawing a lagging quadrature current). If the capacitance of proper value is given, the current that can flow will be large enough to increase the flux existing in the air gap. An increase of the air gap flux will result in higher voltage, larger exciting current drawn by the capacitance, more air gap flux and so on, until the terminal voltage of the machine reaches its final build up value. This value is determined by the saturation curve of the machine and by the capacitive reactance of the connected capacitance.

An analysis of the build up of the induction generator with capacitive excitation with reference to o.c.c. in fig.(36) will be discussed here. Open circuit characteristics or saturation curve of the induction generator is the relation between magnetising current and terminal voltage of the machine. A straight line through origin is drawn, which cuts the o.c.c. at a particular point. Slope of straight line corresponding to this point is the capacitive reactance 'X_c' which is necessary to build up the voltage necessary for that particular point on o.c.c. This corresponds indentically to the behaviour of the d.c. shunt generator for which, if the saturation curve of the machine is known, the final build up voltage for any particular field resistance can be predetermined, by plotting on the same sheet and to the same seals, the saturation curve and the field resistance $R_f = I_f$. The point where the straight line, the slope of which is rf intersects the saturation curve, is the point, where the voltage will cease to build up. In like manner, if the saturation curve, of the induction generator is known, the final build up voltage for any particular capaitive reactance can be predetermined as shown in fig.(38).

Loss and restoration of residual magnetism

Operating as a self excited generator, a short circuit or too great a load will cause induction generator to lose its voltage and the residual magnetism of the rotor is destroyed, preventing the machine from again build up. Any method that gives temporary excitation to the iron will restore the residual magnetism.

A few methods that have been found are (1) Running the machine as a motor from existing system. (2) Discharging a charged condenser through the stator windings while the machine is in operation. (3) Connecting a 6 volts battery across 2 terminals of the machine for a few moments, while the machine is at rest.

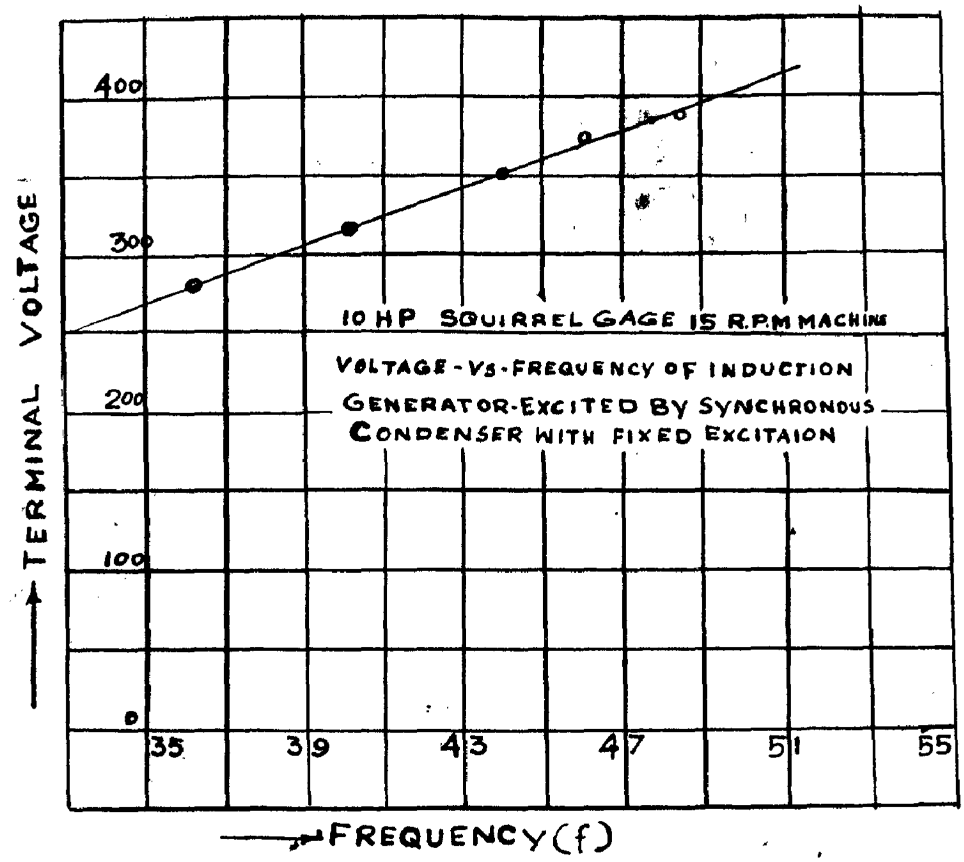
All these methods are quite successful in restoring the residual magnetism, thus enabling the machine to build up its voltage, but the 3rd method, that of using a storage battery is by far the most practical, while dealing with isolated generator, where power from an existing system cannot be obtained.

Self excited induction generator by synchronous condenser

It is an well known fact that when a synchronous motor is over excited, it behaves like a condenser. This fact has been taken advantage of in exciting a 400 rpm volt P. induction machine which was driven by a d.c. motor. A 4.4 kVA 1500 rpm 50 cycles synchronous machine was used for this purpose.

