DETERMINATION OF TRANSIENT STABILITY LIMIT OF INTER-GRID POWER TRANSFER

BY

MD. YEAKUB HUSSAIN

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL
AND ELECTRONIC ENGINEERING IN PARTIAL FUL-
FILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN ENGINEERING(ELECTRICAL)

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA, BANGLADESH

MAY , 1984

CERTIFICATE

THIS IS TO CERTIFY THAT THIS WORK HAS BEEN DONE BY ME AND IT HAS NOT BEEN SUBMITTED ELSEWHERE FOR THE AWARD OF ANY DEGREE OR DIPLOMA OR FOR PUBLICATION.

COUNTERSIGNED

Ahmed

(DR. JAMALUDDIN AHMED)
SUPERVISOR

SIGNATURE OF THE CANDIDATE

Hussain

(MD. YEAKUB HUSSAIN)

ACCEPTED AS SATISFACTORY FOR PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF M.SC. ENGINEERING IN ELECTRICAL ENGINEERING

BOARD OF EXAMINERS

Ahmed

1. (Dr. Jamaluddin Ahmed)
   Supervisor,
   Assistant Professor
   Dept. of Electrical &
   Electronic Engineering
   BUET, Dhaka.

   Chairman

A m Zahoorul Huq

2. (Dr. A.M. Zahoorul Huq)
   Professor,
   Deptt. of Electrical &
   Electronic Engineering,
   BUET, Dhaka.

   Member

3. (Dr. Shamsuddin Ahmed)
   Professor & Head,
   Deptt. of Electrical &
   Electronic Engineering,
   BUET, Dhaka.

   Member

Rahman

4. (Dr. Sayed Fazl-i-Rahman)
   Professor,
   Deptt. of Electrical &
   Electronic Engineering,
   BUET, Dhaka.

   Member

5. (Dr. Nazrul Islam)
   Chairman,
   Bangladesh Steel & Engineering
   Corporation.

   Member
   (External)

ACKNOWLEDGEMENT

The author expresses his indebtedness and deep sense of gratitude to Dr. Jamaluddin Ahmed, Assistant Professor of Electrical & Electronic Engineering Department, BUET, Dhaka for his continuous guidance, valuable suggestions and constant encouragement throughout the course of this work.

The author wishes to express his sincere gratitude and thanks to Prof. Shamsuddin Ahmed, Head of the Department, Prof. A.M. Zahoorul Huq, Professor S.F. Rahman and Mr. Hamidul Haque , Assistant Professor of Electrical and Electronic Engineering Department, BUET, Dhaka for their encouragement and advice during this work.

The author also wishes to thank the staff of the Computer Centre of BUET for their assistance in using the Computer.

In the end, it must be recorded that this work would have been well nigh impossible without co-operation, help and inspiration from the authors' wife, Mrs. S.P. Hussain, son, Master Pyen and daughter Miss Ypa to whom this thesis is dedicated.

ABSTRACT

An algorithm has been developed to compute the transient stability limit of Inter-grid power transfer as a function of clearing time. The integrated grid system of Bangladesh Power Development Board(BPDB) has been taken as the model for this study. The BPDB Power network is divided into two major zones- The East Zone and The West Zone and the two zones are connected by an overhead 3-phase double circuit transmission line called the East-West interconnector. The interconnector is designed for 230KV and presently energized at 132KV. A system study for the integrated BPDB grid system was done by Acres International(Canada) Ltd. in 1968 in which they studied the operation of the East-West Interconnector both at 132KV and 230KV levels. By plotting swing curves they determined the transient stability limit for inter-grid power transfer at both voltage levels.

In this algorithm developed the inter-grid power transfer is directly computed as a function of clearing time. In order to be able to compare the results with that of Acres International the system models used for 132KV and 230KV operation are exactly same as that used by Acres International. The network for 132KV operation is slightly different from the present network, The network for 230 KV operation is expected to exist around 1987.

The interconnected network has been converted to a two-machine system. All machines of the Eastern Zone are grouped together to a single equivalent machine and similarly all machines of the Western Zone are grouped together to another single equivalent machine. The networks of the Eastern Zone and the Western Zone are reduced separately by star-mesh conversion principle. The transient stability limit for inter-grid power transfer is computed for instantaneous clearing, for sustained fault and for various intermediate clearing times.

