BEHAVIOUR OF SYNCHRONOUS MACHINES
ON
LONG TRANSMISSION LINES

By

S. PRAKASH

UNIVERSITY of ROORKEE CENTRAL LIBRARY
Library No: 62503
Date 25.1.63
C 82
f. 64.

Dissertation submitted in
partial fulfilment for the
award of MASTER OF ENGINEERING
DEGREE in Electrical machine
design.

January, 1962.

Electrical Engineering
Department
University of Roorkee

ACKNOWLEDGEMENT.

The Author wishes to express his deep gratitude to Prof. C.S. Ghosh, Head of the Electrical Engineering Department, University of Roorkee and Dr. T.S.M. Rao, Reader in Electrical Engineering, University of Roorkee for their valuable guidance and their continued and never failing help for the completion of this work. He has been greatly helped by the technical discussions he had with Dr.T.S.M.Rao.

The Author is indebted to Shri S. Swayambu Director, Power Research Institute, Central Water & Power Commission (Power Wing), Government of India for his great interest and the indispensible help and guidance, without which this work would not have been possible.

He is also obliged to Prof. H.N.Ramachandra Rao, Head of the Electrical Engineering Department and Shri B.N.N. Iyengar, Assistant Professor in Electrical Engineering, Department of Power Engineering, Indian Institute of Science, Bangalore for their valuable guidance in the studies carried out on the A.C. Network Analyzer.

S. PRAKASH

CONTENTS.

Page

CHAPTER- I.

CHAPTER- II.

CHAPTER- III.

CHAPTER- IV.

****

BEHAVIOUR OF SYNCHRONOUS MACHINES ON LONG TRANSMISSION LINES.

INTRODUCTION.

Hydro electric generators are usually located at a distance from the load centres and are frequently required to excite H.V. Lines on no load. A long transmission line constitutes virtually a pure capacitive load so the generator has to supply a large KVAR output at almost zero P.F. Leading.

It is true that heavy load due to energizing the line is only a matter of few minutes but it is an unavoidable transition-period and as such is extremely important from operating point of view.

The fundamental drawback is that since on zero P.F. leading the armature ampere turns magnetise in the same sense as the magnet wheel ampereturns, the voltage has a tendency to rise. The excitation of the machine under such a condition is to be reduced to a very low value. Naturally the problem comes as to what is the lowest limit of excitation so that the machine runs stable.

On commercial power systems, the larger machines are synchronous type, these include generators and condensers and a considerable part of motors. The maintenance of synchronism during steady state conditions and regaining of synchronism after a disturbance are of prime importance to Electrical Utilities; electrical manufacturers are also likewise concerned because these considerations determine many special features of apparatus and their cost.

By using the well-known 2 axis theory of Blondel, the steady state characteristics of synchronous salient pole machines is developed. From these it is shown that appreciable economics can be realised by relating the short circuit ratio and thus the synchronous reactance of an alternator to the stability characteristics required by the load. It is also shown that in case of leading KVAR to be supplied by the machine, further economics can be obtained by designing the excitation system to supply positive and negative field currents.

Transient stability studies for a power system were carried out with the help of network Analyser and the results determined. The severe type of disturbances on the power system like 3 phase faults, double-line to ground, single-line to ground have been studied. Whether the system is stable during faults will depend not only on the system itself but also on the type of fault, rapidity of closing and the method of closing (whether or not the line is reclosed). For any constant set of these condition, the question of whether the system is stable or not depends upon how much power it was carrying before the occurance of the fault. Whether the system stays in synchronism is determined from the swing curve, i.e. the curve of angular positions of the various machines plotted against time. Brief discussion of the theory and the practical work done in this direction have been included together with the derivations of the various equations involved which it is hoped will assist in the clarification of the procedure.

S. PRAKASH.

CHAPTER- I.

ANALYSIS OF THE PERFORMANCE OF SALIENT POLE AND CYLINDRICAL ROTOR MACHINES UNDER STEADY STATE

1.1 To start with, the conventional 2 axis vector diagram for a salient pole alternator supplying a lagging p.f. load is shown below. To simplify the treatment the following assumptions are made:

i) Magnetic saturation is neglected as saturation has influence only on the region of operation corresponding to rated load and P.F. while the more important characteristic of synchronous machines such as stability related to under excited conditions, where the error is negligible.

ii) The machine is operated in parallel with a large capacity system, i.e., it is connected to infinite busbar whose voltage is unaffected by load changes in the machine.

iii) All load changes take place within a time interval longer than the S.C. transient time constant of the machine. The analysis is restricted to steady state conditions only.

O.A. is the terminal voltage V (Fig.1 -page 2) which is the reference vector. The terminal voltage is constant as the machine is connected to infinite

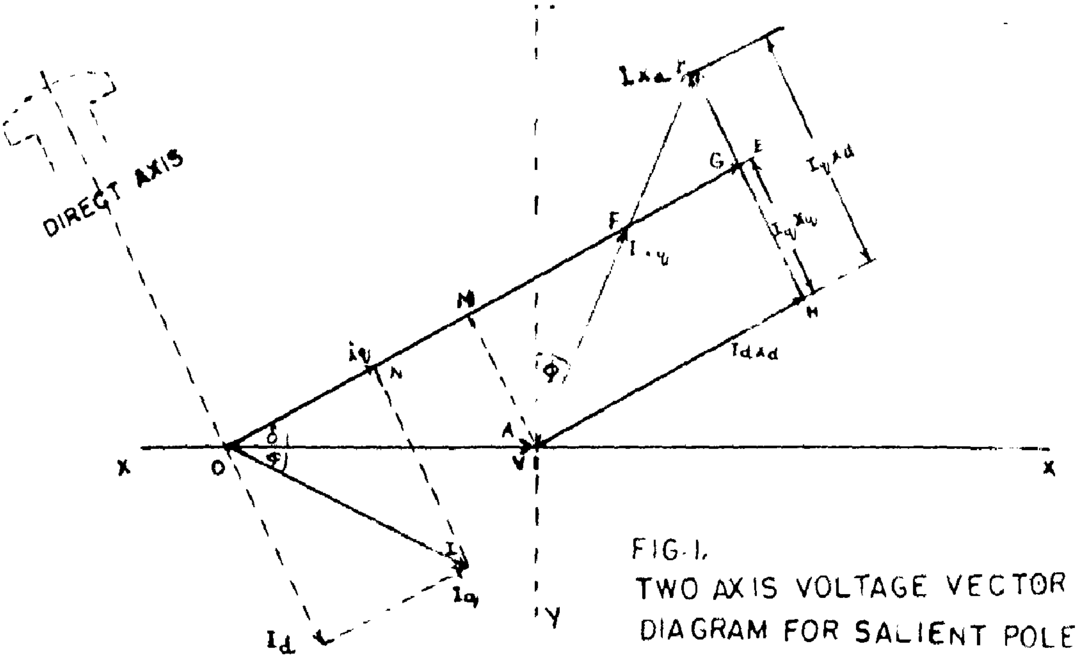


FIG. 1.
TWO AXIS VOLTAGE VECTOR DIAGRAM FOR SALIENT POLE ALTERNATOR (LAGGING P.F.)

busbars. I is the armature current lagging behind the terminal voltage by angle ø. The line AF is drawn at ø angle to the axis YY or perpendicular to current vector I and AF = IX$_q$. Then OF represents the quadrature axis.

The component of the armature current producing an mmf acting in line with the axis of the poles is called the direct axis component of the armature current and is designated as Id. The component of I producing an mmf acting in line with the axis between the poles is called the quadrature axis component of the armature current and is designated as I$_q$. X$_d$ is the reactance offered to the flow of direct axis armature current and is called the direct axis synchronous reactance. Likewise X$_q$ is known as quadrature axis synchronous reactance. OF represents the quadrature axis; it can be easily shown as follows:

Draw AM perpendicular to OF

Triangle OIN is similar to triang: AMF - all sides being mutually perpendicular.

$$\text{Hence } \frac{ON}{AM} = \frac{OI}{AF} \quad \text{or} \quad \frac{i_q}{AM} = \frac{I}{IX_q} = \frac{1}{X_q}$$

$$\therefore \; AM = i_q x_q$$

which is necessary requirement for proper location of the quadrature axis.

Adding reactance drops I_dX_d and I_qX_q as shown, we get the internal voltage E of the machine. Developing the diagram further:

Extend HG to B so that $HB = I_qX_d$, $AB = IX_d$ (Fig: 2). From B draw a line parallel to AH and produce AO to meet at C. Draw a semi-circle on OO.

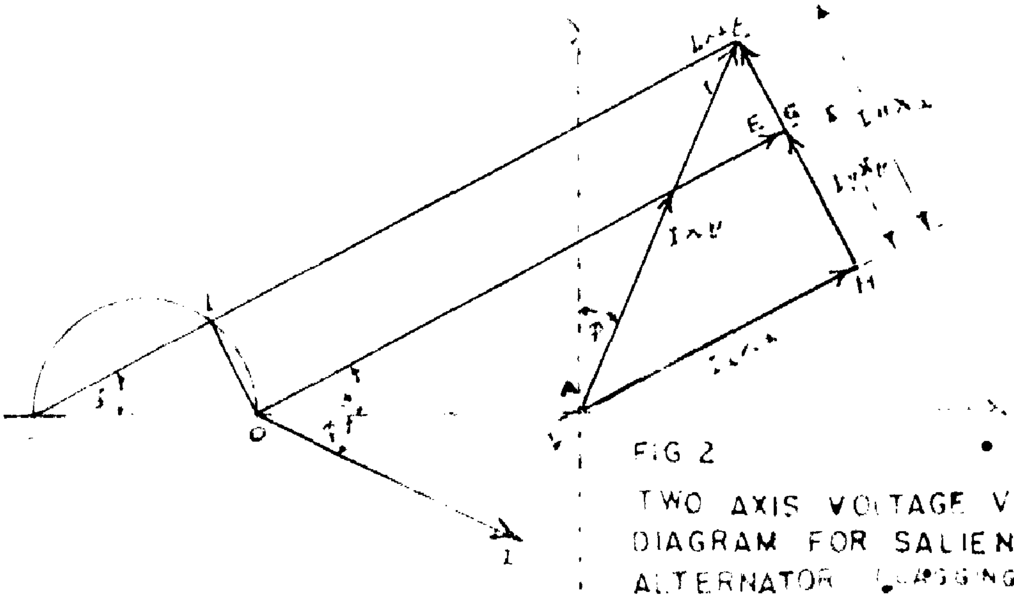


FIG 2

TWO AXIS VOLTAGE VECTOR DIAGRAM FOR SALIENT POLE ALTERNATOR (LAGGING P.F.)

$$OC = \frac{V(X_d - X_q)}{X_q} \quad ; \qquad OD = I_q(X_d - X_q)$$

$$\begin{aligned} OC = OD/\text{Sin. }\theta &= OD/\frac{I_q X_q}{V} \\ &= \frac{I_q\,(X_d - X_q)\,V}{I_q \cdot X_q} \\ &= \frac{(X_d - X_q)\,V}{X_q} \end{aligned}$$

$BD = OC = E$

In order to get current vector diagram, it is merely necessary to divide the four sides of a polygon ODBA by X_d thus obtaining the current polygon.

$OA = \frac{V}{X_d}$ = short circuit current of the armature with no load excitation.

$AB = \frac{IX_d}{X_d}$ = I, the armature current

$BD = \frac{E}{X_d}$ = i.e., internal voltage/X_d

= the short circuit current with full load excitation.

Since with the assumption of no saturation, the vector E also represents the full load field current I_f; E/X_d can also be written as I_f/X_d .

$$OD = I_q \frac{(X_d - X_q)}{X_d} = I_q \left(1 - \frac{X_q}{X_d} \right)$$

$$OC = V \frac{(X_d - X_q)}{X_d \cdot X_q} = V \left(\frac{1}{X_q} - \frac{1}{X_d} \right)$$

By simplifying the vector diagram we get the following diagram (Fig: 3) which gives us relation between short circuit current, load current, armature current. We can easily get the relation between P.F., Field Current and armature current.

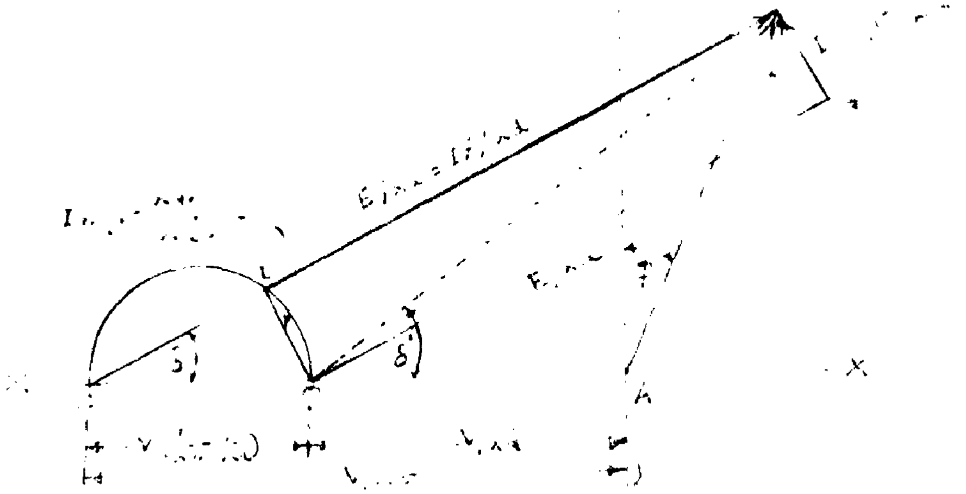


FIG. 3. TWO AXIS CURRENT VECTOR DIAGRAM FOR SALIENT POLE ALTERNATOR (LAGGING P.F.)

if $X_d = X_q$ the semi-circle is reduced to zero and we get a simple diagram of a round rotor machine.

Since P.F. angles are measured from the ordinate OY as zero, the projections of the current vectors on the vertical axis represent active power and similar projections on the horizontal as reactive power. The reason for this rotation of the vector diagram through 90° is that the original vector diagram was divided by reactance X_d.

Counter clock-wise direction of rotation has been assumed in all diagrams to be positive. Negative values of ϕ correspond to lagging P.F. and positive values for leading power factor.