First of all the synchronous motor was run from a 440V supply mains and a curve of its exciting current Vs capacitive

FIG-38



400
300
200
100
0
35
39
43
47
51
55
TERMINAL VOLTAGE
FREQUENCY (f)
10 HP SQUIRREL GAGE 15 R.P.M MACHINE
VOLTAGE - VS - FREQUENCY OF INDUCTION
GENERATOR - EXCITED BY SYNCHRONOUS
CONDENSER WITH FIXED EXCITAION

kVA was determined which is shown in fig.(37). If the O C C of the induction generator is known, it is possible to fix up the exciting current of the synchronous machine from fig.(37) which will give the normal self-excited voltage.

Theory for build up of generator voltage by Static Capacitors

In an induction generator, just as in synchronous machine, there are a certain number of flux linkages in the rotor or field of the machine.

The rotor flux linkage = ϕ'_2

$$\phi'_2 = I'_2 \frac{(x'_2 + x_m)}{\omega} - I_1 \frac{x_m}{\omega} \qquad (1)$$

I^1 and $I^1 2$ are complexors referred to the axis rotation with the rotor.

This means that during normal operation

$$I'_2 = |I'_2|\, e^{j s\omega t} \qquad s = \text{rotor slip};$$

In this treatment all complexors are referred to the rotor axis unless otherwise instated.

$$I'_2 = I_1 + \frac{V_1 + I_1(r_1 + jx_1)}{jx_m} \qquad (2)$$

Then equations given in this treatment are with reference to the equivalent circuit given in fig. (8′) in which iron loss component in the machine is neglected.

Or $$I'_2 = \frac{V_1}{jx_m} + I_1 \frac{[r_1 + j(x_1 + x_m)]}{jx_m}$$

Substituting in the equation (1) for flux linkage we get

$$\phi'_2 = \frac{x'_2 + x_m}{j\omega x_m}\left[V_1 + I_1\left(r_1 + jx_1 + jx_m - j\frac{x_m^2}{x'_2 + x_m}\right)\right]$$

$$= \frac{x'_2 + x_m}{j\omega x_m}\left[V_1 + I_1(r_1 + jx')\right] \quad \ldots (3) \quad x' = x_1 + \frac{x_m x'_2}{x'_2 + x_m}$$

In the rotor itself, since there is no excitation voltage other than changing flux linkages.

$$I_2' r_2' + \frac{d\phi_2'}{dt} = 0 \qquad (4)$$

Let e = open circuit voltage of the rotor for a rotor current=I_2'

$$e = jI_2' x_m = V_1 + I_1[r_1 + j(x_1 + x_m)]$$

Let e^1 be the voltage that would exist at the terminals of the generator, if the breaker were suddenly opened while the generator is carrying load current.

ϕ_2 (before breaker is opened) = $\frac{x_2' + x_m}{j\omega x_m}\left[V_1 + I_1(r_1 + jx_1')\right]$

ϕ_2 (Just after breaker is opened = $j\frac{I_2'}{\omega}(x_2' + x_m)$

V_1 (after breaker is opened) = $jI_2' x_m = e$

Combinding this with the fact that

ϕ_2 (after) = ϕ_2 (before

$$I_2' \text{ (after)} = \frac{1}{jx_m}\left[V_1 + I_1(r_1 + jx_1')\right] \qquad (5)$$

$$\text{and } e' = V_1 + I_1(r_1 + jx_1') \qquad (6)$$

Comparing equation (3) and (6) it is seen that e^1 is proportional to rotor flux linkages. Combining equatioms (3),(4) and (6) we get

$$e\frac{r_2'}{jx_m} + \frac{x_2' + x_m}{j\omega x_m}\frac{de'}{dt} = 0$$

$$e + \frac{x_2' + x_m}{\omega r_2}\frac{de'}{dt} = 0 \qquad (7)$$

$$\text{or } e + T_o\frac{de'}{dt} = 0 \qquad (8) \qquad \text{where } T_o = \frac{x_2' + x_m}{\omega r_2'}$$

The equation (8) is similar to the fundamental equatoon used in the analysis of the transient behaviour of synchronous machine relating ed, ed^1 as follows $e_d + T_{do}\frac{de'_d}{dt} = e_x$

where ex = exciter voltage. Naturally there is no corresponding term to ex in the induction generator system.

So equation $e + \frac{x_m + x'_g}{\omega r'_g}\frac{de'}{dt} = 0$ = 0 is the starting point of voltage build up of the induction generator with a series impedance of z = Re + Jxe across the equivalent circuit (8).

Both e and el are phasers with an angle with respect to some referenal axis of the rotor. They are also moving with synchronous speed with respect to stator and they have a fixed angular relationship with the synchronous field of the stator. Thus any change in relative angular position of e and e^1 will amount to a change in angular position of the rotor with respect to the synchronous field of the stator of equal magnitude and opposite sign. The rate of change of the angle of e and e^1 corresponds to the slip of the rotor.