The swing equation has been converted to a universal swing equation independent of inertia constant with respect to a machine time τ. The clearing time has been calculated from the clearing angle by solving the swing equation by Runge-Kutta method of fourth order approximation.

Three phase fault at (i) middle point and (ii) near bus end of one of the lines of the interconnector have been studied. The reference bus voltages at the two ends of the interconnector are equal to the nominal system voltage. Also the actual bus voltages at the two ends of the interconnector have been used from various load flow studies of Acres International.

A Computer program has been developed to compute and plot inter-grid power transfer as a function of clearing time and the BUET Computer IBM-370 has been used for various studies.

There are five sub-programs used with the main program to solve the boundary conditions, to calculate clearing angle and corresponding clearing time.

The result obtained using this algorithm are compared with those of Acres International in order to prove the validity of the algorithm.

NOMENCLATURE

Symbol	
E	Generator Voltage.
E'_q, E'	Machine voltage behind transient reactance.
E_d, E'_d	Direct-axis steady state and transient excitation voltage.
I	Line current, Armature current.
I_d, I_q	Direct-axis and Quadrature-axis armature current.
I_f	Field current.
I_g	Quadrature-axis of field current.
P	Real Power.
P_i	Initial Power or Shaft Power.
P_m	Maximum Electrical Power.
P_u	Electrical output Power.
Q	Reactive Power.
r_1	Ratio of during fault curve to pre-fault curve.
r_2	Ratio of post-fault curve to pre-fault curve.
t, t_c	Clearing time, critical clearing time.
V	Bus Voltage.
X_{12}	Mutual reactance.
X_d, X'_d	Direct-axis synchronous & Transient reactance.
X_q, X'_q	Quadrature-axis synchronous and transient reactance.
Y_{11}, Y_{12}	Driving point and Mutual Bus admittance.
y_{01}, y_{12}	Line admittance.
Z_F	Fault Shunt Impedance.
Z_o	Zero sequence impedance.

Symbol	
Z_2	Negative Sequence Impedance .
δ, δ'	Torque angle .
δ_o	Initial torque angle.
δ_c	Critical clearing angle .
$\delta_{max.}$	Maximum torque angle .
θ, θ''	Impedance angle .
γ	Angle .
ρ, ρ_c	Modified clearing and critical clearing time.
τ, τ_c	Modified clearing and critical clearing time.

LIST OF FIGURES

CONTENTS

1.2 Definition and Type of Stability:

In general, there are three types of stability associated with the system.(1)

(a) Steady state stability

(b) Transient stability

(c) Dynamic stability

This work is concerned only with the transient stability limit of a power system.

Suddenly large disturbance occurs when a large block of generation or load is lost or a fault occurs on a transmission line. In such cases the system must be able to withstand the disturbance. Transient stability is the ability of the system to remain in synchronism following a sudden system disturbance. This ability depends to a great extent on how quickly the fault is isolated from the system and the time in which the fault must be cleard in order to maintain system stability is called critical clearing time. The maximum transferable power is a function of this critical clearing time. For a circuit breaker, the clearing time is the sum of the relay sensing time and the circuit breaker operating time. If the fault on the system is cleared within it's critical clearing time, the system will be stable otherwise it will go out-of-step and loose synchronism.

The transient stability limit refers to the maximum possible flow of power through a point without loss of stability when a sudden large disturbance occurs (2,16,17). This power limit is a function of fault clearing time. The power limit increases as the fault clearing time decreases.

Since the transient stability limit is a function of fault clearing time, the purpose of this research is to develop an algorithm to compute inter-grid transient stability power limit as a function of fault clearing time.

1.3 Method of Determination:

The curve for power transfer through an inter-grid circuit as a function of fault clearing time can be achieved by two different methods:

Method - I:

The power flow through an inter-grid circuit can be obtained by the method of load flow study. For each value of power flow through the grid a number of transient stability analysis are performed at different clearing times to determine the critical clearing time for that particular power flow by using step-by-ste method or Runge-Kutta method for solution of swing equation. The process is repeated for a number of power flow and the inter-grid power limit is then plotted as a function of clearing time.