1.2 The Generalised Power Diagram:

The vector diagram can be further extended to include the armature current locii at various fractions of full load field current. It will give the performance of the synchronous machine as generator operating from zero lagging to zero leading p.f. and as a synchronous motor operating from zero leading to zero lagging p.f. This has been shown in Fig: 4.*

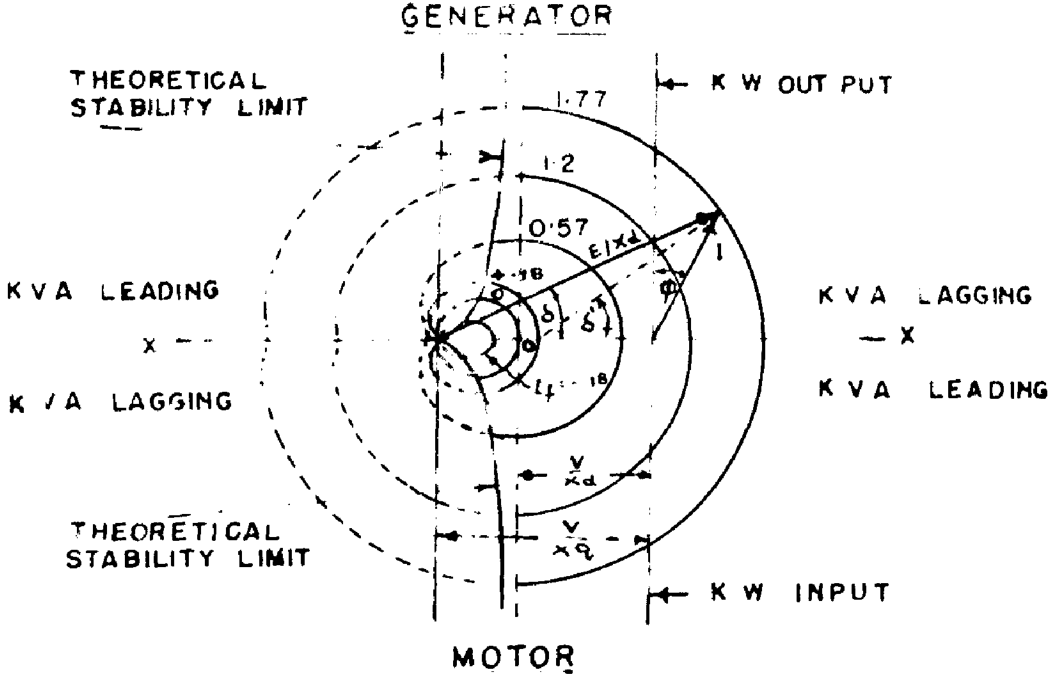


FIG 4: ARMATURE CURRENT LOCI FOR FIXED FIELD CURRENTS (SALIENT POLE MACHINE Xd = 1.1 P.U, Xq = 0.7 P.U) RATED P.F = 0.9 (LAGGING)

---

* W.H.Walker, Operating characteristics of salient pole machines. Proc.IEE 100(11)1953 page 13.

machines. Proc.IEE 100(11) 1953 page 13.

Perpendicular through O at $\frac{V}{X_d}$ represents the stability limit of round rotor machine. The stability limit of salient pole machine decreases asymptotically towards the perpendicular at $\frac{V}{X_d}$. The perpendicular at $\frac{V}{X_d}$ is the theoretical stability limit of the cylinderical rotor machine/in which the locus of the armature current is circle with centre O.

1.3 Power output of salient pole machine and round rotor machine.

It can be seen that when a salient pole machine is operating at about rated output and P.F. the maximum output given by a salient pole machine is slightly greater than the round rotor machine. However, if the machine is operating at a low leading P.F. i.e., charging a long transmission line during light loads, then the machine has a much higher maximum output than is given by cylinderical rotor machine. This increased output can be obtained only by operating the machine with reversed field current in rotor winding, the maximum value being obtained in the stable region corresponding to $\frac{V}{X_q}$ at zero leading P.F. The armature current is $\frac{V}{X_q}$ and maximum negative excitation is $V\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$.

We can also interpret the shape of these curves mathematically, $r = \frac{E}{X_d} + V\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \text{Cos. } \theta$ ..(1

where r is the length of any ray from C (Fig: 3). It is interesting to note the shape of the loci of armature current obtained from various values of excitation, i.e. E/X_d. (Fig: 4)

if $\frac{E}{X_d}$ is greater than $V\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$ then the smooth outer curve is obtained.

if $\frac{E}{X_d} = \left(\frac{V}{X_q} - \frac{V}{X_d}\right)$ then equation(1) becomes,

$r = \left(\frac{V}{X_q} - \frac{V}{X_d}\right)(1 + \text{Cos. } \theta)$ which is euation of a cardiod.

if $\frac{E}{X_d}$ = less than $V\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$ then the loci is a loop.

if $\frac{E}{X_d} = 0$ i.e. zero field excitation then equation (1) is

$r = V\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \text{Cos.} \theta$ which is the equation of a circle.

1.3.1 POWER

We can also find out the power output from the diagram (Fig: 3)

$$\text{Power} = V.r \operatorname{Sin}\delta \quad =$$

$$= V.\frac{E}{X_d} \operatorname{Sin}.\delta \quad + V^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\operatorname{Cos}.\delta \ \operatorname{Sin}\delta$$

$$= \frac{VE}{X_d} \operatorname{Sin}\delta \quad + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \operatorname{Sin}.2\delta \quad \ldots(2$$

The power output for a round rotor machine is $\frac{VE}{X_d}$ Sinδ

The additional power developed by a salient pole machine is $\frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)$ Sin. 2δ which is due to the difference in the magnetic reluctance of the direct axis and the quadrature axis.

When $X_d = X_q$ the reluctance power is zero. It is interesting to note that salient pole machine will devlop power even if no excitation is applied(E=o).

1.4 Alternator Power Chart.

The power diagram in Fig.4 does not indicate any limits for armature and field currents by permissible temperature rise of windings. Combining Figs: 3 & 4 and introducing limitations on turbine input, stator current, field current and stability, the operating chart shown in Fig.5 can be constructed.

Y axis represents MW and X axis represents MVAR output. All values on the power chart are on per unit basis. The p.u. scale is the same for active and reactive power as well as for stator current.

$$OS = \frac{V}{X_d} ; \qquad OC = \frac{V}{X_q}.$$

OS also represents the no load excitation of the machine which fixes the excitation scale.

SV represents the full load excitation of the round rotor machine. Circular arc qv drawn with centre S fixes the field current limit.

The smooth curve qR fixes the field current limit for the salient pole machine and is determined by drawing a number of rays through C and then marking off along each ray from the periphery of the semi-circle a length representing $\frac{I_f}{X_d}$.

Vertical line ST represents the theoritical stability limit for round rotor machine.

Asymptote uc represents the theoritical stability limit for salient pole machine.

The difference in the charts of the two types of machines are in the region of low MW loads at low leading Pf. The stability limit of cylindrical rotor machine on leading p.f. side is considerably less as compared with salient pole machine. It would not be advisable to operate an alternator close to the theoritical stability limit as slight change in load is likely to pull out the machine from synchronism. The latter is replaced here in the chart by the practical

---

* W.H.Walker, Operating characteristics of salient pole machines. Proc. IEE 100 (II) 1953. page 13.

stability limit which is arbitrarily reduced by 10% rating of the machine. Fig. 5(a) shows a graphical method of determining the practical stability limit for a round rotor machine and it is self explanatory. The assumed constant active power increment n expressed as a percentage of the machine KVA rating represents the safety factor of the practical stability limit and it is taken as 10%.

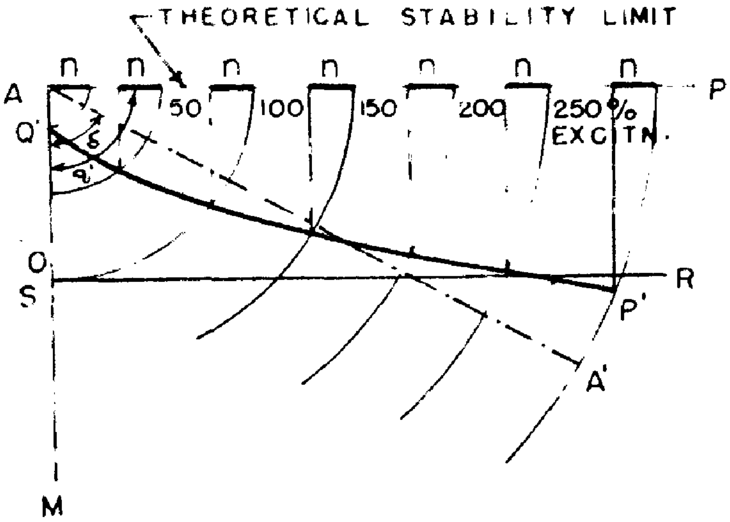


FIG 5a. METHOD OF DETERMINING THE "PRACTICAL STABILITY LIMIT"

Theoritical stability limit for salient pole machine actually runs in the region of negative field current. Large alternators have generally no provision for negative excitation. Main exciter is also not fitted with bias field to overcome the residual effect. Under these conditions, the excitation system is not capable of reducing the alternator field voltage to zero.

---

* Zwander. Fundamental electric characteristic of synch: turbo-generator, Vol.91,Part II IEE 1944 page 185.

Therefore, the alternator field voltage is fixed at 5% of the normal field voltage. The limit is shown as segment on the left hand side of the diagram.

The working point placed within this area at once defines the MVA, MW, MVAR, Current, P.f. and excitation. The load angle can be found by measurement.

1.4.1 The above chart can be of considerable assistance for determining the capabilities of machines under various conditions of load. The readily interpretable form has been shown in Fig.6 which can be used as a dial of a combined watt and VAr meter. As already stated, the machine is assumed to be connected to a large capacity system and its output is relatively a small fraction of the system capacity.

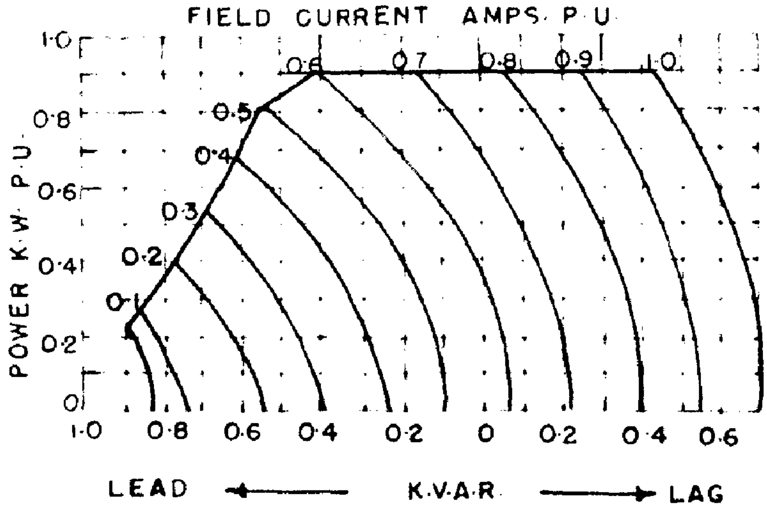
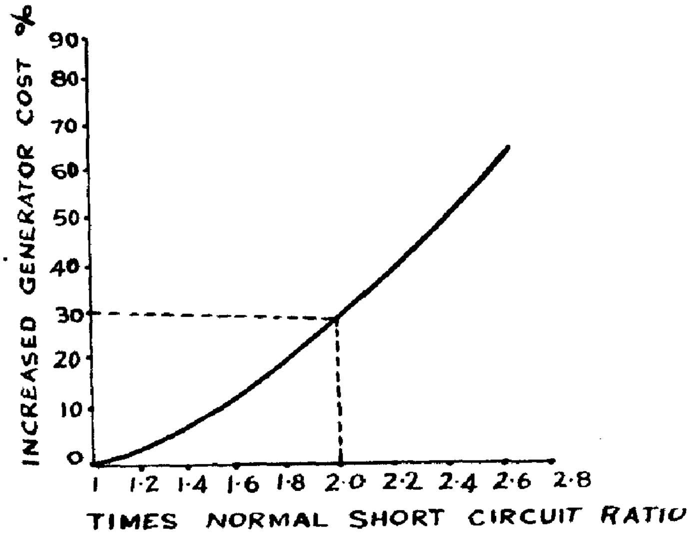


FIG.6:- SIMPLIFIED POWER CHART
(SALIENT POLE ALTERNATOR)

Say during night the machine is operating at 0.1 kw and 0.6 kVAR leading with field current of 0.2 amps. In the morning there may be a request to increase the active power quickly to 0.8 kw. If the turbine governor is set for 0.8 kw without adjusting the field then the apparent power will increase along the curve for 0.2 amps. of field current and the machine may fall out of step. However, if the operator has vector meter and chart in front of him, he can at once see at a glance that before such an active power increase takes place, how much field current must be increased.

1.5 Short Circuit Ratio and the Safe Operation Limit with Capacitive Load.

From all this discussion, we have seen that the behaviour of a particular synchronous machine under various operating conditions and its maximum power output under stable region can be determined. If we know the operating condition of a machine and the exciter system available, suitable selection of the direct axis synchronous reactance of a machine can be made. If saturation is neglected, the short circuit ratio of the machine is equivalent to $\frac{1}{X_d}$. Higher short circuit ratio machines mean more cost as the dimensions of the machine increases. The curve in Fig.7 gives us the increased generator cost for the increase in the short circuit ratio.



FIG·7

Short circuit ratio is defined as:

$$S.C.R. = \frac{\text{Excitation for normal voltage on open circuit}}{\text{Excitation for rated stator current on s.c.}}$$

The fundamental equation for induced stator Emf. $E = KfT\phi$ shows that same voltage can be obtained with various combinations of working flux and stator turns T. A large flux demands larger dimensions in the magnetic circuit to carry it at an economic flux density: thus the core length of the machine must be greater (the diameter being limited by speed) but with fewer stator turns the stator copper area is decreased. On the other hand, the number of stator turns is greater, a smaller flux is needed and core length can be shorter but the stator copper section is increased.

One component, say F_t is used to magnetise the machine, the remainder opposes the armature reaction F_a. The net excitation then produces the working flux, which in turn generates the internal emf.

If to increase the S.C.R. fewer stator turns are used the armature reaction MMF F_a (proportional to T^2) will be decreased leaving more of the available rotor MMF F_t for magnetising: the air gap must consequently be lengthened. Thus with a longer gap and fewer stator turns the numerator of the S.C.R. will be increased and its denominator decreased.

An increase in the short circuit ratio increases the cost of the machine but the charging capacity is also directly proportional to the short circuit ratio, as the line charging capacity with positive excitation is equal to $\frac{V}{X_d}$.

Long high tension lines can represent considerable capacitive load. A 220 kv overhead line $\frac{100\ \text{KM}}{62\ \text{mls.}}$ long takes about 13500 KVAR capacitive wattless load. Charging KVA for 100 miles long of a line is about 20.5%

of the surge impedance loading.

If the excitation system is capable of supplying the positive excitation only, reactance X_d must not be greater than the reactance X_c of the capacitive load. This often provides a limit for the synchronous reactance of a machine.

But if the excitation system is capable of supplying positive or negative excitation, the safe operating limit at zero p.f. leading is determined by X_q, the line charging capacity being $\frac{V}{X_q}$ at a negative excitation of $V\left(\frac{1}{X_q}-\frac{1}{X_d}\right)$. In this case X_q is less than X_c which is less than X_d.

For machines of standard construction however, the condition X_q less than X_c represents in all cases a practical limit which must not be passed.

If $X_q = 1$ per unit, then $X_d = 1.6$ per unit. With low S.C. ratio, the alternator can be provided at a lower cost even after accounting for the increase in cost of the excitation system capable of providing negative excitation (by about 12%).

But in actual practice, the value of X_d for alternators on long transmission lines is not taken more than 1, as then the steady state limit is $P'max = \frac{E.V.}{X_d}$

and the maximum charging current is $\frac{V}{X_d}$ at zero p.f. leading.

The following table gives the value of direct axis synchronous reactance generally adopted for turbo-alternators and water wheel alternators.