Considering following equations

$$V_1 = I_1 (R_e + jx_e) \quad (9)$$

$$e^1 = V_1 + I_1 (r_1 + jx') \quad (10)$$

$$e = V_1 + I_1[r_1 + j(x_m + x_1)] \quad (11)$$

using these equations e^1 and e can be expressed in terms of V_1 the terminal voltage of the generator, by the following equation.

$$e' = V_1 \left[1 + \frac{(r_1 + jx')}{R_e + jX_e}\right] = V_1 \frac{[r_1 + R_e + j(x_e + x')]}{R_e + jX_e} \quad (12)$$

$$e = V_1 \left[1 + \frac{r_1 + j(x_m + x_1)}{R_e + jX_e}\right] \quad (13)$$

Combining equation (12) and (13) with the differential equation relating e and e^1, the following expression is obtained.

$$V_1 \left[\frac{r_1+R_e+j(x_e+x_m+x_1)}{R_e+jx_e}\right] + \frac{x_m+x_2'}{r_2'} \left[\frac{r_1+R_e+j(x_e+x')}{R_e+jx_e}\right] V_1 = 0$$

After simplification we get

$$V_1 \left[\frac{r_1+R_e+j(x_e+x_1+x_m)}{R_e+r_1+j(x_e+x')}\right] \frac{r_2'\omega}{x_m+x_2'} + \frac{dV_1}{dt} = 0 \qquad (14)$$

or $\quad V_1 A + \frac{dV_1}{dt} = 0 \quad (15) \qquad A = \frac{R_e+r_1+j(x_e+x_m+x_1)}{R_e+r_1+j(x_e+x')} \frac{r_2'\omega}{x_m+x_2'} = a+jb$

After rationalising the left-hand side and equating for a and b we get

$$a = \frac{(r_1+R_e)^2 + (x_e+x_m+x_1)(x_e+x')}{(r_1+R_e)^2 + (x_e+x')^2} \frac{\omega r_2'}{x_m+x_2'}$$

$$b = \frac{(r_1+R_e)(x_m+x_1-x')}{(r_1+R_e)^2 + (x_e+x')^2} \frac{\omega r_2'}{x_m+x_2'}$$

The solution of the differential equation takes the following form $V_1 = V e^{-At}$ where 'V' is determined so that $e^1 (t = 0) = e_i$ where e^1i is the value of e^1, the instant before the induction generator and capacitors are disconnected from the system.