Method - II

In this method the multimachine system is converted into a two-machine system. The group of machines of which the internal angular swings are similar, are replaced by an equivalent machine. The equivalent transient reactance will be the parallel combination of the transient reactances of the individual machines of the group. The whole network is reduced, by star-mesh conversion principle, to a two-machine system being connected by the power line whose power transfer is to be studied. The inertia constant of the equivalent machines will be the sum of the inertia constants of the individual machine of the group.

Practically instantaneous clearing or zero clearing time is never possible. But it may be regarded as the limit approached as the clearing time is reduced. Instantaneous clearing is obtainable only by disconnecting a faulted line when there is no fault on it. The initial power transfer through this line will be called the maximum power flow at zero clearing time if the system remains stable. The infinite clearing time(2,5) may be regarded as the time when the faulted line will not be cleared at all and the power flow for this condition will be the maximum power at sustained fault or at infinite clearing time if the system remains stable.

The initial voltage behind transient reactances of the two machines and their initial operating angles are found out at sustained fault, at instantaneous clearing and at a number of intermediate load values. Sin δ_o is plotted as a function of r_1 and r_2.

Where $r_1 = \dfrac{X_{12}(\text{before fault})}{X_{12}(\text{during fault})}$

and, $r_2 = \dfrac{X_{12}(\text{before fault})}{X_{12}(\text{after fault cleared})}$

The initial maximum amplitude of power,

$$P_m = \frac{E_1 E_2}{X_{12}}$$

and mechanical input power,

$P_i = P_m \sin\delta_o$ are calculated and tabulated as function of $\sin\delta_o$.

where, E_1 = Voltage behind transient reactance of equivalent machine-1,

E_2 = Voltage behind transient reactance of equivalent machine-2.

X_{12} = mutual reactance between machine-1 & machine-2.

and δ_o = relative rotor angle between the two machines.

For instantaneous clearing, $\sin\delta_o$ is determined from the graph for r_2 then from the value of $\sin\delta_o$ the value of Pi is calculated by trialling with various current values. Then this Pi will be the maximum possible power flow at zero clearing. For intermediate points for different values of $\sin\delta_o$'s the corresponding values of Pi are found from the earlier calculated table. The critical clearing angle for corresponding value of Pi is calculated from the values of δo, δmax, r_1 and r_2 using equal area criterion. The critical clearing time corresponding to the critical clearing angle is then computed by solving swing equation using Runge-Kutta method.

For sustained fault condition, Sinδo is determined from the graph for r_1 then from the value of sinδo the value of Pi is calculated by trialling with various current values. Then this Pi will be the maximum possible power flow at infinite clearing time or while there is no clearing. Then inter-grid power transfer limit is plotted as a function of clearing time. This second method is adapted in this research undertaken here.

1.4 Utility and Objectives:

For stable operation of a power system, the maximum power flow through any grid should be pre-determined so that proper breaker arrangement can be made available. The Western zone and Eastern zone of BPDB network system have been connected by an interconnector over Jamuna river. The power crisis of Western zone is met by supplying gas-fired cheap power from the Eastern zone through this inter-connector. Therefore a study is essential to find out the maximum power flow of the line so that the integrated system can function smoothly and remain stable even if there is a fault on the interconnector.

Earlier, this stability limit was studied with the help of equal-area-criterion method in conjunction with a set of pre-calculated swing curves and the curves for determining critical clearing time.(2,3) With the knowledge of thie research, it is possible to calculate the maximum power transfer through the interconnector after any change in the layout of the system.

For future expansion of the system this study will help to select proper circuit breaker and relay arrangement required for the maximum expected power flow.

CHAPTER - II

REPRESENTATION OF DEVICES IN THE NET WORK SYSTEM

A power system with generators, transformers, static and/or syncheonous condensers and loads, can be represented by one-line diagram showing all the machines and elements as shown in Fig.2-1