	Turbo Alternators.	Water Wheel Alternators.		
		1000-500 RPM	500-250 RPM	250-50 RPM
X_d	2.4 - 2.0	1.5 - 20	1.3-0.95	1.1-0.9
X'_d	0.18-0.28	0.25 -0.35	0.25-0.35	0.25-0.4

Quadrature axis synchronous reactance

i.e. $X_q = 0.5$ to $0.7\ X_d$

We find that value of X_d for water wheel alternators is 0.9 to 1.5 p.u. and the value of transient reactance i.e. $X'_d = 0.25$ to 0.4 p.u. for salient pole machines.

In turbo alternators, due to their high speed, the short circuit ratio has to be kept low due to mechanical reasons as high S.C. ratio means larger size. Efficiency is also high for low S.C. ratio alternators as less empre tuns for the field are required.

1.6 Power Factor & System Voltage.

Hydro electric generators supplying long transmission lines operate at approximately Unity P.F.

and in general the generator P.F. should be selected to correspond as nearly as possible to the sytem requirement. A generator with a low power factor rating used at higher power factor is more unstable than a generator of the same size and cost rated more nearly to the actual P.F. This is evident since operating at power factor higher than rated requires field current less than the rated.(If generator is to be operated at high power factor then the rated one, shunt reactors can be used at the generator terminals to increase the field loading. This is only a makeshift arrangement.)

On the other hand a generator operated at a lower power factor than the rated one is more stable but the trouble here is that this may cause heating of the field. To achieve this, the field winding should be of liberal design. Also there is margin in the field heating, voltage can be increased so increasing the stability limit.

In the operation of long high voltage transmission lines, it has been found desirable to se the voltage at the receiving end lower than the generator voltage to permit the generator to operate at unity power factor or slightly lagging even on light loads. This means that leading KVAR for light load conditions should be furnished from the receiver end. This can be done by connecting a synchronous condenser at the receiver end which can operate to supply this charging current. When the power system is fully loaded, the system voltage is likely to go down due to some loads being of inductive nature like induction motor loads etc. Synchronous condenser also provides the lagging KVAR in such cases. Synchronous condensers improve the voltage condition of the system thereby increase the stability of the power system. The size of the synchronous condenser used at intermediate station for improving the stability may be quite large as compared to the size required for improving the p.f.

1.7 Synchronous Condenser.

Synchronous condenser is an idle running syn: motor across the line at the receiving end with automatic excitation control. The main purpose of the synchronous condenser on large power systems is to maintain constant voltage by supplying variouse amounts of lagging or leading power as required by the system. The only active power loading on the machine is represented by its losses which are supplied from the line. Losses are about 2 - 3% which are practically constant.

The power chart shown in Fig:4 (below the horizontal line) will be of interest to investigate the performance of the synchronous condenser. When the synchronous condenser operates at zero p.f. leading, the internal voltage and thus the field current is given by the arithmetic sum of the short circuit current $\frac{E}{X_d}$ p.u. and the armature current p.u. The important characteristi is when the synchronous condenser operates at zero lagging p.f. as this relates to the under excited region. It may be seen that in order to operate with small positive field current, it is necessary to restrict the lagging power to about 50% of the rating at zero leading p.f. However, if the excitation system is designed to reduce the excitation to zero and then increase in negative direction, it may be possible for the machine to supply 90% of the output at zero lagging p.f. without any change in the size of the machine.

The usual value of X_d for synchronous condenser =
$= 1.7$ p.u. and
$X_q = 1.0$ p.u.

It may be better to leave the choice of X_d to the machine designer and to specify the transient reactance of the synchronous condenser (as obtained from network analysis from stability point of view) and the ratio of the lagging power to that of the rating at zero leading P.f. to get the most economical arrangement.

It may also be possible to operate some of the idle generators at the generating station to operate as synchronous condensers. Some arrangements are essential so that the prime mover could be run idle as load.

1.8 Excitation system.

The inherent regulation of long transmission lines can be accomplished best by automatic excitation system. Rejection of load and overspeed due to relative slow action of the governor on the wicket gates of the water wheel causes rise in generator voltage. Also there is rise in generator voltaged due to inductive load being thrown off. The automatic excitation system should be of quick response. The representative values for exciter response are 1.5 to 2.0 p.u. for high speed of response, 1.0 to 1.5 p.u. for an average speed of response. It is in general useless to go to higher values as the ranges indicated confer the essential benefits of high speed excitation.

As already mentioned, synchronous condensers or generators with line charging functions must sometimes operate at very low excitation. Because a self excited exciter becomes unstable if operated at too low a voltage range, it is necessary either to use a main generator field rheostat or to separately excite the exciter. The latter alternative is preferable from the point of view of easy control. Excitation system for synchronous condensers or generators supplying long transmission lines must have wide range of excitation control.

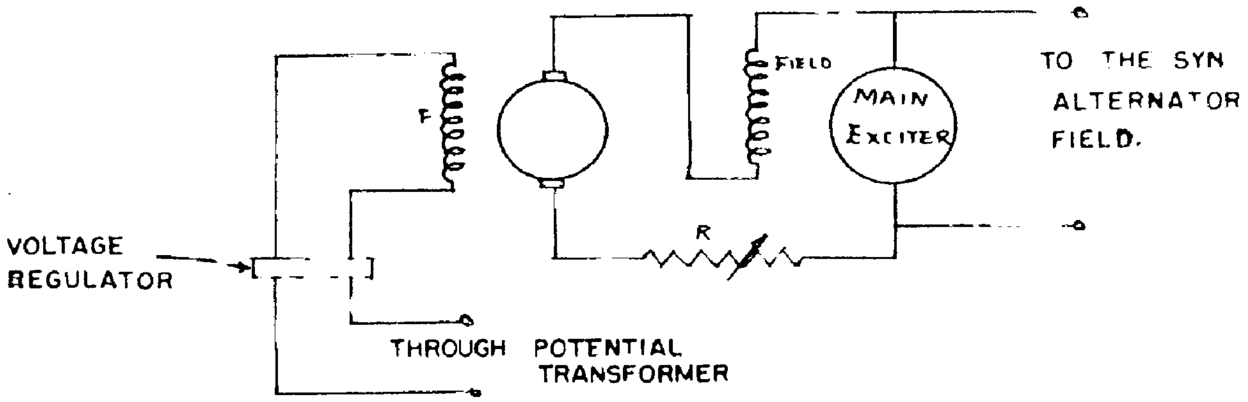


FIG. 8 SELF EXCITED MAIN EXCITER AND STATIC VOLTAGE REGULATOR WITH ROTATING AMPLIFIER

Fig: 8 shows a * recently devloped excitation system for hydro electric generators supplying long transmission lines which appears to have desirable characteristics. It consists of " self excited main exciter and a static voltage regulator with a rotating amplifier".

Fig:9 shows a separately excited main exciter.

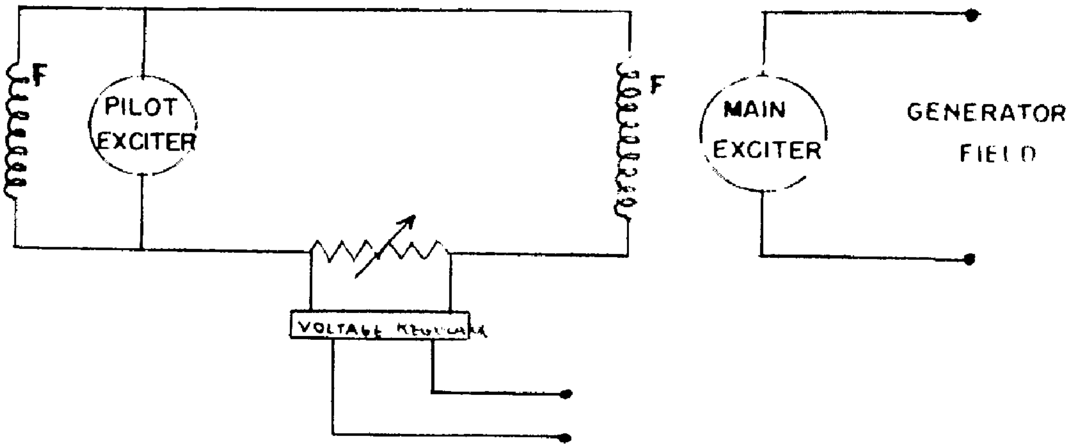


FIG. 9 SEPARATELY EXCITED MAIN EXCITER

If there is great rise in the sending end voltage due to rejection of load etc., in order to prevent the generator becoming self excited, it is common practice to provide an over voltage relay which

---

* C.L. Kihlgore, Excitation problems in Hydro Electric Generators supplying long transmission lines, AIEE Transaction Vol.66, 1947.
Fig:8&9. E.W. Kimbark, Power System Stability Vol.III (John Willy) Chapter XIII, Pages 141, 143.

cuts off the line if there is an excessive rise in sending end voltage.

Excitation system effects stability under both transient and steady condition as the power transferred in two machine system is proprtional to the product of the internal voltages of the two machines divided by the reactance. The same is true for the multi machine system. This statement holds regarding the power at any particular value of angular separation and hence also for maximum power. Therefore, it is apparent that raising the internal voltages increase the stability limit.

Summing up a system is said to be in steady state stability limit if an increase of the angle between the sending and receiving end voltages results in increased power transfer towards receiving end. In an ideal system with no resistance, the power transferred between two generators will very sinusoidally from zero to maximum as the angle between the voltages at the sending and receiving ends is increased from '0' to '90' degrees. As the angle is further increased from 90° to 180°, the power will decrease sinusoidally until at 180° it is again zero. Therefore, the maximum theoritical stability limit is 90°.

This limit cannot be approached in practice because if a system were operated upon at, or very near to, the steady state stability limit, the smallest power surge such as might be caused by sudden switching on a small load, would cause the system to lose stability. The system must be operated at considerably less than the steady state stability limit. There is a single steady state stability limit for specified circuit impedance and internal voltage conditions. It follows of course that if the excitation of any machine is changed so as not to correspond to internal voltages assumed, the stability limit will be correspondingly changed.

Usually the important practical limit is the transient stability limit discussed in the next chapter. Steady state limit, of course, provides a quick estimate of the transient limit.

CHAPTER II.

PERFORMANCE OF SYNCHRONOUS MACHINES UNDER TRANSIENT CONDITIONS.

So far as we have considered the maximum power that can be transmitted in a steady state without loss of synchronism.

If some sudden load comes on the generator or there is short circuit, the ability of a generator to remain in synchronism is known as transient stability.

2.1 Dynamic Stability Limit.

When sudden disturbances occur the flux in the field circuit is maintained by a current induced in the field winding (const. flux linkages theorm): therefore the induced EMF E remains constant.

$$P \text{ Pullout} = \frac{E.V.}{X_d'}$$

where X_d' is the -transient synchronous reactance of the machine, reactance of the transformer and the line. Here the last portion is usually greater than in the case of static stability because the disturbance may be due to short circuiting or earthing of a line. It is desirable to keep X_d' small.

If the machine does not have a voltage regulator, the field current ultimately decays back to its original value and as it decays the flux linkages also decay. The time constant of the decay is of the order of 2-5 seconds. During the first swing the flux linkages do not decrease much in a machine, so it may not fall out of step on first swing. If the fault is sustained for a long time, the flux linkages may be so much reduced, that the system will ultimately become unstable.

If the machine have voltage regulators, the regulators will tend to maintain constant terminal voltage which would mean increase in field flux linkages. Regulators are generally not so quick to act in the first swing so the machine must be able to stand first swing.

The transient stability limit in a single machine problem can be estimated by the maximum angle of fault clearing, by simply balancing positive and negative areas on the power angle diagram. This is possible because the movement of only one machine rotor is to be followed. In the case of two or more machines the equal area method cannot be applied; stability or instability is determined by the relative angular position of two machines. The maximum rotor displacement angle before fault isolation is not determined from the power angle diagrams but will be found by the angle-time or swing curves which are most conveniently determined by the step by step integration method.

2.2 Derivation of the equations involved in step-by-step swing-curve calculation. *

Derivation of the equations involved in the step-by-step swing curve calculations will assist in the clarification of the procedure.

In mechanical units,

$$Ta = \frac{WR^2}{g} \cdot \frac{d^2\theta}{dt^2} = \frac{WR^2}{g} \cdot \frac{d^2\theta}{dt^2} \qquad \text{——} \; (1)$$

where,

Ta = accelerating torque in lb.-ft.

WR^2 = moment of inertia in lb-ft.^{2}

g = acceleration of gravity in ft. per sec. per sec.

θ = angle in mechanical radians,

θ' = angle in mechanical radians with respect to a synchronously rotating reference,

t = time in seconds.

$$\delta = \frac{(360)(60)\, f\, \theta'}{2\pi(\text{rpm})} \qquad \text{— — —} \; (2)$$

where,

δ = angle in electrical degrees with respect to a synchronously rotating reference

---

*AC Network analyser manual(Indian Inst. of Science)Pub:

f = frequency in cycles per sec.

Substituting equation (2) in (1)

$$Ta = \frac{WR^2}{g} \cdot \frac{2\pi (rpm)}{(360)(60)f} \frac{d^2\delta}{dt^2} \qquad \text{———} \quad (3)$$

In per unit system,

$$(\text{Base } T) = \frac{33000}{2\pi(rpm)(0.746)} (\text{Base KW}) \quad \text{——} \quad (4)$$

$$\text{Per unit } Ta = \frac{Ta}{\text{Base } T} \qquad \text{———} \quad (5)$$

$$\text{Per unit } Ta = \frac{WR^2 \, 2\pi(rpm)}{g(360)(60)f} \cdot \frac{2\pi(rpm)\ (0.746)}{33000\ (\text{Base KW})} \frac{d^2\delta}{dt^2} \quad \text{—} \quad (6)$$

$$= \frac{0.231\ (WR^2)\ (rpm)^2}{180\ f(\text{Base KW})} \times 10^{-6} \cdot \frac{d^2\delta}{dt^2} \qquad \text{———} (7)$$

In per unit system,

Base kw = Base kva

Therefore,

$$\text{Per unit } Ta = \frac{0.231\ (WR^2).\ (rpm)^2 \ \times\ 10^{-6}}{\text{Base KVA}} \times \frac{1}{180f} \ \frac{d^2\delta}{dt^2} \quad \text{—}(8)$$

If we let

$$H = \frac{0.231\ (WR^2)\ (rpm)^2\ 10^{-6}}{\text{Base KVA}} \quad \text{—— ——} \quad (9)$$

$$\text{and } K_1 = \frac{180\ f}{H} \quad .. \quad .. \qquad \text{—— ——} \quad (10)$$

$$\text{then, } \frac{d^2\delta}{dt^2} = K_1 Ta \ .. \ . \qquad \text{—— ——} \ (11)$$

H is called the per unit inertia constant of the machine (or group of machines) and is equal to the energy of the machine at rated speed expressed in kw-sec per base kva. If the base kva is taken equal to the machine kva rating, H will be the per-unit inertia constant of the machine on its own base and will have a characteristic value for each type of machine.