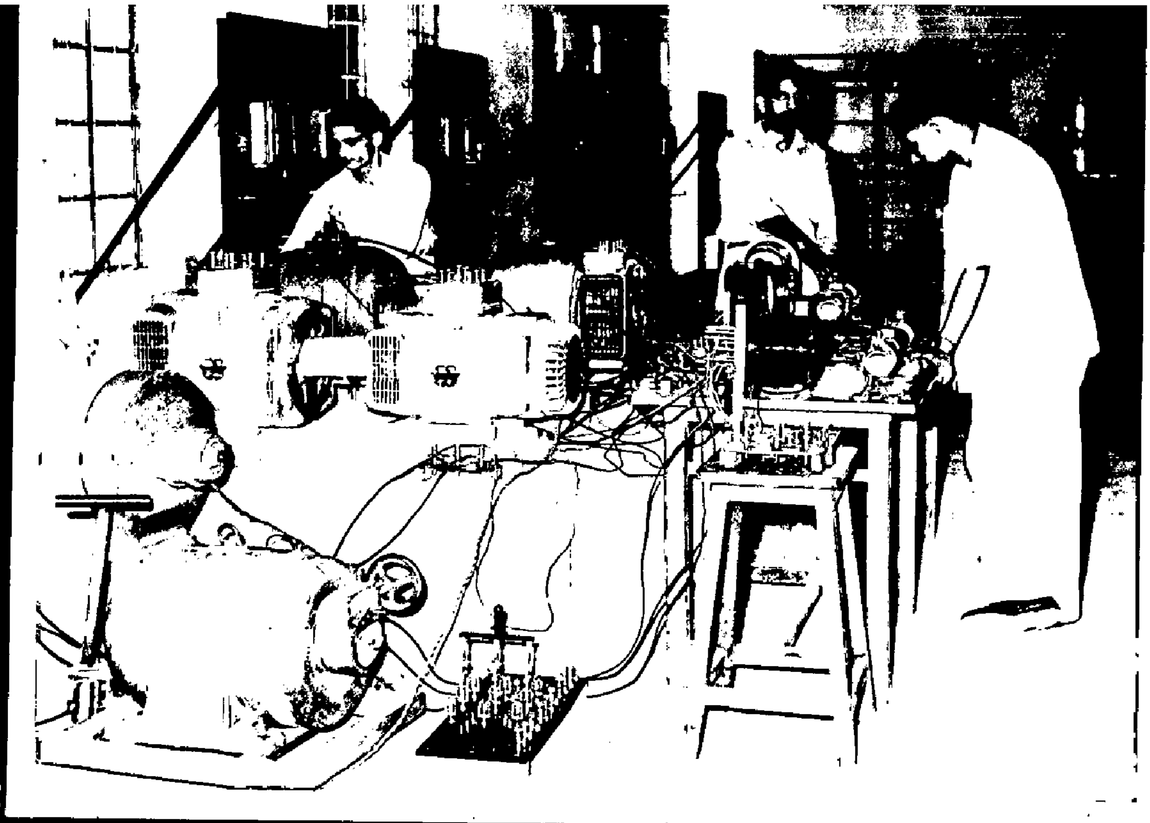
This equation gives

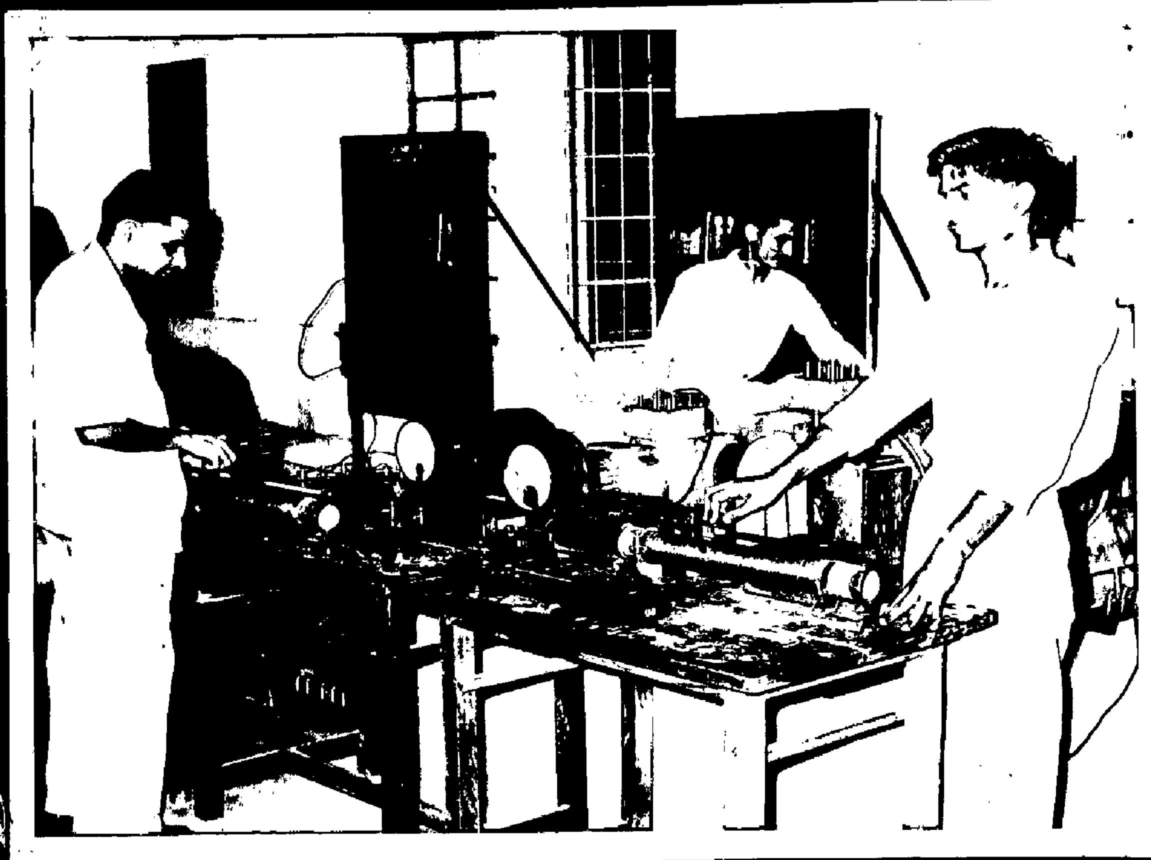
$$e'(t=0_+) = V\left[\frac{r_1+R_e+j(x_e+x')}{R_e+jx_e}\right] = e_i' \qquad (16)$$

$$V = e_i' \frac{R_e+jx_e}{r_1+R_e+j(x_e+x')} \qquad |V| = |e_i'| \sqrt{\frac{R_e^2+x_e^2}{(r_1+R_e)^2+(x_e+x')^2}}$$

If after disconnection V is to remain same as e^1i than $(v) = e'_i$ is the condition which can be substituted in the above equation. and neglecting r_1 ($r_1 = 0$)

or $\qquad x_e^2 = (x_e+x')^2$





$$\text{or} \quad x_1 + \frac{x_m x_2'}{x_m + x_2'} = 0$$

$$x_1 = -\frac{x_m x_2'}{x_m + x_2'} \quad . \quad . \quad . \quad (17)$$

This condition in (17) can be obtained if capacitance is included in series with stator per phase.

By breaking up the exponential equation the behaviour of the terminal voltage can be studied more easily.

$$V_1 = V \ e^{-at} \ . \ e^{-jbt}.$$

The first part of the equation is a damping term and tells whether the voltage is building up decaying.

If 'a' is positive, voltage decays

If 'a' is negative, voltage increases

An examination of the expression for 'a' reveals that its sign w will be same, as the sign of the expression

$$(r_1 + R_e)^2 + (x_e + x_m + x_1)(x_e + x')$$

Thus if this expression is positive and voltage will decay.
If the expression $(X_e + x_m + x_1)(X_e + x')$ is negative there are three cases to be considered.

let $xe = - xc$

(1) If xe is very large $xe > (x_m + x_1)$ and $xe > x^1$ than the term will be positive and voltage will decay.

(2) If Xe is shuch that $Xc > X^1$ and $x_c < x_m + x_1$ than $(X_e + x_m + x_1)(x_c + x')$ is negative, if the expression is greater in magnitude than $(r_1 + R_e)^2$ 'a' is negative and voltage buiods up.

(3) If Xe is very small, so that $Xc < x'$ & the term or expression is a-gain positive and the voltage will decay.

'Case 2' is the most interesting case since under this condition the voltage builds up, after the machine is disconnected from the system, In the actual machine, the reactance xm decreases as the voltage increases and finally reaches a value such that $X_c < (X_m + X_1)$ and a = 0.

This represents the stable operating condition, since if the voltage gradually decreased and 'a' becomes negative in the process since Xm increases and the voltage again increases.