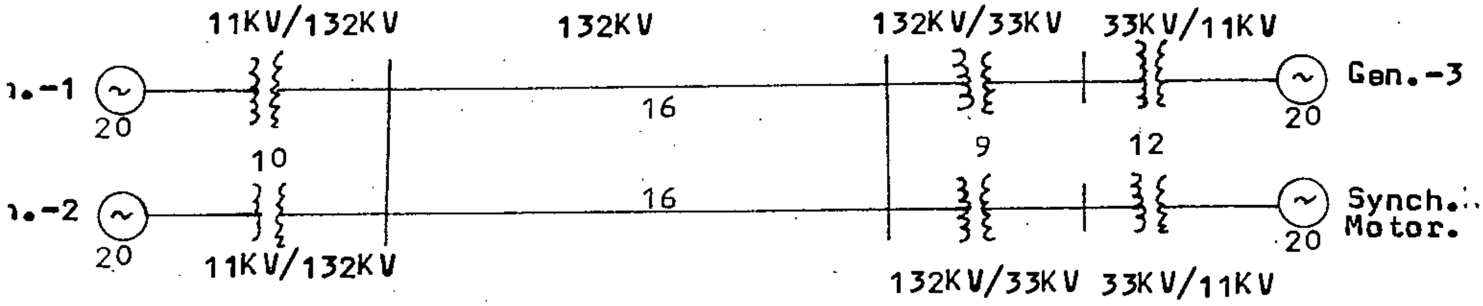


Fig. 2.1

One line diagram

One line impedence or reactance diagram can be drawn from Fig. 2-1 with proper reactance values on a system base voltage and base MVA. The one line reactance diagram for the circuit in Fig.2-1 is shown in Fig.2-2.

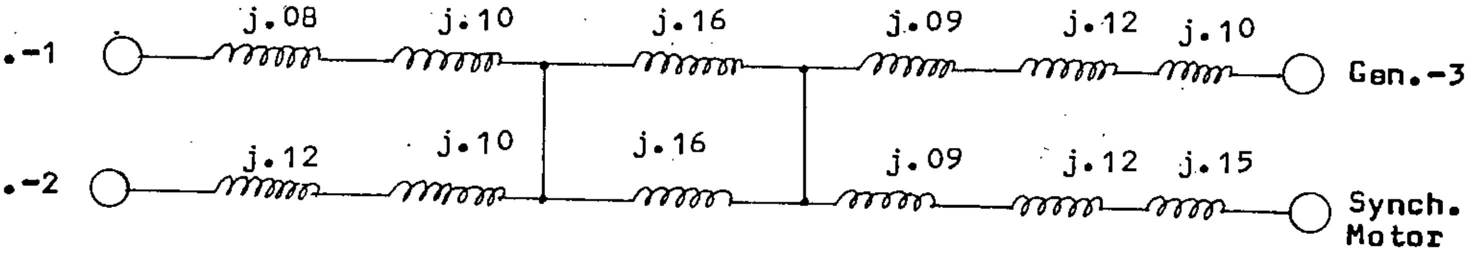


Fig. 2.2

Reactance diagram

In stability limit study, various Ckt. elements are represented as follows:

1. The generators or other synchronous motors are represented by its direct axis transiant reactance in series with a constant voltage source. Armature resistances are normally neglected.

2. Transformers:

   Two winding transformers are represented by series impedence Z equivalent to short-Ckt. impedences and the exciting impedences are neglected. Also the resistance part is neglected for large transformers .

   Three-winding transformers are represented by Y-circuits such that the sum of the reactances of each pair of branches equals the short-circuit reactance between the corresponding pair of windings with the remaining winding open.

3. Transmission lines and cables.

   These are represented by their nominal or equivalent π circuits.

4. Loads:

   The loads on a power system vary with time of day and from one year to another year. For example annual peak load and the minimum load may be taken for the study. Loads are assumed to be lumped on the buses of major stations and substations. They should be expressed as vector power $P+jQ$, where P represents the active power and Q represents the reactive power. Each load is then represented by a shunt admittance $Y=\frac{P-jQ}{|V|^2}$, where V is the voltage across the load.

5. Representation of faults:

   A three-phase short circuit is represented by connecting the point of fault to the neutral bus . Other faults are represented by connecting the point of fault to the neutral bus through a fault-shunt combining negative and/or zero sequence impedence depending on the type of fault.