7. Add 6 to 2, obtaining velocity at $t_{3/2}$

8. Assume velocity at $t_{3/2}$ is average for full interval t_{1-2} and calculate

$$\Delta\delta_{1-2} = (k\ Ta_0 \frac{\Delta t}{2} + k_1 Ta_1\ \Delta t)\ \Delta t$$

9. Determine $\delta_2 = \delta_1 + \Delta\delta_{1-2}$ and plot on swing curve.

10. Determine Ta_2 at t_2 and δ_2 from analyzer readings.

11. Calculate $k_1\ Ta_2\ \Delta t$ = velocity change in interval $t_{3/2\ -\ 5/2}$

12. Add (11) to (7) obtaining velocity at $t_{5/2}$

13. Assume velocity at $t_{5/2}$ is average of full interval t_{2-3} and calculate

$$\Delta\delta 2\text{-}3 = (\ k\ Ta_0 \frac{\Delta t}{2} + kTa_1\ \Delta t + K_1 Ta_2\ \Delta t)\ \Delta t$$

14. Determine $\delta_3 = \delta_2 + \Delta\delta_{2-3}$ and plot on the swing curve.

15. $\delta_n = \delta_o + \Delta\delta_{o-1} + \Delta\delta_{1-2} +\ 2\text{-}3\ + \Delta\delta_{(n-1)n}$

$$= \delta_o + (k_1 Ta_o \frac{\Delta t^2}{2}) + (k_1 Ta_o \frac{\Delta t^2}{2} + k_1 Ta_1\ \Delta t^2\ )$$

$$+ (k_1 Ta_o \frac{\Delta t^2}{2} + k_1 Ta_1\ \Delta t^2 + k_1 Ta_2\ \Delta t^2\ )$$

$$+ (k_1 Ta_o \frac{\Delta t^2}{2} + k_1 Ta_1\ \Delta t^2 + k_1 Ta_2\ \Delta t^2\ +$$

$$k_1\ Ta(\ n-1)\ \Delta t^2\ )$$

Since the machine speed does not vary appreciably from synchronous speed during the swing curve, per-unit torque and per unit power are assumed to be equal and are used interchangeably.

The swing-curve is calculated as outlined in the following steps:

δ_n = Angle in electrical degrees at time t_n
Ta_n = Per-unit accelerating torque at time t_n
$\Delta\delta_{n-(n+1)}$ = Change in angle between time t_n and time t_{n+1}.

$$K_1 = \frac{180\ f}{H}$$

1. Determine Ta_0 at t_0 and δ_0 from analyzer readings.
2. Calculate $K_1\ Ta_0\ \Delta t/2$ = Velocity change (elect: degrees per Δt) in interval $t_{0-\frac{1}{2}}$ = velocity at $t_{\frac{1}{2}}$
3. Assume velocity at $t_{\frac{1}{2}}$ is average for full interval t_{0-1} and calculate $\Delta\delta_{0-1} = (K\ Ta_0 \frac{\Delta t}{2})\Delta t$.
4. Determine $\delta_1 = \delta_0 + \Delta\delta_{0-1}$ and plot on swing curve.
5. Determine Ta_1 at t_1 and δ_1 from analyzer readings.
6. Calculate $k_1 Ta_1 \Delta t$ = velocity change in interval $t_{1/2-3/2}$

16. In order to simplify the calculations required thereby saving time and reducing chances of making arithmetical errors, the acceleration constant K on the step-by-step swing-curve calculation sheet (as shown further) is equal to $K_1 \Delta t^2$. That is,

$$K = K_1 \Delta t^2 = \frac{180 f \Delta t^2}{H}$$

17. $$\delta n = \delta_0 + \frac{K Ta_0}{2} + \left(\frac{K Ta_0}{2} + K Ta_1 \right)$$

$$+\left(K \frac{Ta_0}{2} + K Ta_1 + K Ta_2\right) +$$

$$+\left(K \frac{Ta_0}{2} + K Ta_1 + K Ta_2 + K Ta(n-1)\right)$$

The operation indicated above has been adopted for actual calculations.

CHAPTER. III

STABILITY STUDIES FOR MULTIMACHINE SYSTEM ON A.C. NETWORK ANALYSER AT THE INDIAN INSTITUTE OF SCIENCE, BANGALORE

3.1 Setting up the problem on the analyser.

For transient stability solutions on A.C. network analyzer the studies of the Andhra Pradesh power system were carried out. The A.C. network analyser is essentially a means of representing an electric power network to scale. The power syste to be analysed is set up on the analyser in miniature and to scale by interconnecting various calibrated adjustable circuit elements to form a network representing the actual system network.

In solving problems with the network analyser, the same approach is ordinarily followed as in solving them by long hand calculations in which per unit system is employed. Problems involving balanced three phase currents and voltages are solved as single phase problems on a line to neutral basis. Problems involving unbalanced conditions are solved in a similar manner using the method of symmetrical components with the various sequennce networks.

The network analyser operates at a frequency of 480 cycles per second and has a nominal or base voltage of 50 V and a nominal or base current of 50 M.A. Consequently, the base power is 2.5 watts and base impedance is 1,000 ohms. All adjusting dials and instrument scales are marked in per unit of the base quantities. The 480 cycle power for the analyser is obtained from a separate motor-generator set.

Each generator unit consists of two machines – a phase shifter and a voltage regulator. The phase shifter has a three-phase stator and a single phase rotor for phase angle control. The voltage regulator has a two-phase stator and a single phase rotor for voltage control. The three phase stator of the phase shifter normally receives 220 V., 480 cps power from the M-G set through an auto-transformer. The rotor output voltage is applied to one quarter-phase stator winding of the voltage regulator. By turning the single phase rotor of this machine the voltage may be varied smoothly from zero to a maximum of 2.5 per unit volts (125 V) at essentially constant phase angle. The phase angle adjustment provides stepless control over a total range of 360 electrical degrees. In studies of normal power system operation, the voltage magnitude adjustment simulates adjustment of the

TABLE - I. NUMBER & RANGE OF CIRCUIT UNITS.

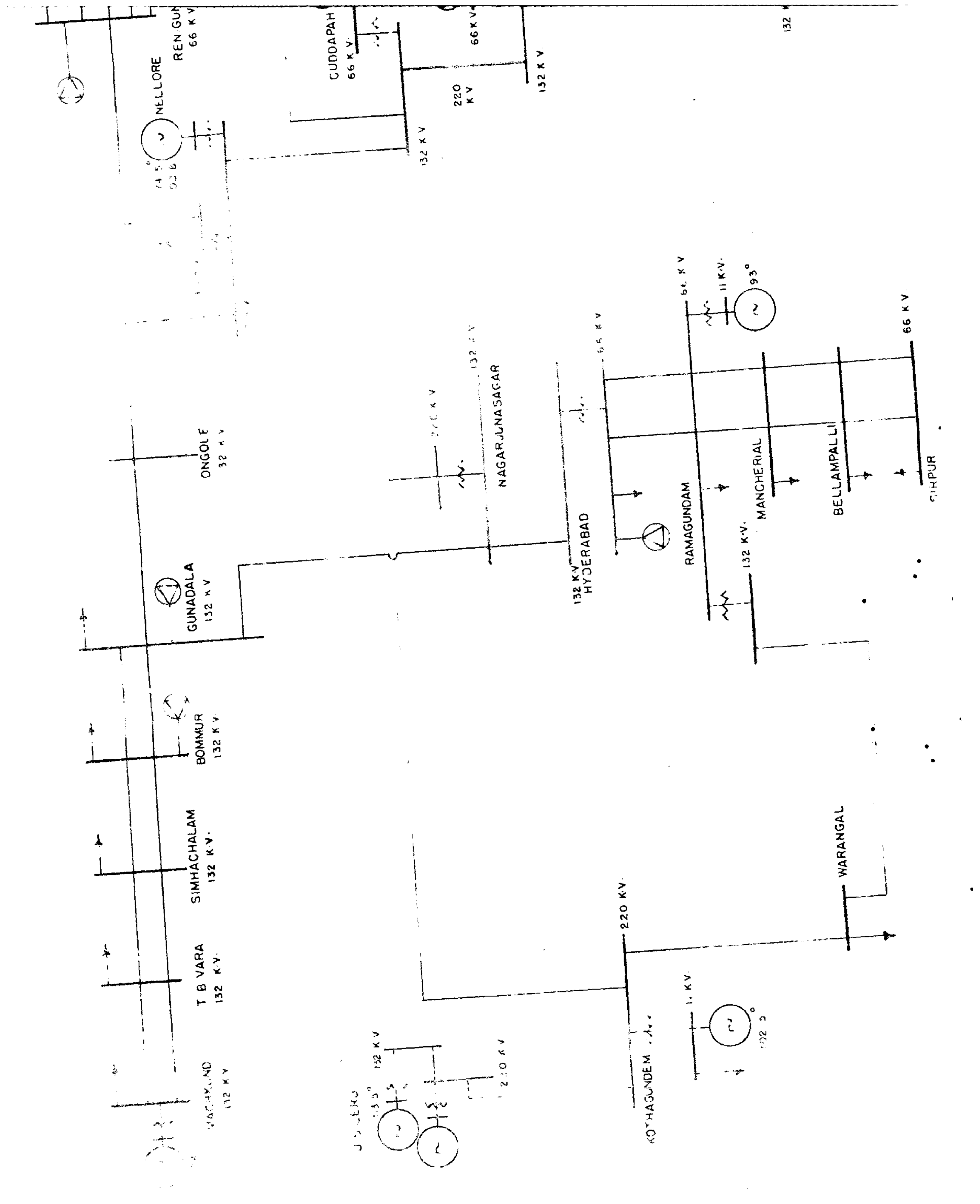
Type of unit.	Total No.	Numbers assigned to units.	Per unit range.	Steps.	Rating P.U.Volts.	 P.U.amps.
Generator units.	16	G 1 to G 16	V 0-2.5 $\phi 0 \pm 180^\circ$	Continuous	2.5	10.0
Synchronous impedance (Series R +jX)	16	1 to 16	R 0-0.11 X 0-1.11	0.001 0.001	1.25	5.0
Line units (Series R + jX)	76	100-175	R 0-0.51 X 0-0.81	0.001 0.001	1.25	5.0
Pi-Line units.	24	201,203..,247	R 0-0.51 X 0-0.81	0.001 0.001	1.25	5.0
Capacitor units (Susceptance)	48	300-347	0-1.1	0.01	1.25	
Load units (Series or parallel R+jX)	50	400-449	R 0-16.1 X 0-16.1	Continuous 0.01	1.25	5.0
Load units auto-Trans.	50	400-449	V 0- ± 15%	1%	1.25	5.0
Auto-Transformer units.	32	50-81	V 0- ± 30.5%	0.5%	1.25	5.0
Mutual Trans.units,	8	M 1- M8	1:1 Ratio		1.25	5.0
Metered jumpers	60	500-559				
Unmetered Jumpers	30	J 1- J 30				
Plug and Jack cabinets	3					
Instrument cabinet	1					

excitation of the represented machine and the phase adjustment corresponds to the adjustment of the governor of the prime mover.

Table No.1 gives details of the number and range of circuit units available at the A.C. network analyser installed at the Indian Institute of Science, Bangalore.

Transient stability studies are made for the purpose of determining the ability of a system to maintain synchronism following a disturbance such as short circuit. The problems are solved on the analyser by the step by step method involving representation of successive conditions. For each generator the angular changes from the normal synchronous positions are calculated by using the generator acceleration constant and the analyser readings giving the power before and after the disturbance. Whether the system stays in synchronism is determined from the swing curve i.e., the curve of angular position of the various machines plotted against time.

In using the analyser for swing curve calculations the same general principles are follwed as in making them with entirely by long hand methods. To simplify the work without much sacrificing the


REN GUN
66 K V
NELLORE
CUDDAPAH
66 K V
66 K V
220 K V
132 K V
132 K V
132
ONGOLE
132 K V
NAGARJUNASAGAR
132 K V
HYDERABAD
132 K V
66 K V
RAMAGUNDAM
132 K V
66 K V
11 K V
93°
MANCHERIAL
BELLAMPALLI
66 K V
SIRPUR
GUNADALA
132 K V
BOMMUR
132 K V
SIMHACHALAM
132 K V
T B VARA
132 K V
132 K V
WARANGAL
220 K V
KOTHAGUDEM
11 K V
132 K V
220 K V

SCHEDULE OF MACHINE CONSTANTS. (Transient Stability Studies)

KVA Base. 50,000

Station.	Make.	Capacity of each machine MVA	No. of Gen: sets.	R.P.M.	P.F.	Percentage Transient Reactance.			Moment of inertia lbs.Ft^2 x 1000 per machine.	Inertia Constant.		
						To Machine base per machine.	To common base per machine.	For all the machines in the Gen: station on common base.		To Machine base per machine	To common base per machine.	For all the machines in the Gen: station on common base.
A. Hydro-Electric Generating Station.												
Machkund I	Westinghouse	20.0	3	600	0.85	20.6	51.5	0.075	924	-	1.528	9.96
Machkund II	B.B.C	25.0	3	600	0.85	20.0	40.0		1077	-	1.792	
Upper Sileru	-	66.7	2	187.5	0.90	23.0	17.3	0.086	-	300	4.00	8.00
Tungabhadra I	B.B.C.	10.6	4	214.3	0.85	22.0	104.0	0.119	3540	-	0.752	4.88
Tungabhadra II	-	10.6	4	214.3	0.85	18.7	88.0			3.0		
B. Thermal Power Stations.												
Kothagudem	-	82.0	1	3000.0	0.80	19.0	11.6	0.116		4.0		6.55
Ramagundam	Metropolitan Vickers.	15.62	3	3000.0	0.80	21.0	67.2	0.224	23.8		0.996	2.97
Nellore	-	30.0 (MW)	1	3000.0	0.90	17.8	25.4	0.254			3.00	3.00

accuracy, the following assumptions are made:

(1) Synchronous-machine transient reactance in the direct and quadrature axis are assumed to be alike.

(2) Voltages behind transient reactance of the synchronous machines are assumed to remain constant during the first swing.

(3) Damping torques are neglected.

(4) Influence of saturation is neglected.

(5) Constant shaft torques are assumed for all of the machine groups, the governor-action and load-speed characteristics are neglected.

(6) Results are based on the first swing of the machine with the longest period.

(7) The changes in machine speeds are assumed to be negligible to the extent that per unit power and per unit torque are used interchangeably.

3.1.1 The grid map of the Andhra Pradesh power system on which transient stability studies were carried out is given here. The detailed data also for the Andhra Pradesh Power system regarding transformers, vast network of transmission lines with Positive and zero sequence impedances is given in the Appendix. The line constants have been calculated from the data available in the Westinghouse Electrical Transmission and Distribution reference book. The direct and quadrative axis reactance have been assumed equal for these studies on the analyser.

2. There are three major Hydro-electric generating stations and three thermal power stations included in the transient stability studies. The details of the machine constants and the total installed capacity at each power station for 1964 load conditions is given herewith. Transient reactances and inertia constants have been calculated at 50 MVA base, the figure adopted throughout these studies. The equivalent circuit for each sequence are set up as viewed from the fault by imagining currents of the particular sequence to be circulated through the network from the fault.