While, if the voltage goes above this limit, Xm decreases still more and 'a' becomes positive, causing the voltage to decrease. Therefore when the induction generators are disconnected, from the system the voltage will increase until

$$(r_1+R_e)^2+(x_c+x_m+x_1)(x_c+x_1') = 0$$

and the region for an increasing self excitation is given by

$$(r_1+R_e)^2+(x_c+x_m+x_1)(x_c+x_1') < 0 \qquad (18)$$

Another point of interest is 1/a . Since the magnitude of the terminal voltage increases, 10.5 per cent during each 1/10a secs.

$$\frac{1}{a} = \frac{(r_1+R_e)^2+(X_c+x_1')^2}{(r_1+R_e)^2+(X_c+x_1')(X_c+X_m+X_1)} \frac{x_m+x_2'}{\omega r_2'} \qquad (19)$$

It starts at a value greater than the open circuit time constant and increases to infinity as $(r_1+R_e)^2+(x_c+x_1')(x_c+x_m+x_1)$ approaches to zero. The quantity 'b' can be related to slip of the rotor. The term e^{-jbt} gives the angular change of position of VI with time. Since there is always a fixed angle between V1 and e^1. This also gives the change in the angular position of e^1. The rate of change of angular position of e^1 with the -b or the slip of rotor in percent of the synchronous speed corresponding

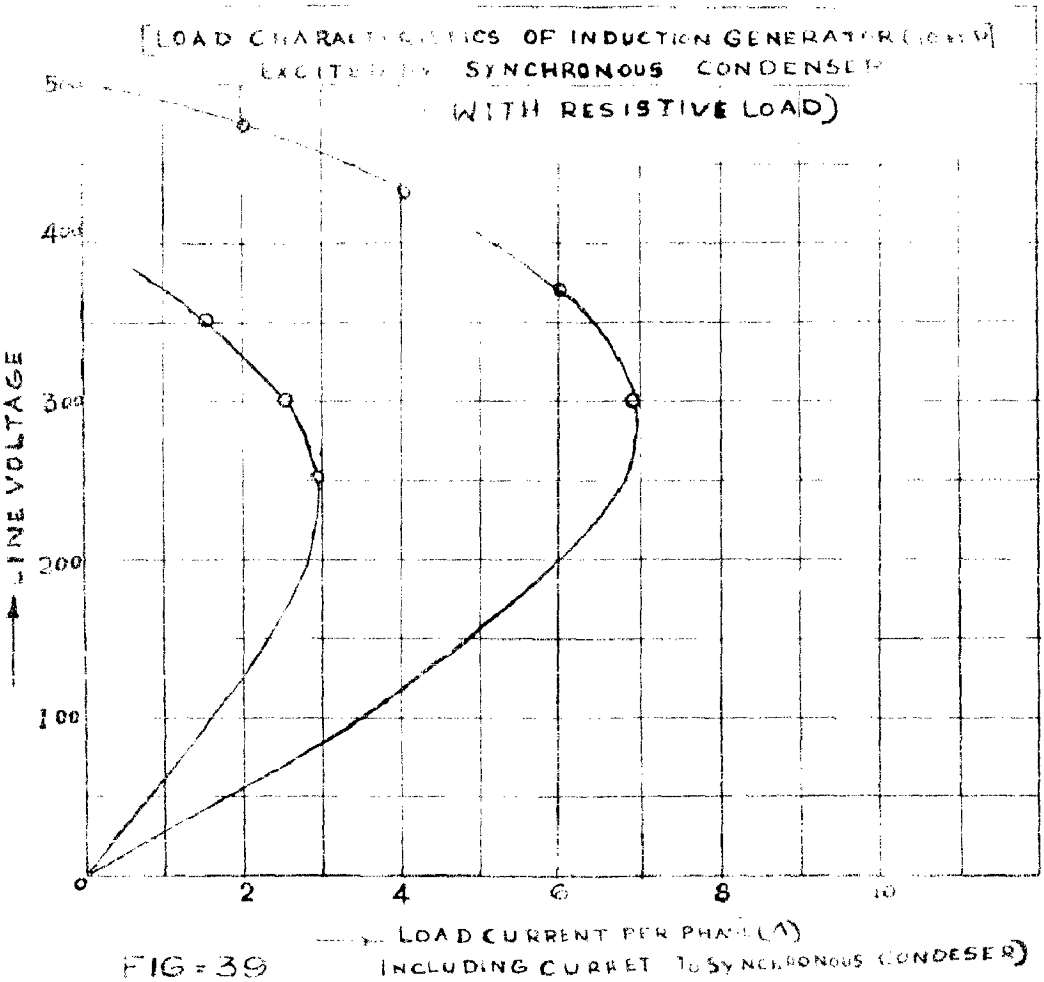

LOAD CHARACTERISTICS OF INDUCTION GENERATOR
EXCITED BY SYNCHRONOUS CONDENSER
(WITH RESISTIVE LOAD)
LINE VOLTAGE
500
400
300
200
100
0
2
4
6
8
10
LOAD CURRENT PER PHASE (A)
(INCLUDING CURRET TO SYNCHRONOUS CONDESER)

FIG = 39

to stator frequency is

$$-\frac{b}{\omega} = -\frac{(r_1+R_e)(x_m+x_1-x')}{(r_1+R_e)^2+(x_c+x')^2} \quad \frac{r_2'}{x_m+x_2'} \qquad (20)$$

If Re = 0 and r_1 = 0 (Stator resistance neglected)