The type of faults and the fault shunts are given below:

Type of fault	Impedence of Fault shunt
	ZF
a. Line to ground	$Z_0 + Z_2$
b. Line to line	Z_2
c. Two-line to ground	$Z_0Z_2/(Z_0+Z_2)$
d. Three phase	0

6. Miscelleneous equipment:

Closed C.B. and switches, current transformers and buses have negligible impedence on high voltage systems and, therefore, are disregarded. Similarly potential transformers, lighting arrestors and coupling capacitors have impedences so high that they are considered as open circuits.

7. Representation of the remote portion of the system:

In studies of part of a large interconnected system it is neither necessary nor feasible to represent all the stations and lines of the entire system. The out-lying portions can be represented by equivalent circuits.

A remote part connected at only one point of system being studied can be replaced by its equivalent Thevenin's circuit consisting of an impedence in series with a constant voltage source. The impedence is found by network reduction or by a knowledge of the short-circuit kilo-volt amperes level at the point of connection. A remote part of the network connected to the system at two points can be represented by a power source and a Y- circuit.

The inertia constant assigned to the generator of each of these equivalent circuits should be equal to the sum of the intertia constants of all the machines therein and , in the absence of more definite information, may be calculated from an average value of H and the known aggregate generating capacity.(2) If the total inertia is large compared to that of the portion of the network being studied, it may be considered infinite with little error.

CHAPTER - III

DEVELOPMENT OF NETWORK REDUCTION PROCESS

A network system may have several nodes and terminal points. For system stability study, only the terminal self- and mutual admittances are required. Therefore, the extra nodes in the network may be eliminated by a process known as network reduction.

Let us take a network consisting of five nodes, of which one node is to be eliminated. The nodal equations are written as:

$$\left.\begin{aligned} I_1 &= Y_{11}E_1+Y_{12}E_2+Y_{13}E_3+Y_{14}E_4 \\ I_2 &= Y_{21}E_1+Y_{22}E_2+Y_{23}E_3+Y_{24}E_4 \\ I_3 &= Y_{31}E_1+Y_{32}E_2+Y_{33}E_3+Y_{34}E_4 \\ I_4 &= Y_{41}E_1+Y_{42}E_2+Y_{43}E_3+Y_{44}E_4 \end{aligned}\right\} \quad 3.1$$

Suppose, node 4 is to be eliminated. It can be eliminated only if it has no external connection, i.e. the terminal 4 is considered to be open circuited;

Hence, $I_4 = 0 = Y_{41}E_1 + Y_{42}E_2 + Y_{43} + E_3 + Y_{43}E_4$

Solving for E_4 and substituting the expression in place of E_4 give,

$$I_1=(Y_{11}-\frac{Y_{14}Y_{41}}{Y_{44}})E_1+(Y_{12}-\frac{Y_{14}Y_{42}}{Y_{44}})\,E_2\;+(Y_{13}-\frac{Y_{14}Y_{43}}{Y_{44}})\,E_3 \text{ etc.} \qquad (3.2)$$

which may be written in standard form;

$$I_1 = Y'_{11}E_1 + Y'_{12}E_2 + Y'_{13}E_3$$

Similarly, $I_2 = Y'_{21}E_1 + Y'_{22}E_2 + Y'_{22}E_3$ etc. (3.3)

In which Y′s are the new terminal admittances and related to the old one by

$$\left.\begin{aligned} Y'_{11} &= Y_{11} - \frac{Y_{14}Y_{14}}{Y_{44}} \\ Y'_{22} &= Y_{22} - \frac{Y_{24}\,Y_{42}}{Y_{44}} \\ Y'_{12} &= Y_{12} - \frac{Y_{14}\,Y_{42}}{Y_{44}} \end{aligned}\right) \qquad (3.4)$$

So in general form this may be written as:

$$Y'_{jk} = Y_{jk} - \frac{Y_{j4}\,Y_{4k}}{Y_{44}} \quad \text{where } j = 1,2,3 \qquad (3.5)$$

$$k = 1,2,3$$

Assume that both old and new network are of standard type having one and only one element between each pair of terminals and having no coupling with each other.