3.1.2 Unbalanced faults.

By using symmetrical component methods to determine the proper fault impedance, swing curves may be obtained for unbalanced as well as for balanced fault conditions. The procedure is the same as in both cases, except that for unbalanced faults, instead of grounding the point of fault directly as for a three phase short circuit, a line unit representing the required fault impedance is connected between the point of fault and ground. The proper setting for fault impedance usually can be determined by measurement. Since positive and negative impedances are nearly the same, it is sufficiently accurate to assume that they are identical, in which case negative sequence impedance can be determined by the equivalent positive sequence impedance of the network viewed from the point of fault.

Type of fault.	Shunt impedance of fault.
1. Single line to ground.	$Z_2 + Z_o$
2. Line to line	Z_2
3. Two line to ground.	$\frac{Z_2 \cdot Z_o}{Z_2 + Z_o}$
4. 3 Ph. fault	0

If the network in question is a positive sequence network, all machine reactances are temporarily grounded by connecting them to the ground terminals of their respective generator. With any convenient generator unit used as a power source, a voltage is applied at the point of fault. For safety of the instrument it is advisable to start with a low voltage which may be increased until sufficient deflections are obtained on both the voltmeter and the ammeter to give accurate results. The vector component of this voltage and of the resulting current are recorded from which the equivalent impedance of the network viewed from the fault can be determined by simple vector division.

The equivalent Z_o of the network can be viewed from the point of fault in a similar manner by setting the zero sequence network on the analyser. The zero sequence network diagram for power system is attached herewith. Calculations have been made on 50 MVA base.

In case where single pole breakers are used only the faulty phases are cleared and reclosed. The effect of unsymmetrical open circuit (in single phase to line fault only faulty phase is isolated and the other two healthy phases supply power and in double line to ground fault one healthy phase supplies power to the system) in such cases can be represented by a series impedance Z_f, where Z_f is equal to:-

(i) $\frac{Z_o Z_2}{Z_o + Z_2}$ in case of one conductor open

(ii) $Z_o + Z_2$ in case of two conductors open

(iii) ∞ In case of three conductors open.

In the cases studied, for double line to ground fault

(a)(Case No.1) shunt impedence

$$\frac{Z_0 Z_2}{Z_0+Z_2} = j\,0.019$$

where $Z_0 = .001 + j0.029$

$Z_2 = 0.008 + j.056$

Series impedence after fault is cleared is

$Z_2 + Z_0 + .3Z$ line $= .06 + j.0.392$

where $Z_2 = 0.021 + j.147$

$Z_0 = .0087 + j.062$

Z line $= .01 + j0.061$

(b) for single line to ground fault (Case No.2)

shunt impedance $Z_2 + Z_0 = .009 + j0.085$

where $Z_0 = .001 + j0.029$

$Z1 = Z_2 = .008 + j0.056$

and series impedance after fault is cleared $= .01 + j\,0.138$

~~[illegible]~~

~~[illegible]~~

Acc. 62503
CENTRAL LIBRARY UNIVERSITY OF ROORKEE
ROORKEE.

Z line = 0.01 + j.061

$Z_2 = Z_1 = 0.021 + j\,0.147$

Z_0 + .008 + Jo.0623

Z_2 + Z Line = .031 + J.208

Z_0 + Z Line = .018 + Jo.123

3.2 Plotting of Swing Curves.

3.2.1 Fault on.

With the voltages behind transient reactance held constant, the fault is applied to the system and measurements of power behind transient reactances for all the machine group are made. In per unit, these values represent the load torque on the machine, rotors. With the torque input Ti, and the load torque To known, the accelerating torque on each rotor Ta = Ti - To, can be determined. The accelerating torque will cause a change in the rotor position angle δ which is measured with respect to axis that rotate at constant speed in synchronism with the frequency of the system before fault.

After the change in position angle $\Delta\delta$ caused by the accelerating torque Ta has been calculated, the new value of δ is determined for each machine group. The phase angle adjusting dials of the analyser generator units are then changed to the new values of rotor position angles just determined; values of torque output To , are again measured, and the process described above is repeated until a complete swing-curve has been obtained.

At each step of the swing-curve, the quantity, Ti-To is recorded in the column of the calculation sheet headed Ta. The product KTa is recorded in the next column to the right, but one space lower on the sheet. The one exception to this is in the calculation of the first step at which time an additional multiplier of ½ is used and the product ½ KTa is recorded. During any interval, the change in angle, $\Delta\delta$ is found by adding the new value of KTa to the last proceding value of $\Delta\delta$; and each new value of is found by adding the new value of $\Delta\delta$ to the last preceding value of δ . In the calculation for the first interval, $\Delta\delta$ and ½ KTa are equal because there is no initial velocity.

3.2.2 After Fault is cleared.

When the fault is cleared completely by opening all circuit breakers feeding in fault, the procedure is the same as followed above except at the time interval immediately following the change in circuit conditions. The power outputs of all the machines are read before and after tripping. The output torque is calculated for both conditions and then averaged, the average value being used in determining the accelerating torque. The calculation are continued in the normal manner until another change occurs such as reclosing or/until swing curve has been carried far enough to determine whether the group of machines will remain in synchronism or go out of step.

The shape of the curve for the fastest moving machine can usually be determined with sufficient accuracy by using time interval of 0.05 sec. This time interval has been followed in the calculations all through.

Case No.1.

The first case studied is double line to ground fault on 220 KV Sileru-Kothagundam line at Sileru end. (calculations for fault impedance have already been shown). The fault is cleared after the 0.1 seconds, clearing only the faulty lines, and the breaker reclosed 0.4 seconds after the occurances of the fault. It would be seen from the swing curves (*) plotted that Upper Sileru is affected the maximum.

page 45(i)

The machine at U.Sileru is accelerating even after the fault is cleared. The other machines are affected the least. No readings were taken after 0.20 seconds of the fault, as the reading taken upto 0.2 seconds were sufficient to show that the system is unstable. The power angle between upper Sileru and Thungabadhra being 93° at that instant.

Case No.2.

Next case studied is the single line to ground fault on 220 KV Sileru-Kothagudam line at Sileru end. (Calculation of fault impedance is shown on page 40). The fault is cleared after 0.10 seconds and the line reclosed after 0.4 seconds. The system *page 45(iii) is stable as shown, from the curves.* The maximum power angle between the leading machine at U. Sileru and the lagging machine at Tungabhadra is about 78°.

Case No.3.

Studies were made for the most severe fault on the power system i.e. 3 phase fault with fault on one 132 KV line between T.B.Vara and Machkund. (In case of three phase fault, the shunt impedance of fault is zero. Impedance of other parallel circuit is changed from 0.019 + j.o. 056 to 0.038 + j o.112) Fault clearing time is 0.1 sec. with no reclosing.

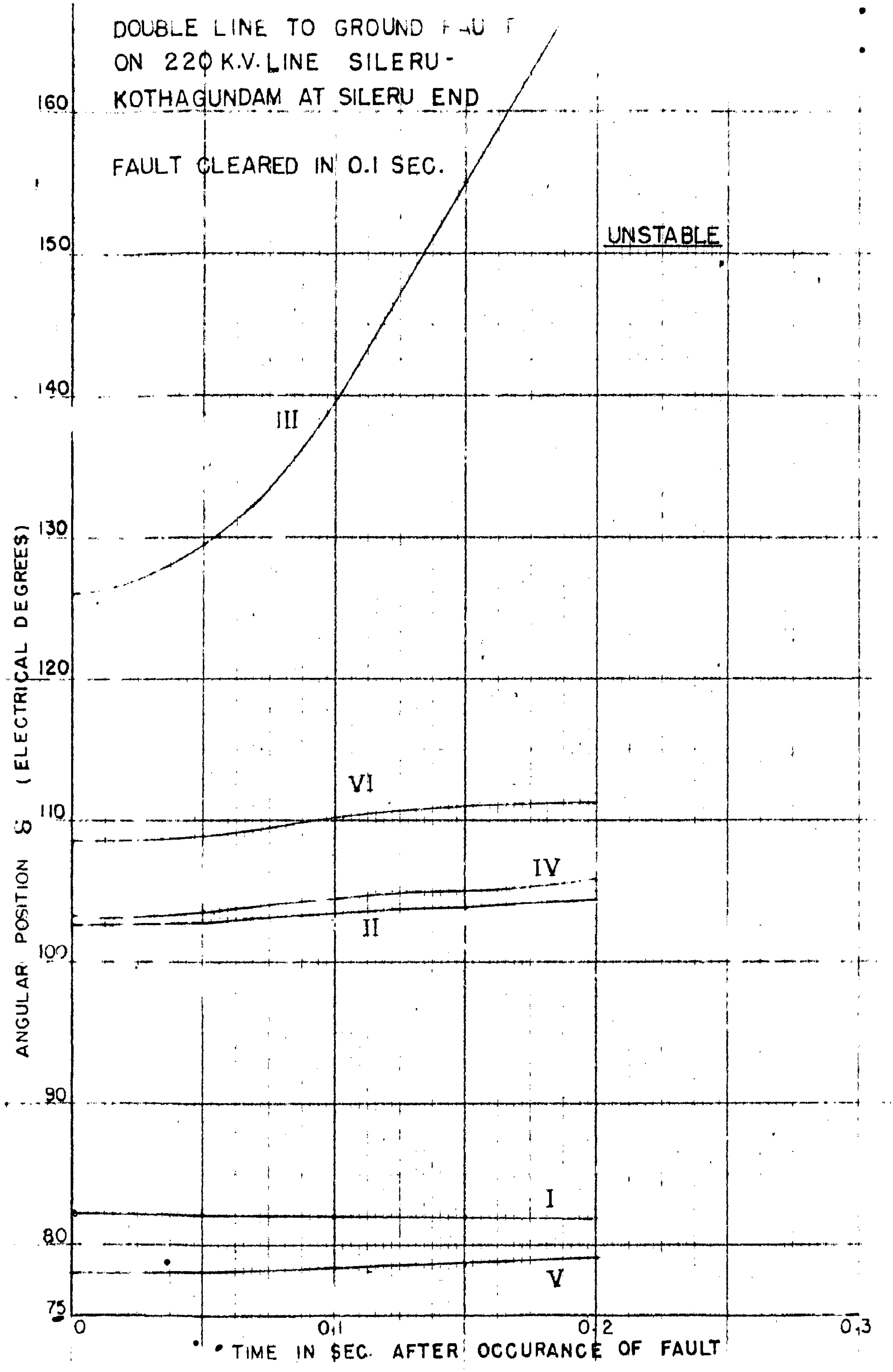
page 45(iv) It can be seen from the swing curves for different machines that all the machines are affected appreciably and the system tries to take up the fault as a whole. However, machine No.4 (i.e. Machkund) the nearest to the fault starts leading. The system is stable as shown by the curves.

Case No.4.

A very interesting case with the same 3 phase fault on one 132 KV line between T.B.Vara and Machkund was studied but with the fault clearance time of 0.2 seconds instead of 0.1 seconds as in case No.3. It will be seen that machine No.4 (@) i.e. machine at Machkund starts accelerating rapidly. The other machines do not see to the fault much. The angular difference between the machines at 0.35 seconds after the fault is about 113°. The machine is still swinging out of step further. The system is unstable. This emphasises the importance of putting very fast circuit breakers.

(@) swing curves on page 45(vi)

Transient stability limit of a system can be greatly increased by decreasing the time of fault clearing as has been shown in cases 3 & 4 above. The time of fault clearing is the sum of the time that the protective relay takes to close the circuit breaker


DOUBLE LINE TO GROUND FAULT
ON 220 K.V. LINE SILERU-
KOTHAGUNDAM AT SILERU END
FAULT CLEARED IN 0.1 SEC.
UNSTABLE
III
VI
IV
II
I
V
160
150
140
130
120
110
100
90
80
75
ANGULAR POSITION δ (ELECTRICAL DEGREES)
0
0.1
0.2
0.3
TIME IN SEC AFTER OCCURANCE OF FAULT

Double line to Ground fault on 220 KV Sileru-Kothagundam Line at Sileru end (Fault cleared in 0.1 sec: Line reclosed in 0.40 sec:)

RESULTS ON THE STEP-BY-STEP SWING CURVE CALCULATIONS.

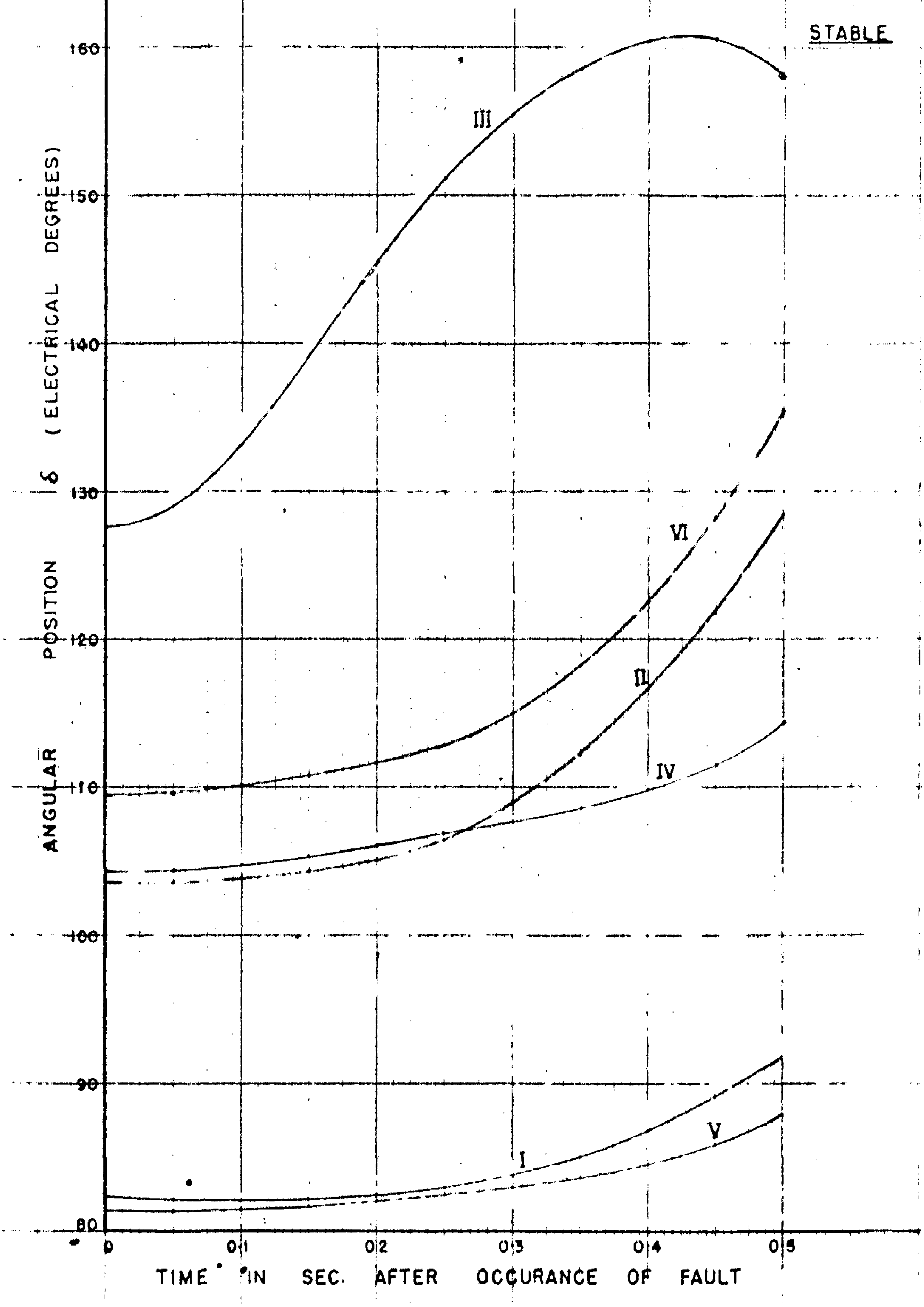
Time in seconds.	Angular displacement in degrees.					
	Gen.1	Gen.2	Gen.3	Gen.4	Gen.5	Gen.6
0	82.3	102.7	126.2	103.3	78.3	108.5
0.05	82.2	102.8	129.6	103.5	78.3	108.9
0.10	82.1	103.5	139.9	104.2	78.5	110.2
0.15	81.9	104.1	155.1	105.0	78.8	111.1
0.20	81.8	104.4	172.1	105.8	79.1	111.2

.... Unstable ......

t = 0.05 seconds.   KVA Base 50,000

	Gen.1	Gen.2	Gen.3	Gen.4	Gen.5	Gen.6
Power Input to Rotor	0.57	0.76	2.44	2.28	1.60	1.26
Inertia constant H	3.00	2.97	8.00	9.96	4.88	6.55
Accln: constant k	7.5	7.58	2.82	2.26	4.60	3.44
Initial angle in degrees. (before fault)	82.3	102.70	126.20	103.30	78.30	108.50

SINGLE LINE TO GROUND FAULT ON 220 KV LINE - SILERU KOTHAGUNDEM LINE AT SILERU END.
FAULT CLEARED IN 0·1 SEC.