Slip + 0 or the machine is to run at synchronous speed to generate open circuit voltage at synchronous frequency and there is no loss incurred in the machine, since all the resistances are negligibly small so the slip = 0

using the fact $(r_1+R_e)^2 + (x_m+x_1+x_c)(x_c+x') = 0$

$$s = \text{slip} = \frac{-r_2'}{R_e+r_1}\left[\frac{x_m+x_1+x_c}{x_m+x_2'}\right]$$

<u>Experimental results on induction generator excited by Static Capacitor.</u>

(a) <u>Open circuit characteristics</u> -

Static capacitors are connected in star across the generator. From the full load value of the magnetising current of the machine, the approximate value of capacitance is calculated per phase and the values are set for excitation. The machine is started by d.c. motor and 3 phase supply was switched to induction machine as well as bank of capacitor, with proper phase sequence. Subsequently the 3 phase supply is cut off, but the capacitor is kept connected to generator terminal. Normal voltage and frequency is adjusted by varying speed and the value of capacitance . For various values of capacitance o.c.c. is drawn in fig. (40).

OPEN CIRCUIT CHARACTERESTICS OF A 10 H.P 1500 R.P.M INDUCTION GENERATOR (WITH STAR CONNECTED STATIC CAPACITOR)

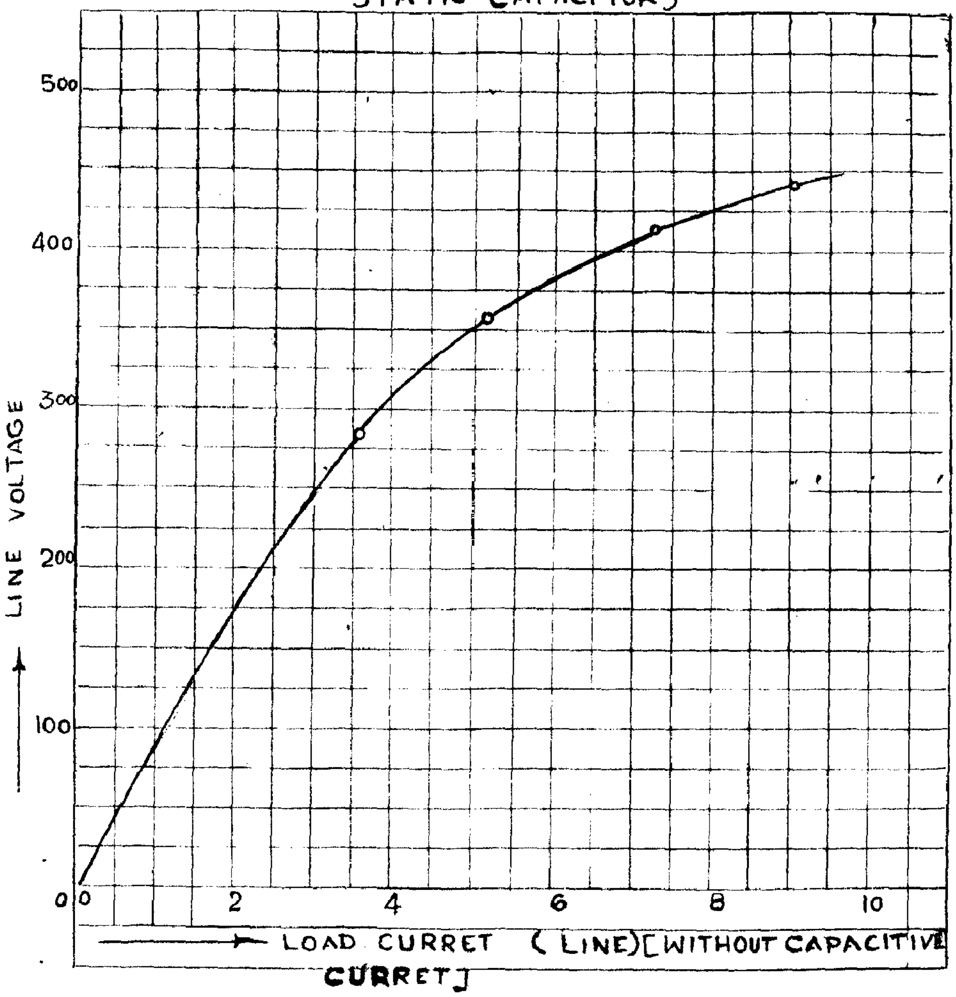


FIG 40

(b) Load characteristics (Resistive load)

The machine in this case is excited by static capacitor as described above. Normal voltage and frequency is adjusted and the machine is loaded by 3 phase balanced resistive load. Load characteristics of this self excited (with shunt capacitor) induction generator is shown in fig.(41). Its characteristics resembles that of d.c. shunt generator.

(c) Load characteristics with 80 per cent P.F. load

The machine is also loaded with 80 percent power factor load and the load characteristics is given in fig.(42). From this figure it is seen that the voltage drops quite rapidly with the load and the behaviour of the machine with this type of load is far from satisfactory.

Determination of o.c.c. of induction generator

(a) By using static capacitor, the o.c.c. of this 10 h.p. 1500 rpm induction machine was determined, which is shown in fig.(40). The details of this experiment has been described in this chapter.