The relations between elements of old and new networks can be derived as follows:

$$\left.\begin{aligned} Y_{11} &= y_{01} + y_{12} + y_{13} + y_{14} \\ Y_{44} &= y_{04} + y_{14} + y_{24} + y_{34} \text{ etc.} \\ Y_{12} &= -y_{12} = Y_{21} \\ Y_{34} &= -y_{34} = Y_{43} \text{ etc.} \end{aligned}\right) \qquad (3.6)$$

Similarly,

$$\left.\begin{aligned} Y'_{11} &= y'_{01} + y'_{12} + y'_{12} + y'_{13} \\ Y'_{33} &= y'_{03} + y'_{13} + y'_{23} \quad \text{etc.} \\ Y'_{12} &= Y'_{21} = -y'_{12} \\ Y'_{23} &= Y'_{32} = -y'_{23} \end{aligned}\right\} \qquad (3.7)$$

Substituting equations 3.7 and 3.6 into equation 3.4, we get,

$$\left.\begin{aligned} y'_{12} &= y_{12} + \frac{y_{14}\,y_{24}}{y_{04}+y_{14}+y_{24}+y_{34}} \\ y'_{13} &= y_{13} + \frac{y_{14}\,y_{34}}{y_{04}+y_{14}+y_{24}+y_{34}} \\ y'_{01} &= y_{01} + \frac{y_{04}\,y_{14}}{y_{04}+y_{14}+y_{24}+y_{34}} \end{aligned}\right\} \qquad (3.8)$$

In general form these may be written as;

$$\left. y'_{jk} = y_{jk} + \frac{y_{j4}\,y_{k4}}{\sum\limits_{i=0}^{4-1} y_{i4}} \right\} \qquad (3.9)$$

i.e. every element of the new or reduced network is the result of paralleling the corresponding element of the old network with an element arising from star-mesh conversion.

The network reduction process is summarised as below:

(1) Series and/or parallel combinations of impedence elements are made where necessary.

(2) The impedences are converted to admittances.

(3) Nodes are eliminated by star-mesh conversion, giving preference to node having least number of elements.

(4) The new elements resulting from the conversion are made parallel with old elements.

(5) The process (3) and (4) are repeated until all desired nodes are eliminated.

(6) The terminal admittances are computed from the element admittance for stability study.

If the star contains n points, similar formula holds, but the expression Σy should have n terms. We have Y - Δ conversion only if n = 3. If n =2 we have a simple series combination.

In general, the conversion from mesh to star for $n > 3$ is not possible.

CHAPTER - IV

METHODOLOGY OF DETERMINATION OF STABILITY LIMIT

4.1 Development of Power-angle equation and Swing Equation:

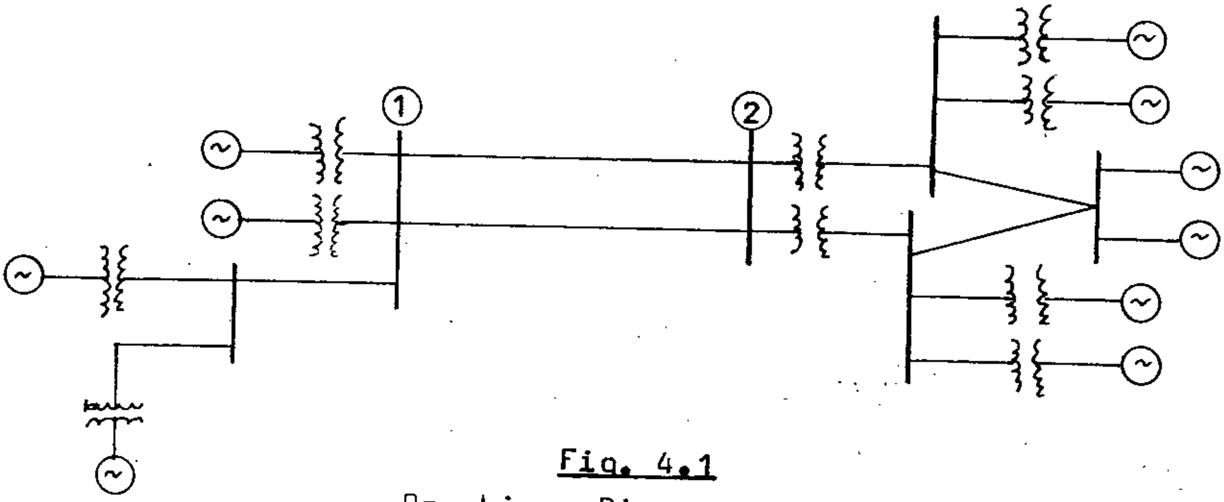


Fig. 4.1
One Line Diagram

Consider a power system network shown in Figure 4.1. The stability limit for power transfer between bus (1) and bus(2) is to be determined. The network of the whole power-system reduced to a series circuit in series with bus(1) and bus (2) . The machines in each side which swing together are grouped in a single equivalent machine and are replaced by a voltage behind the transient reactance in series with an equivalent transient reactance shown in Fig. 4.2