SINGLE LINE TO GROUND FAULT ON 220 KV SILERU-KOTHAGUDAM LINE AT SILERU END.

Gen.No.1 (NELLORE)

Indian Institute of Science- A.C. Network Analyzer.

Andhra Pradesh Power System.

STEP-BY-STEP SWING CURVE CALCULATION.

Date: 22.9.1960
KVA Base. 50,000

Inertia constant $H = \frac{(0.231)(WR)^2\,(RPM)^2\,(10)^{-6}}{\text{Base Kva}} = 3.00$

Acceleration constant $k = \frac{180\, f\, (\Delta t)^2}{H} = 7.5$ $\Delta t = 0.05$ sec.

Condition.	Time in Sec. t	Voltage Behind X'd E in P.U.	Initial angle in degrees. δ	Power Input to Rotor						
				Reading.	Mult:	T_1 in 0/1				
Before fault	0-		82.3	0.49	1	0.49				
				Power Out to System.			Acceler Torque $T_a = T_1 - T_o$	kT_a	$\Delta\delta_n = \Delta\delta_{n-1} + kT_a$	Angular Displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
				Reading.	Mult:	T_o in 0/1				
	0+			0.077	6.4	0.493	-0.003 X½	-	-	82.3
	0.05			0.077	6.4	0.493	-0.003	-0.011	-0.011	82.3
	0.10			0.074	6.4	0.474		-0.0225	-0.033	82.27
Fault cleared				Average		0.482	0.008			
	0.10			0.49	1	0.490				
	0.15			0.465	1	0.465	0.02	0.06	0.027	82.3
	0.20			0.45	1	0.45	0.04	0.15	0.15	82.5
	0.25			0.45	1	0.45	0.04	0.30	0.48	83.0
	0.30			0.425	1	0.425	0.065	0.41	0.89	83.8
	0.35			0.425	1	0.425	0.065	0.41	1.30	85.1
	0.40-			0.42	1	0.42	0.070	0.51	1.81	86.9
Line Reclosed				Average		0.41				
	0.40 +				1	0.39	0.08			
	0.45			0.40	1	0.40	0.09	0.60	2.36	89.3
	0.50							0.675	3.04	92.0

Gen.No.2 (RAMAGUNDAM)

Date: 22.9.1960
KVA Base. 50,000

Andhra Pradesh Power Systems.

STEP-BY-STEP SWING CURVE CALCULATION.

Inertia constant $H = \frac{(0.231)(WR)^2(RPM)^2(10)^{-6}}{\text{Base Kva.}} = 2.97$

Acceleration constant $k = \frac{180\,f\,(\Delta t)^2}{H} = 7.58$ $\Delta t = 0.05$ sec.

Condition.	Time in Sec t	Voltage Behind X'd E in P.U.	Initial angle in degrees. δ	Power Input to Rotor		
				Reading.	Mult:	T_1 in 0/1
Before fault	0-		103.7	0.725	1	0.725

		Power Out to System			Accelerated Torque $T_a = T_1 - T_o$	kT_a	$\Delta\delta_n = \Delta\delta_{n-1} + kT_a$	Angular displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
		Reading.	Mult:	T_o in 0/1				
	0+	0.112	6.4	0.716	0.009 X			103.7
	0.05	0.110	6.4	0.703	0.022	0.034	0.0341	103.7
	0.10	0.130	6.4	0.66		0.167	0.2	103.9
Fault cleared		Average		0.70				
	0.10+	0.74	1	0.74	0.025			
	0.15	0.68	1	0.68	0.045	0.190	0.4	104.3
	0.20	0.629	1	0.629	0.096	0.34	0.74	105.0
	0.25	0.61	1	0.61	0.115	0.73	1.47	106.5
	0.30	0.585	1	0.585	0.140	0.87	2.34	108.8
	0.35	0.61	1	0.61	0.115	1.06	3.4	112.2
	0.40	0.655	1	0.655		0.87	4.27	116.5
Line Reclosed		Average		0.583	0.142			
	0.40	0.51	1	0.51				
	0.45	0.575	1	0.575	0.150	1.08	5.35	121.9
	0.50					1.14	6.49	128.4

Gen.No.3 (UPPER SILERU)

Date. 22.9.1960
KVA Base. 50,000

Andhra Pradesh Power System.

STEP-BY-STEP SWING CURVE CALCULATION.

Condition,	Time in Sec. t.	Voltage Behind X'd E in P.U.	Initial angle in degrees. δ	Power Input to Rotor		
				Reading.	Mult:	T_1 in 0/1
Before fault	0-		127.4	2.40	1	2.40

Inertia constant $H = \frac{(0.231)\ (WR)^2\ (RPM)^2\ (10)^{-6}}{\text{Base Kva}} = 8.00$

Acceleration constant $k = \frac{180\ f\ (\ \Delta t)^2}{H} = 2.82 \quad \Delta t = 0.05$ sec.

Condition	Time in Sec. t.	Power Out to System			Acceler Torque $T_a = T_1 - T_o$	kT_a	$\Delta\delta_n = \Delta\delta_{n-1} + kT_a$	Angular displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
		Reading.	Mult:	T_o in 0/1				
	0 +	0.212	6.4	1.35	1.05 X½			127.4
	0.05	0.220	6.4	1.41	0.95	1.48	1.48	128.9
	0.10	0.235	6.4	1.50		2.80	4.28	133.2
Fault cleared		Average		1.81				
	0.10	2.11	1	2.11	0.59			
	0.15	2.35	1	2.35	0.05	1.67	5.95	139.2
	0.20	2.59	1	2.59	-0.19	0.14	6.09	145.3
	0.25	2.80	1	2.80	-0.40	-0.535	5.55	150.9
	0.30	2.80	1	2.80	-0.40	-1.128	4.42	155.3
	0.35	2.85	1	2.85	-0.45	-1.128	3.29	158.6
	0.40	2.80	1	2.80		-1.127	2.02	160.6
Line Reclosed		Average		3.13	-0.73			
	0.40	3.45	1	3.45				
	0.45	3.25	1	3.25	-0.85	-2.06	-0.04	160.6
	0.50		1			-2.40	-2.44	158.2

Gen.No.4 (MACHKUND)

Date. 22.9.1960
KVA Base. 50,000

Andhra Pradesh Power System.

STEP-BY-STEP SWING CURVE CALCULATION.

Condition	Time-in Sec. t.	Voltage Behind X'd E in P.U.	Initial angle in degrees. δ	Power Input to Rotor Reading.	Mult.	T_1 in 0/1
Before fault	0–		104.3	2.24	1	2.24

Inertial constant $H = \frac{(0.231)\,(WR)^2\,(RPM)^2\,(10)^{-6}}{\text{Base Kva}} = 9.96$

Acceleration constant $k = \frac{180\,f\,(\Delta t)^2}{H} = 2.26$ $\Delta t = 0.05$ sec.

Condition	Time-in Sec. t.	Power Out to System Reading.	Mult:	T_o in o/1	Acceler Torque $T_a = T_1 - T_o$	k Ta	$\Delta\delta_n = \Delta\delta_{n-1} + kT_a$	Angular displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
	0+	0.33	6.4	2.12	0.12 X½			104.3
	0.05	0.33	6.4	2.12	0.12	0.136	0.136	104.4
	0.10	0.325	6.4	2.08		0.27	0.406	104.8
Fault cleared		Average		2.165	0.07			
	0.10+	2.25	1	2.25				
	0.15	2.23	1	2.23	0.01	0.16	0.566	105.4
	0.20	2.21	1	2.21	0.03	0.02	0.586	106.0
	0.25	2.21	1	2.21	0.03	0.067	0.653	106.7
	0.30	2.10	1	2.10	0.14	0.067	0.720	107.4
	0.35	2.10	1	2.10	0.14	0.316	1.036	108.4
	0.40	2.06	1	2.06		0.316	1.352	109.8
Line Reclosed		Average		2.00				
	0.40			1.95	0.24			
	0.45	1.90	1	1.90	0.34	0.533	1.885	111.7
	0.50					0.77	2.665	114.4

Gen.No.5 (TUNGABHADRA)

Date: 22-9-1960
KVA Base: 50,000

Andhra Pradesh Power System.

STEP-BY-STEP SWING CURVE CALCULATION.

Condition	Time in Sec. t	Voltage Behind X'd E in P.U.	Initial Angle in Degrees. δ_0	Power Input to Rotor: Reading.	Mult.	T_1 in 0/1
Before fault.	0-		81.3	1.16	1.	1.16

Inertia constant $H = \frac{(0.211)\,(WR)^2\,(RPM)^2\,(10)^{-6}}{\text{Base Kva.}} = 4.88$

Acceleration constant $k = \frac{180\,f\,(\Delta t)^2}{H} = 4.6 \quad \Delta t = 0.05$ sec.

	Power Out to System. Reading	Mult.	T_0 in 0/1	Acceler Torque $T_a = T_1 - T_0$	kT_a	$\Delta\delta_n = \Delta\delta_{n-1} + kT$	Angular displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
0+	0.176	6.4	1.125	0.035 X½	-	-	81.3
0.05	0.176	6.4	1.125	0.035	0.08	0.08	81.4
0.10	0.176	6.4	1.125		0.16	0.24	81.6
Fault cleared	Average		1.142	0.018			
0.1	1.16	1	1.16				
0.15	1.15	1	1.15	0.01	0.0825	0.32	81.9
0.20	1.155	1	1.155	0.005	0.46	0.366	82.3
0.25	1.17	1	1.17	-0.01	0.023	0.389	82.7
0.30	1.11	1	1.11	0.05	-0.05	0.34	83.0
0.35	1.10	1	1.10	0.06	0.23	0.57	83.6
0.40	1.09	1	1.09		0.276	0.85	84.5
Line Reclosed.	Average		1.065	0.095			
0.40		1	1.04				
0.45	1.02	1	1.02	0.14	0.436	1.29	85.8
0.50					0.644	1.93	87.7

Gen.No.6 (KOTHAGUDAM)

Date: 22-9-1960
KVA Base. 50,000

Andhra Pradesh Power System.
STEP-BY-STEP SWING CURVE CALCULATION

Inertia constant $H = \frac{(0.231)\,(WR)^2\,(RPM)^2\,(10)^{-6}}{\text{Base Kva}} = 6.55$

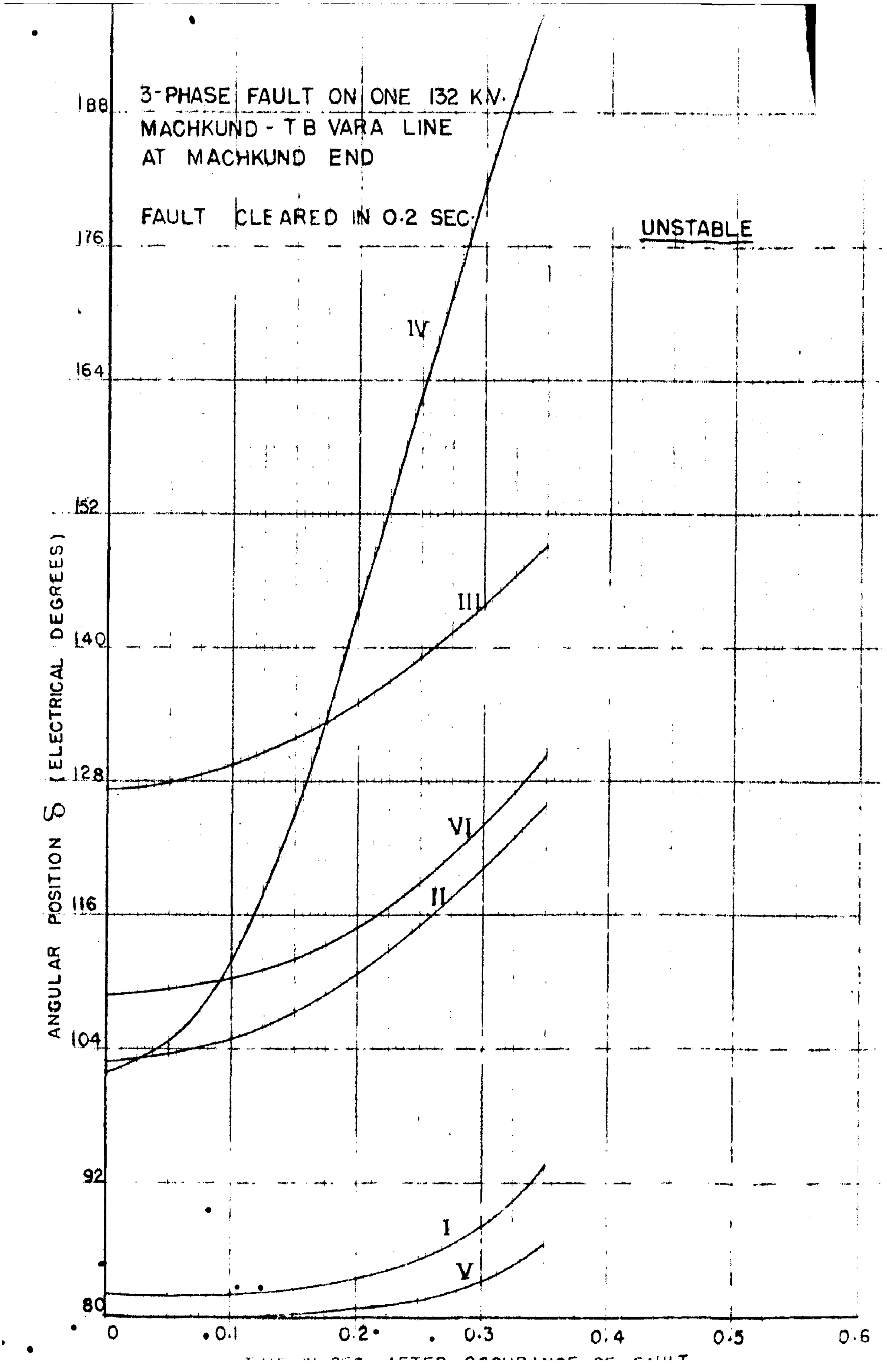
Acceleration constant $k = \frac{180\,f\,(\Delta t)^2}{H} = 3.44$ $\Delta t = 0.05$ sec.