(b) The machine was driven by d.c. motor and with its correct phase rotation, it was switched on to 440 V supply through a 3 phase auto-transformer. Auto-transformer gives the variable voltage to the machine terminals. The excitation of the d.c. motor was so adjusted that the power flow into the induction machine or out of it, is zero. This was observed with the help of an watt-meter. Whatever volt-amp. the motor was receiving from the supply system, at different voltage is the magnetising volt-amps. At different voltages magnetising volt-amps were noted and o.c.c. has been plotted in fig.(36)(a)

(c) By exciting the machine with the help of a synchronous condenser, it is possible to determine the o.c.c. of the machine Tests were conducted on the machine under discussion with the help of a 4.4. kVA, 440V 1500 r.p.m. synchronous motor. The approximate magnetising volt-amps. required for giving the normal voltage was found out from fig.(37) or fig.(36)(β) since both the o.c.c. drawn in (a) and (b) are identical. Corresponding to this volt-amps. the d.c. excitation required for synchronous machine excitation required for synchronous machine was read from fig.(37). This was done as extra precaution to avoid excessive voltage rise in induction generator by over excitation from synchronous condenser.

The induction generator driven by d.c. motor was connected to 440 V mains and the synchronous motor was also connected to same supply system. The d.c. excitation of the synchronous motor was adjusted to the value already determined from fig.(37). Having done this both the sets were disconnected from the supply system, but the connections between them were kept in tact. After disconnection it was found that both the machines continue to run at normal voltage. The synchronous motor received its no load loss from the induction generator and in return it supplied magnetised volt-amps. to the induction generator. By varying the d.c. excitation of the synchronous motor the terminal voltage of the induction generator was made to vary. The no load loss of the synchronous motor remained as a constant load on the induction generator with the help of the motors in the circuit the magnetising current supplied to induction generator at different voltage was determined. Through out the operation, the speed of the d.c.

motor was adjusted, so as to get generated voltage at 50 cycle per sec. The occ was found to be similar to the curves which are already obtained from (a) and (b). Synchronous condenser behaves like an imperfect condenser with variable resistive component. By varying the d.c. excitation of the synchronous motor, the voltage of the induction generator can be controlled.

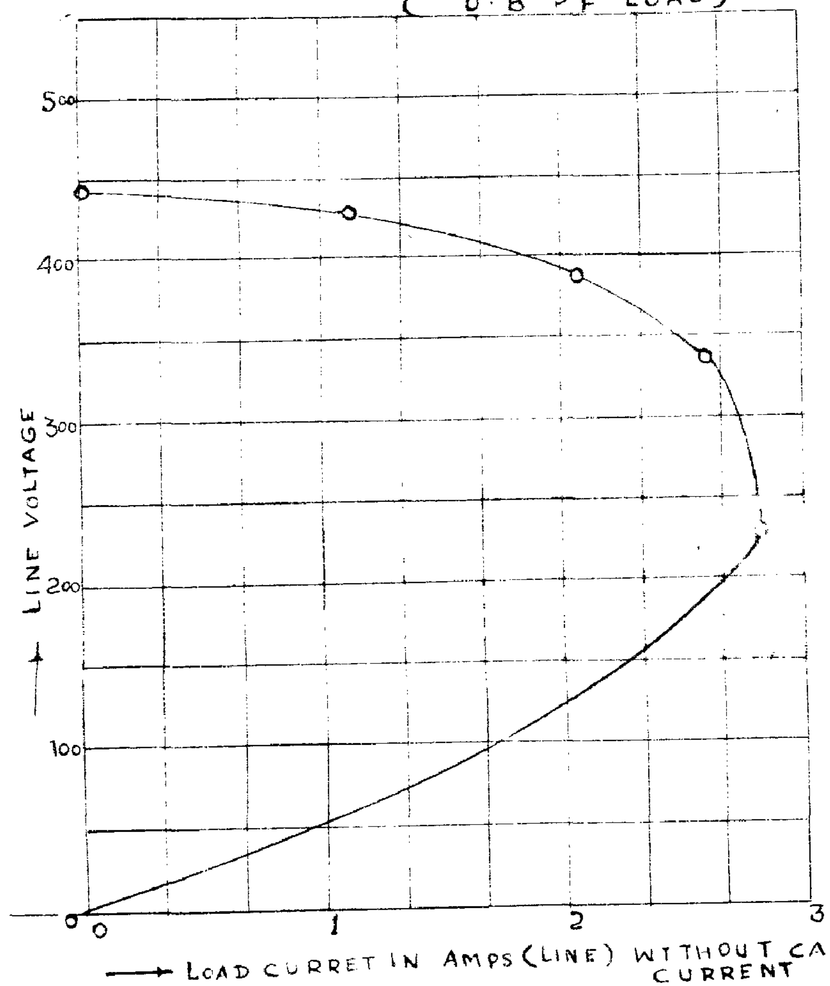
Frequency

As was done in static capacitor, the excitation of the synchronous condenser and the speed of the induction generator was adjusted to give normal 400 V at 50 cycle per sec. By keeping the d.c. excitation of the synchronous condenser unchanged, the speed of the generator was changed and a curve between speed and voltage was drawn which is shown in fig.(38). It is exactly similar to what has been in case of static capacitor.