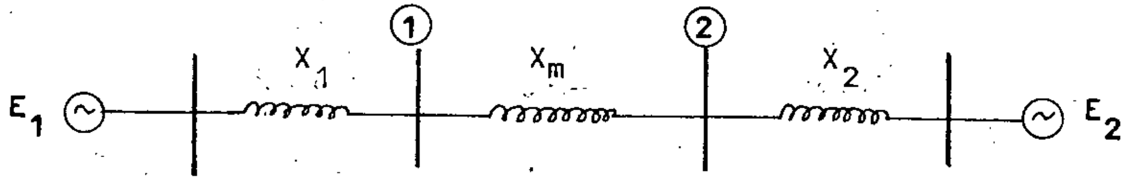


Fig. 4.2

Reactance diagram

Thus a multimachine system can be replaced by a two machine system. From the transfer impedances between the machine terminals, the ratio, r_1 for faulted condition can be found out as $r_1 = \frac{x_{12}\ \text{(Prefault)}}{x_{12}\ \text{(during fault)}}$ (4.1) and the ratio r_2 for post fault condition can be found out as

$$r_2 = \frac{x_{12}\ \text{(Prefault)}}{x_{12}\ \text{(Post-fault)}} \qquad (4.2)$$

r_1 may be zero or a fraction depending on the location of the fault. If the fault occurs near the bus point 1 or 2 the transfer reactance at faulted condition becomes infinitely large and the ratio r_1 will be zero.

Again, a system having two finite machines may be replaced by an equivalent system having one machine and an infinite bus so that the swing equations and swing curves of angular displacement between the two machines are same for both the systems. The equivalent inertia constant, equivalent input and equivalent output are calculated for equivalent finite machine. The equivalent inertia constant is a function of the inertia constants of the two equivalent machines and the equivalent input and output are functions of the inputs and outputs of the two equivalent machines.

The swing equation of the two finite machines are;

$$\frac{d^2\delta_1}{dt^2} = \frac{P_{a_1}}{M_1} = \frac{P_{i_1} - P_{u1}}{M_1} \qquad (4.3)$$

$$\& \quad \frac{d^2\delta_2}{dt^2} = \frac{P_{a_2}}{M_2} = \frac{P_{i_2} - P_{u_2}}{M_2} \qquad (4.4)$$

The relative angle is $\delta = \delta_1 - \delta_2$ (4.5)

Therefore, the swing equation of the equivalent machine is;

$$\frac{d^2\delta}{dt^2} = \frac{d^2\delta_1}{dt^2} - \frac{d^2\delta_2}{dt^2} = \frac{P_{a_1}}{M_1} - \frac{P_{a2}}{M_2} \qquad (4.6)$$

Multiplying each side of the equation (4.6) by $M_1M_2/(M_1+M_2)$, gives ,

$$\frac{M_1M_2}{M_1+M_2}\;\frac{d^2\delta}{dt^2} = \frac{M_2P_{a_1} - M_1P_{a_2}}{M_1+M_2}$$

$$= \frac{M_2P_{i_1} - M_1P_{i_2}}{M_1+M_2} - \frac{M_2P_{u_1} - M_1P_{u_2}}{M_1+M_2} \qquad (4.7)$$

The equation (4.7) may be written as

$$M\;\frac{d^2\delta}{dt^2} = P_a = P_i - P_u$$

where $M = \frac{M_1M_2}{M_1+M_2}$,

$P_i = \frac{M_2P_{i_1} - M_2\,P_{i_2}}{M_1+M_2}$ and $P_u = \frac{M_2P_{u_1} - M_1P_{u_2}}{M_1+M_2}$ which are called the equivalent inertia constant and weighted average of the inputs and outputs of the two finite machines.