Condition	Time in Sec. t	Voltage Behind X'd E in P.U.	Initial angle in degrees δ	Power Input to Rotor Reading	Mult:	T_1 in 0/1
Before fault	0-		109.6	1.25	1	1.25

Condition	Time in Sec. t	Power Out to System Reading.	Mult.	T_e in 0/1	Acceler Torque $T_a = T_1 - T_e$	kT_a	$\Delta\delta_n = \Delta\delta_{n-1} + kT_a$	Angular displacement in degrees. $\delta_n = \Delta\delta_n + \delta_{n-1}$
	0+	0.183	6.4	1.172	0.078 [illegible]	-	-	109.6
	0.05	0.180	6.4	1.152	0.098	0.14	0.14	109.7
	0.10	0.165	6.4	1.06		0.34	0.48	110.2
Fault cleared		Average		1.21	0.04			
	0.1	1.35	1	1.35				
	0.15	1.17	1	1.17	0.08	0.14	0.62	110.8
	0.20	1.18	1	1.18	0.07	0.28	0.90	111.7
	0.25	0.97	1	0.97	0.28	0.24	1.14	112.8
	0.30	0.90	1	0.90	0.35	0.96	2.10	114.9
	0.35	0.935	1	0.935	0. 315	1.20	3.30	118.2
	0.40	1.04	1	1.04		1.07	4.37	122.6
Line Reclosed		Average		0.86	0.39			
	0.40	0.68	1	0.68				
	0.45	0.86	1	0.86	0.39	1.34	5.71	128.3
	0.50					1.34	7.05	135.4

Shunt impedance loads. KVA Base. 50,000

Location.	Desired KW+jKVA in P.U.	P.F.	Series or parallel	Setting R+jX in P.U.
Sirpur	10 + j 6.25	0.85	P	5.0 + j 8.00
Bellampalli	4.0 + j 2.50	0.85	S	9.05+ j 5.65
Mancherial	6.0 + j 3.72	0.85	P	8.33 +j 13.40
Ramagundam	10.0 + j 6.25	0.85	P	5.0 + j 8.00
Hyd'bad 66Kv	63.0 + j 31.2	0.85	P	0.79 +j 1.27
Machkund	12.0 + j 0	1.00	S	4.17 +j 0
T.B.Vara	40.0 + j 19.4	0.90	P	1.25 + j 2.52
Simha'lm.	16.0 + j 10.0	0.85	P	3.13 + j 5.0
Bommur	30.0 + j 3.07		P	1.67 + j 13.4
Tungabhadra	14.0 + j.10.5	0.80	P	3.57 + j.4.77
Bellary	5.5 + j.3.43	0.85	P	9.10 + j 14.6
Adoni	4.0 + j 2.5	0.85	S	9.05 + j 5.7
Kurnool	3.0 + j 1.87	0.85	S	12.10+ j 7.55
Dhone	5.55+ j 3.43	0.85	P	9.10 + j 14.6
Anantapur	2.5 + j 1.56	0.85	S	14.5 + j 9.10
Dharma'vrm	5.5 + j 3.43	0.85	P	9.10 + j 14.6
Gooty	4.0 + j 2.5	0.85	S	9.05 + j 5.65
Gunadala	45 + j 13.0		P	1.11 + j 3.85
Nellore	14 + j 8.75	0.85	P	3.57 + j 5.72
Renigunta	5.0 + j 3.12	0.85	S	7.25 + j 4.53
Pakala	6.0 + j 3.72	0.85	P	8.33 + j 13.4
Chittor	7.5 + j 0	1.00	S	6.69 + j 0
Cuddappah	6.0 + j 3.72	0.85	P	8.33 +j13.4
Kalikiri	7.5 + j 4.70	0.85	P	6.7 + j 11.0


3-PHASE FAULT ON ONE 132 KV.
MACHKUND - T B VARA LINE
AT MACHKUND END
FAULT CLEARED IN 0·2 SEC.
UNSTABLE
ANGULAR POSITION δ (ELECTRICAL DEGREES)
188
176
164
152
140
128
116
104
92
80
0
0·1
0·2
0·3
0·4
0·5
0·6
I
II
III
IV
V
VI

3 Phase fault on one 132 KV Machkund-T.B.Vara Line at Machkund End (Fault cleared in 0.2 sec)

RESULTS OF THE STEP-BY-STEP SWING CURVE CALCULATIONS.

Time in seconds.	Angular displacement in degrees.					
	Gen.1	Gen.2	Gen.3	Gen.4	Gen.5	Gen.6
0	82.1	103.1	127.5	102.0	80.2	108.9
0.05	82.0	103.5	128.0	104.6	80.2	109.2
0.10	82.2	105.0	129.5	112.3	80.2	110.3
0.15	82.6	107.5	131.9	125.1	80.4	112.1
0.20	83.4	111.0	135.2	143.0	80.8	114.9
0.25	85.5	115.0	139.2	162.9	81.6	118.8
0.30	88.1	120.0	143.7	181.5	83.4	124.0
0.35	93.5	126.0	149.1	198.7	86.2	130.7

—— Unstable ——

Power Input to Rotor	0.56	0.76	2.48	2.25	1.175	1.26
Inertia constant H	3.0	2.97	8.00	9.96	4.88	6.55
Accelera-tion con-stant= k	7.5	7.58	2.85	2.26	4.60	3.44
Initial angle in degrees. (before fault.)	82.1	103.1	127.5	102.0	80.2	108.9

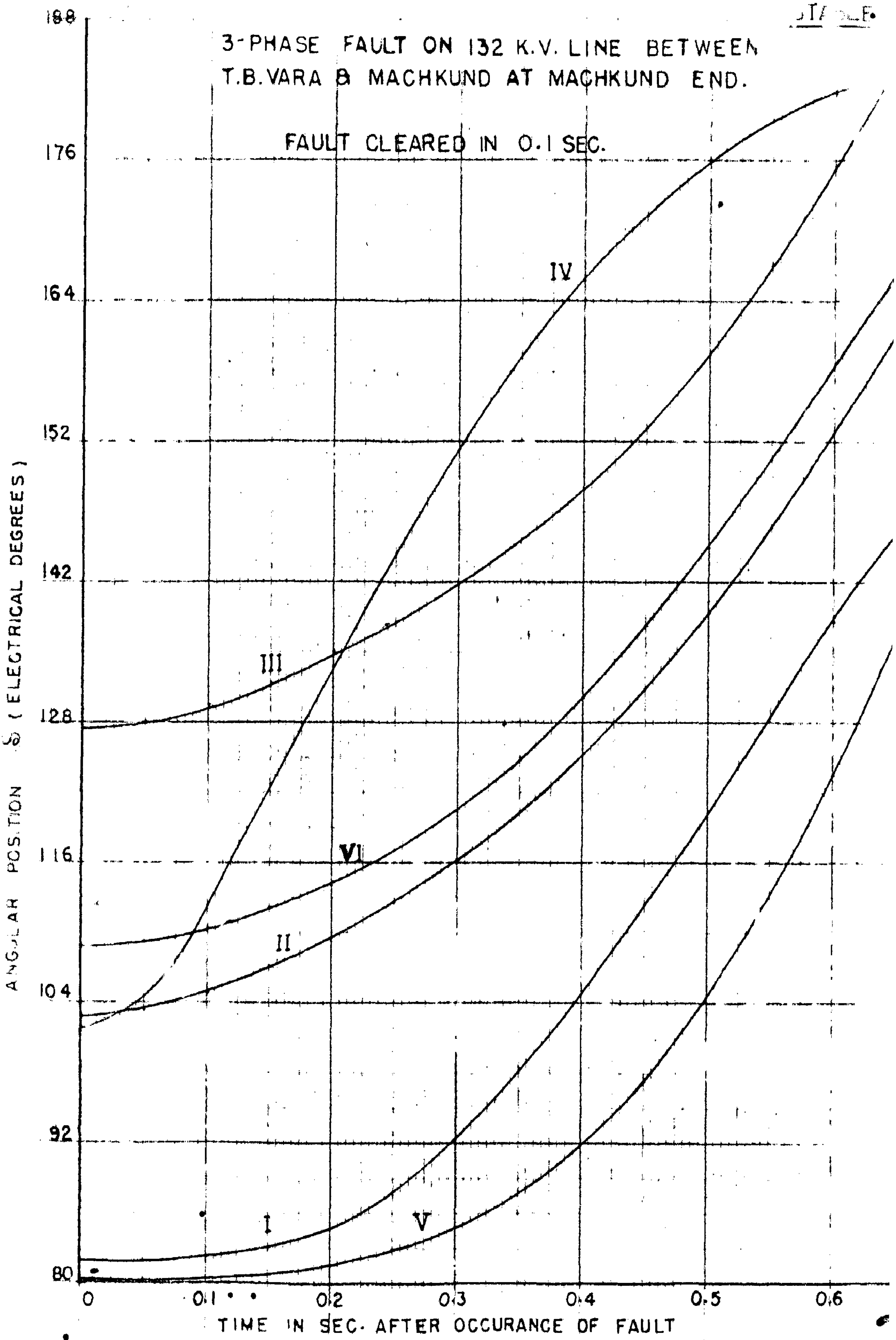
3- Phase fault on one 132 KV Machkund-T.B.Vara Line at Machkund end (Fault cleared in 0.1 sec.)

RESULTS ON THE STEP-BY-STEP SWING CURVE CALCULATIONS.

t = 0.05 sec. KVA Base 50,000

Time in sec:	Angular displacement in degrees.					
	Gen.1.	Gen.2	Gen. 3	Gen. 4	Gen.5	Gen.6
0	82.1	103.1	127.5	102.0	80.2	108.9
0.05	82.0	103.5	128.0	104.6	80.2	109.2
0.10	82.3	105.0	129.5	112.3	80.4	110.4
0.15	83.0	107.2	131.6	122.6	80.8	112.1
0.20	84.8	109.7	134.0	132.8	81.6	114.2
0.25	87.9	112.7	136.7	142.5	82.9	116.9
0.30	92.4	116.2	139.8	151.3	84.9	120.4
0.35	98.2	120.3	143.4	159.1	87.9	124.8
0.40	105.0	125.1	147.8	165.8	92.1	130.1
0.45	112.5	130.8	153.2	171.4	97.7	136.2
0.50	120.4	137.3	159.6	175.9	104.8	143.0
0.55	128.4	144.7	167.1	179.3	113.5	150.4
0.60	136.4	152.9	175.6	181.8	123.7	158.3
0.65	144.3	161.7	184.9	183.6	135.1	166.7

Power input to Rotor	0.56	0.76	2.48	2.25	1.175	1.26
H	3.0	2.97	8.00	9.96	4.48	6.55
k	7.5	7.58	2.85	2.26	4.60	3.44
Initial ang: in degrees.	82.1	103.1	127.5	102.0	80.2	108.9



3-PHASE FAULT ON 132 K.V. LINE BETWEEN T.B. VARA & MACHKUND AT MACHKUND END.

FAULT CLEARED IN 0.1 SEC.

trip circuit and the time required by in circuit breaker to interrupt the fault current. The system which is unstable for a particular type of fault can be made stable by altering the existing relaying system or by modernising the circuit breakers so as to decrease the clearing time.

Effect of type of fault on stability.

The lower the impedance of the fault shunt, the less is the power exchanged between synchronous machines for a given angular displacement and therefore, the lower is the stability limit for a given fault duration. Comparing the fault shunt impedance for several type of faults shows that the impedance is lowest, i.e. zero for three phase short circuit, higher for double line to ground short circuit, still higher for line to line short circuit and highest for the line to ground short circuit. It follows that most severe type of fault as regards power system stability is concerned is the three phase short circuit followed in order of decreasing severity by the other types of faults mentioned above.

In making stability studies some judgement is necessary in choosing the type of fault which is assumed to occur. The assumption of 3 phase fault gives conservative results. However, 3 phase fault do not occur frequently especially on H.V. overhead lines on steel towers. Double line to ground are also not very frequent. Single line to ground faults are the most common one on the power system.

In designing a system or a modification to improve stability it may be essential to know the degree of reliability of service required and the cost of achieving the same.

CHAPTER - IV.

CONCLUSIONS.

4.1 Steady State.

As seen in Chapter I, the power transfer between two generators in an ideal system with no resistance will vary sinusoidally from zero to maximum and will be given by the following relation neglecting Saliency.

$$P = \frac{E_1E_2}{X_d} \sin.\delta$$

$$\text{Maximum power} = \frac{E_1E_2}{X_d} \quad \text{when} \quad \delta = 90°$$

The system will be within steady state stability limit if an increase in phase angle of the leading machine by say 5° and decrease in angle of the lagging machine by some angle say 5° results in increase of power output from leading machine and decrease in power output from lagging machine (if multi-machine system then intermediate machines are adjusted to give the same output). In an integrated network, the maximum phase displacement between the leading and lagging machines is 40 - 60° and cannot approach the theoretical limit of 90°. About 40° phase displacement will be reasonable to meet any transient disturbance in the system.

In the system studied the phase displacement between upper sileru, the leading machine and Tungabhadra the lagging machine is about 46 - 48° to effect the required transfer of power as per planned generation and load schedules. It is found from practice that initial phase angle should not be more than 50-55° otherwise the system will be unstable during transient conditions. To bring down this angle, the transmission system can be strengthened (making low reactance by parallel circuits, compensating the reactance by series capacitors etc.) and generators could be of High Short Circuit ratio.

4.2 Transient Conditions.

Under transient conditions, the power is calculated with the use of transient reactance of synchronous machines and the voltage behind the transient reactance. The major factors affecting the transient stability may be listed as follows:

i) Generator WR^2x rpm^2 - Greater this quantity, the lower the accelerating constant K.

ii) System impedence which must include the transient reactances of all generating units. This affects phase angles and the flow of synchronising power.

iii) Duration of fault chosen - Duration will depend on the circuit breakers speed and the relays.

iv) Generator loading prior to the faults which will determine the internal voltage etc.

v) System loading - which will determine the phase angles among the various internal voltages of the generators.

Transient stability studies as may be seen from Chapter III mainly involve the investigation of these factors so as to give the minimum overall cost.

Item (ii) and (iii) are very important and compromise is sought between the system requirement and the cost. High short circuit ratio generators, stronger tie lines between the various Generating Stations (number of parallel circuits can be increased so as to decrease the electrical distance between far off stations) and high speed circuit breakers with fast relays will no doubt make an ideal power system but the cost will be very much. Minimum requirement of the system can be found out from such studies.