Wave shape of voltage and current

The steady state voltage and magnetising current wave shape of the induction generator excited by synchronous condenser was taken with the help of oscillogram at three different voltages. The set was running under no load. All the oscillographic record, are shown in fig.(39)(a) The induction generator was connected in delta. The wave shape of the current is more sinusoidal than the voltage and the shape of both the voltage and current waves are much better in sinusoidal form at higher voltages. By proper earthing the neutral of the synchronous condenser and designing the induction machine for star connection, it will be possible to get better wave shape of the voltage. It is seen that the synchronous condenser eliminates the higher harmonic quite appreciable, which is a positive advantage for the power sy

LOAD CHARACTERISTICS OF 10 H.P 1500 RPM INDUCTION GENERATOR [EXCITED BY STAR CONNECTED STATIC CAPACITOR) (0·8 PF LOAD)



FIG·42

LOAD CHARRACTERISTICS OF 10 HP INDUCTION GENERATOR [EXCITED BY STATIC CAPACITOR [RESISTIVE LOAD)

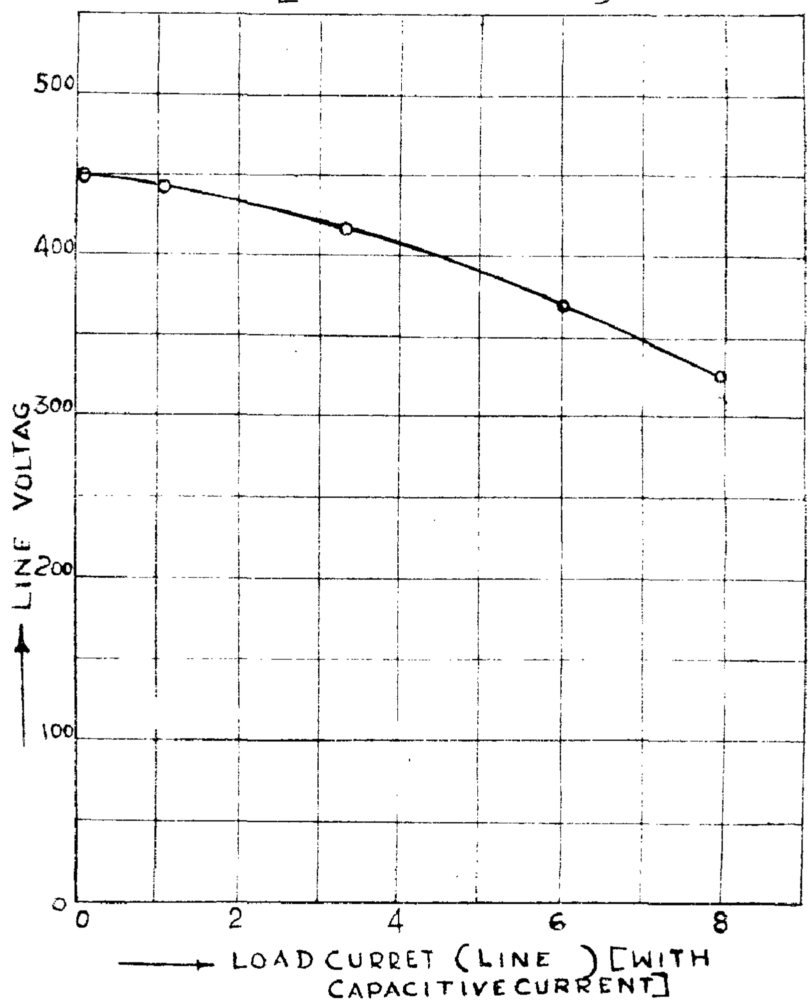


FIG 41

system. Moreover this type of sets, which are easily available in laboratory can produce sinusoidal voltage for experimental purpose without expenditure.

Loading

The load tests were performed on the machine with the synchronous condenser connected across its terminal. First of unity p.f. load was placed and its characteristic is given in fig.(39). It is seen that voltage falls quite rapidly unlike self excited generator by static capacitor and d.c. shunt generator.

Machine was also loaded with .9 p.f. lagging load for voltage regulation characteristics. A 3 phase variable inductance and a set of 3 phase lamp load were used for this test. The lamp load and variable inductance were, so adjusted that each time the p.f. meter gives 0.9 p.f. (lagging). In tis load characteristic it is seen that the above voltage drops more rapidly than what was observed in case of resistive load and it is similar to what was obtained in case of static capacitors.

On the whole, the performance of the induction generator with self excitation from synchronous condenser is similar to the performance curves obtained for induction generator having static capacitor as its source of excitation.

Better flexibility of controlling the voltage is the only advantage which can be obtained by using synchronous condenser. But since such an arrangement warrants a separate synchronous machine, its practical use is altogether ruled out. Its use can only be limited to the laboratory, where considerable amount of study can be made on the behaviour of induction generator.

CONCLUSIONS

(1) The squirrel cage induction generator, due to its simplicity and low cost is well adopted for supporting large power systems, where reactive kVA is available. It can be coupled with gas or water turbines for economical operation and can generate 'by producr' electric power. Simplicity of control is a distinct advantage.

(2) The application of the induction generator, can be extended to any power system, by switching in static capacitor in parallel.

(3) As a self excited generator by static capacitor its voltage regulation is quite good like d.c. shunt generator in resistive load.

(4) Standardization of induction generators, will no doubt bring about reduced first cost. A water turbine driven induction generator is approximately 91 per cent of the cost of an identically rated synchronous machine with exciter. The saving in the induction generator is further obtained by its very low mintenance.

(5) It has been proved by experiment that no serious effects will result from the gradual and sudden short circuit of an induction generator operating with capacitive excitation. In the shunt connection, short circuit can do no harm under any condition. In the compound connection there need be no difficulty.

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