4.3 Voltage of transmission determines to a considerable extent its KW loading. The rated loadings of most of the high voltage transmission lines below 300 miles, is the surge impedence loadings. By surge impedence loading or natural loading is meant a load of approximately 400 ohms equivalent impedence to neutral and is equal to $2.5(kV)^2$ in kWs., corresponding to line length of 300 miles. For this loading I^2X of the line equals the line charging volts- amps, the PF being unity at the sending as well as at the receiving end. For lengths even upto 100 miles the KW loading could not be exceeded greatly over the S.I.L. because of increased KVAR capacity required for transmission of the increased loading.

On these studies the loadings on 220 kV line 50 - 100 miles in length were about 125 - 150 MW per circuit at an average P.F. of about 0.85 with a line conductor of equivalent copper crossection of 0.4 sq. inch. For 132 kV line the load transferred per circuit was about 40 - 50 MW with copper equivalent 0.15 to 0.2 sq. inch.

System loading together with generator loading fix the phase angles over the system and determine the margins in angles available for swings.

4.4 An increase in inertia of the generator would also make possible either slower clearing or transmission of more power without loss of synchronism. The time required for the generators to swing through any given angle varies as $\sqrt{H}$. When a fault occurs, the rotor of a generator nearest to the fault starts accelerating faster as compared to the other generators in the system. Its output delivered to the system decreased and the same is used up in accelerating the rotor (power fed to the fault is negligible, PF being almost zero). The other generators on the other hand get over-loaded, with the result, the phase angle difference increases. The rate of this increase depends on the strength of the transmission system, inertia of the rotors, severity and location of fault etc. When the fault is cleared, the accelerating rotor gets loaded and the others get relieved with the result that the rate of increase in the phase angle starts decreasing. The system will settle back to its steady state conditions if the rotors of the leading and lagging machines have not drifted too much apart at the time of clearing of the fault. This depends on the total time taken between the initiation of the fault and its clearance and also on the initial angular difference between the machines before occurance of the fault. All this interpretation will be quite clear on examination of the swing curves plotted in cases 1 to 4.

4.5 Circuit breakers and relays have been the Principal factors to date in bringing system stability to its present stage. High Voltage A.C. Circuit breakers are available with interrupting speeds of 3, 5 and 8 cycles. For some applications 2-3 cycles operation is common (3 cycles breaker time plus 1 cycle relay time). Fast clearing of faults is considered to be most important factor in maintaining transient stability. 3 phase fault on the system (case 4) was studied with fault clearing in 0.2 seconds (8 cycles breaker time plus 2 cycles relay time). The system was found unstable. By reducing the fault clearance time to 0.1 second (3 cycles breaker time plus 1-2 cycle relay time), the same system for 3 phase fault was found stable. A less severe type or location of short circuit would permit either slower clearing or transmission of more power without loss of synchronism.

High speed reclosure for improving stability is a step in advance of High speed clearing of faults. Its effect on raising stability limits is especially marked when applied to single circuit ties between systems; for without reclosure the power limit for a single circuit tie is zero whereas with reclosure the power limit may be considerable. While the line is open to permit deionization of the arc, the generators at the too ends of the line drift apart in phase. The breakers must be reclosed before the generators drift too far apart if synchronism is not to be lost.

4.6 The system must be able to remain in synchronism in the first swing as the voltage regulators with moderate exciter response (about 2 per unit) are not so quick to act in the first swing. A machine which does not fall out of step in the first swing will not go out of step on subsequent swings as a result of voltage regulator action.

Voltage regulator action cannot be represented on the A.C. network analyser (constant voltage behind transient reactance has been assumed in the first swing). The swing curves drawn are for first swing only.

4.7 Synchronous condenser capacities are in general selected for the purpose of maintaining voltage and consequently their stored energy is very low as compared with that of system generation (unless the synchronous condenser capacity is quite large). They, therefore, contribute little stabilising effect upon the plants of the system. Their action during fault is to follow the system voltage at the points on the system where they are installed on a system equipped with modern High speed relays and circuit breakers. Their main contribution is in their attempt to maintain voltage which improves the flow of synchronising power.

About 80% of all the faults on overhead transmission lines are one line to ground type, hence if a system is stable for single line to ground fault, it should be acceptable unless 100% continuity of service is very essential. With proper structural designs (such as clearances ruggedness of structures, lightning protection, guards against birds and animals etc.) and fast clearing of ground and phase to phase faults, the possibility of 3 phase faults on higher voltage lines can be practically eliminated.

APPENDIX.

ANDHRA PRADESH POWER SYSTEM.

DATA.

Transmission Lines. KVA Base 50,000

Circuit.	K.v.	Length in mls.	Per * unit R.	P.U.X	P.U.Y$_c$**
Sirpur-Bellampalli	66 DC	27	0.063	0.100	-
Bellampalli-Mancherial	66 DC	12.5	0.029	0.046	-
Ramagundam-Manchl:	66 DC	10.0	0.023	0.037	-
Hyd'bd-Ramagundam	66 DC	125.0	0.295	0.470	-
Kothgudam-Bommur	132 SC	85.0	0.054	0.170	-
Hyd'-Ramagundam	132 DC	120.0	0.020	0.104	0.19
Ramag'ndm-Warn'gl	132 DC	70.0	0.012	0.060	0.11
Warangal-Koth'dm	132 DC	70.0	0.012	0.060	0.11
Kurnool-Adoni	66 SC	56.0	0.500	0.442	-
Machkund-U.Sileru	132 SC	50.0	0.027	0.093	-
T.B.Vara-Simahlm:	132 DC	30.0	0.009	0.028	-
Dhoni-Kurnool	66 SC	30.0	0.214	0.242	-
T.B.- Bellary	66 TC	32.0	0.076	0.083	-
Bellary-Adoni	66 SC	56.0	0.500	0.442	-
Gooty-Dhone	66 SC	26.0	0.185	0.210	-
Gooty-Anantapur	66 SC	32.0	0.590	0.260	-
Dharm'vm-An'tpur	66 SC	20.0	0.367	0.162	-
Dharm'vm-Gooty	66 SC	52.0	0.131	0.417	-
Gooty-Bellary	66 DC	48.0	0.111	0.190	-
N.J.Sagar-Kothgdm:	132 SC	112.0	0.037	0.196	0.09
N.J.S'gar-Gunadala	132 SC	88.0	0.056	0.176	0.07
L.Sileru-N.J.Sagar	220 SC	246.0	0.026	0.166	0.53
U.Sileru-Bommur	132 SC	90.0	0.029	0.157	0.07

Transmission lines (contd..)

Circuit	K.v.	Length in mls.	P.U.R. *	P.U.X	P.U.Y_c**
Machkund-T.B.Vara	132 DC	60	0.019	0.056	0.10
Simhachalam-Bommur	132 DC	113	0.041	0.106	0.18
Srisailam-Kurnool	66 SC	75	0.456	0.630	-
Srisailam-Ongole	66 SC	150	0.912	1.260	-
Nellore-Ongole	66 SC	75	0.676	0.615	-
Nellore-Renigunta	66 SC	81	0.729	0.664	-
Chittor-Kalikeri	66 SC	56	0.142	0.448	-
Renigunta-Pakala	66 DC	31	0.140	0.126	-
Pakala-Chittoor	66 DC	16	0.072	0.066	-
Pakala-Kalikiri	66 SC	45	0.414	0.369	-
Cuddappah-Kalikiri	66 SC	56	0.142	0.448	-
Cuddappah-Renigunta	66 DC	81	0.363	0.333	-
Cuddappah-Gooty	66 DC	98	0.455	0.388	-
N.Sagar-Hyd'bad	132 SC	88	0.056	0.176	0.06
N.Sagar-Srisailam	220 SC	40	0.004	0.026	0.09
Bommur-Gunadala	132 DC	82	0.030	0.077	0.13
Gunadala-Ongole	132 SC	78	0.086	0.140	0.06
Nellore-Ongole	132 SC	78	0.086	0.140	0.06
Srisailam-Cuddapah	220 SC	150	0.016	0.098	0.33
Nellore-Cuddappah	132 SC	96	0.095	0.180	0.07
Cuddappah-Gooty	132 SC	98	0.097	0.184	0.07
Gooty- T.Bhadra	132 SC	80	0.080	0.152	0.06

Note. (*) The resistance of the reactors is not negligible and averages about 5%. The p.u.value of R shown here has been reduced by 5% of p.u.X setting.

(**) The value of Y_c (line susceptance) has been shown only for Pi lines. The value is for one side of the line susceptance.

......

Transformer Impedances. KVA Base 50,000

Location.	Kv	Capacity	P.U.X.
Machkund	11/132	3 x25.0) 3 x20.0) MVA	0.031
Nellore	132/66	2 x 20.0 MVA	0.075
Nellore	11/132	1 x 40.0 MVA	0.113
Cuddappah	132/66	2 x 20.0 MVA	0.075
Gooty	132/66	2 x 20.0 MVA	0.075
Tungabhadra	66/132	2 x 20.0 MVA	0.075
Tungabhadra	11/66	7 x 10.6 MVA	0.065
Nagarjunasagar	220/132	2 x 60.0 MVA	0.028
Hyderabad	132/66	2 x 50.0 MVA	0.060
Ramagundam I	11/66	3 x 15.0 MVA	0.067
Ramagundam	66/132	2 x 50.0 MVA	0.030
Kothagudem	11/220	2 x 75.0 MVA	0.030
Sirpur	132/66	2 x 20.0 MVA	0.075
Ramagundam	11/132	2 x 40.0 MVA	0.060
Upper Sileru	11/132	2 x 75.0 MVA	0.030

Transmission lines. KVA Base. 50,000

Zero sequence impedances (self & mutual impedences combined).

Circuit	KV.	Length in miles	P.U.Ro[*]	P.U.Xo
Machkund-T.B.Vara	132 DC	60	0.063	0.286
Garividi-T.B.Vara	132 DC	34	0.035	0.086
T.B.Vara-Simhachalam	132 DC	30	0.032	0.143
Simhachalam-Bommur	132 DC	113	0.115	0.532
Bommur-Gundala	132 DC	81	0.081	0.380
Hyd'bad-Ramagundam	66 DC	125	0.165	0.566
Gunadala-Nellore	132 SC	150	0.290	0.865
Nellore-Renigunta	66 SC	81	0.949	2.320
Cuddappah-Renigunta	(Equivalent impedance)		0.321	0.767
Cuddappah-Gooty	132 SC	98	0.205	0.510
Cuddappah-Gooty	66 DC	98	0.845	2.649
Gooty-Tungabhadra	132 SC	80	0.167	0.415
Gooty-Bellary	66 DC	48	0.261	0.807
Bellary-Tungabhadra	66 TC	32	0.202	0.605
Bellary-Adoni	66 SC	56	0.892	2.240
Adoni-Kurnool	66 SC	56	0.892	2.240
Kurnool-Dhone	66 SC	30	0.307	0.745
Kurnool-Dhone	66 DC	30	0.141	0.339
Dhone-Gooty	66 SC	26	0.264	0.690
Dhone-Gooty	66 DC	26	0.123	0.294

Note. (*) The resistance of the reactors are not negligible and averages about 5%. In the value shown for zero sequence resistance, 5% of the zero sequence reactance value has been subtracted.

For Pi lines, the zero seq: capacitive susceptance of overhead lines in grounded systems can generally be neglected as in the fault studies involving zero seq:network, it will have no appreciable effect unless unusually long lines are involved.

KVA Base. 50,000

Transformers. (Zero sequence impedances)

Station.	Voltage. KV	No.& Capacity MVA	Connections.	P.U.(Xo) X_{oH}	X_{oL}	X_{oT}
Machkund	11/132	3 x 25.0 3 x 20.0	Delta/Star with grounded neutral	0.031	-	-
Garividi	132/33-11	3 x 15.0	Star/star both neutrals grounded with tertiary delta	0.094	0.003	0.039
Simha'chlm	132/33-11	3 x 4.00 2 x 7.50	-do-	0.118	0.006	0.044
Gunadala	132/33-11	3 x 7.50	-do-	0.145	0.005	0.074
U.Sileru	11/220	1 x 150	Delta/Star with grounded neutral	0.04	-	-
Nagara'gr.	220/132	2 x 100	Star/auto with an aux: delta winding neutrals grounded.	0.031	-0.017	0.065
Kothag'dm	11/220	2 x 75.0	Star/star with both neutrals grounded & tertiary delta.	0.25	0	0.013
Hyd'bad	132/66-33	2 x 50.0	-do-	0.049	0.002	0.025
Ramagundam	11/66	3 x 15.0	Star/inter star both neutrals grounded.	0.09	-	-
Nellore	11/132	1 x 40.0	Delta/star neutral grounded.	0.096	-	-
Nellore	132/66	2 x 20.0	Star/auto with an aux: delta winding, neutral grounded.	0.113	-0.05	0.185

Transformers. (Zero sequence impedances) .. contd..

Station	Voltage KV	No.& Capacity MVA	Connections.	P.U(X_o)		
				X_{oH}	X_{oL}	X_{oT}
Cuddappah	132/66	2 x 20.0	Star/auto with an aux: delta winding, neutral grounded.	0.113	-0.05	0.185
Gooty	132/66	2 x 20.0	-do-	0.113	-0.05	0.185
Tungabhadra.	132/66	2 x 20.0	-do-	0.113	-0.05	0.185
Tungabhadra.	11/66	7 x 10.6	Delta/Star neutral grounded.	0.055	-	-

KVA Base. 50,000

Generator Adjustment for Transient studies.

Location.	X_d	Terminal loading.			$E_{gen.}$ (Voltage behind X'_d)
		Voltage.	M.W.	MVAR	
Nellore	0.254	100.9	28.8	4.0	105
Ramgundam	0.224	102.2	38.0	22.5	114.5
Sileru	0.086	101.0	123.0	14.5	107.0
Machkund	0.075	102.2	113.0	17.0	106.5
Tungabadhra	0.119	103.0	57.5	25.5	110.4
Kothagundam	0.116	101.2	62.5	34.5	110.5

Generation(Rated output)

Location	M.W.	MVAR
Nellore	30	18.7
Ramagundam	37.5	28.2
Tungabhadra	58.0	36.2
U. Sileru	120.0	58.0
Machkund	110.0	68.6
Kothagundam	66.0	49.5

Condenser Capacities.

Location.	MVAR
Hyderabad	24
Renigunta	5
Cuddappah	12
Gooty	5
Bommur	15
Gundala	15

BIBLOGRAPHY.

E.W. Kimberk, Power System Stability
Volume I,II,III John Willy Publication,
New York.

S.B. Crary, Power System Stability,
Volume I, John Willy Publication,
New York.

Electrical Transmission & Distribution
Reference Book (Westinghouse Publication)

Wegner & Evens, Symmetrical Components,
McGrawHill, New York.

W.H. Walker, Operating Characteristics of
salient pole machines, proceedings IEE
100 (II) 1953 Page.13.

C.L. Kihlgore, Excitation problems in
Hydro-Electric Generators supplying long
transmission lines, AIEE Transaction
Volume 66, 1947.

A.C. Network Analyzer Manual (Indian
Institute of Science, Bangalore, publication)

Zwender "Fundamental electrical characeteristics for synchronous turbo-generators" Vol.91-Part.II. JIEE 1944
page 185.