The law of combination of the inertia constant is similar to that for the parallel combination of impedances. Since the inertia constant is the accelerating power divided by the acceleration, this law will appear quite reasonable in case of two machine system because the accelerating power of the generator is nearly equal (except in sign) to that of the motor while the relative acceleration is the sum of the acceleration of the generator and the retardation of the motor. This is in contrast to the equivalent inertia constant of a machine equivalent to a group of machines that swing together. There, the accelerating power of the group is the sum of the accelerating power of the individual machines and the accelerations of all machines are equal. In that case, the inertia constants combine like impedences in series.

The power-angle equations of a two-machine system are-

$$Pu_1 = E_1^2 \; Y_{11} \; \mathrm{Cos} \; \theta_{11} + E_1E_2Y_{12} \, \mathrm{Cos}(\theta_{12} - \delta_1 + \delta_2) \qquad (4.8)$$

and, $$Pu_2 = E_2E_1Y_{21}\mathrm{Cos}(\theta_{21} - \delta_2 + \delta_1) + E_2^2 \; Y_{22} \; \mathrm{Cos}\theta_{22} \qquad (4.9)$$

substituting these values of Pu_1 and Pu_2 and the relative angle $\delta = \delta_1 - \delta_2$ into the expression of equivalent output gives,

$$Pu = \frac{M_2E_1{}^2Y_{11}\mathrm{Cos}\theta_{11} - M_1E_2{}^2Y_{22}\mathrm{Cos}\theta_{22}}{M_1+M_2} + \frac{E_1E_2Y_{12}[M_2\mathrm{Cos}(\delta-\theta_{12}) - M_1\mathrm{Cos}(\delta+\theta_{12}]}{M_1+M_2}$$

$$= \; Pc + Pm \; \mathrm{Cos}(\delta - \theta'') = Pc + Pm \; \sin(\delta - \gamma) \qquad (4.10)$$

where $$Pc = \frac{M_2E_1^2 \; Y_{11}\mathrm{Cos}(\theta_{11}) - M_1E_2^2 \; Y_{22} \; \mathrm{Cos} \; \theta_{22}}{M_1+M_2}$$

and, $$Pm = E_1E_2Y_{12}M''$$

$$M'' = \sqrt{\frac{M_1^2 + M_2^2 - 2M_1M_2 \; \mathrm{Cos} \; 2\theta_{12}}{M_1+M_2}}$$

and, $$\theta'' = \tan^{-1}\left(\frac{M_1+M_2}{M_1-M_2} \tan \theta \; 12\right)$$

and $$\gamma = \theta'' - 90^\circ$$

Then the swing equation becomes

$$M \frac{d^2\delta}{dt^2} = Pi - P_c - Pm \; \sin(\delta - \gamma) = P_i' - Pm \; \sin\delta' \qquad (4.11)$$

where, $P_i' = P_i - P_c$ & $\delta' = \delta - \gamma$

The equation (4-11) is dependent on equivalent maximum power, Pm and equivalent inertia constant of the machine. This equation can be made dimentionless by dividing it by Pm and introducing a new quantity τ, defined by

$$\tau = t\sqrt{\frac{\pi}{180}\ \frac{P_m}{M}} = t\sqrt{\frac{f\pi P_m}{GH}} \qquad (4.12)$$

Then the swing equation becomes ;

$$\frac{\pi}{180}\ \frac{d^2\delta'}{d\tau^2} = \frac{P_i'}{P_m} - \sin\delta' = p - \sin\delta' \qquad (4.13)$$

where, δ' is in electrical degrees.

or, $$\frac{d^2\delta'}{d\tau^2} = p - \sin\delta' \qquad (4.14)$$

where δ' is in electrical radians.

For faulted condition prefault power Pm is replaced by during fault power r_1 Pm .

If the resistance part of the network is neglected then the impedence angle $\theta_{11} = \theta_{22} = -90^0$ and $\theta_{12} = 90^0$.

$\therefore$ $P_c = 0$ and $M'' = 1$ and $P_m = E_1E_2Y_{12}$ and δ' (4.15)

becomes δ, the relative torque angle between the machines. Then the equation 4-11 for during fault condition, becomes

$$M\,\frac{d^2\delta}{dt^2} = P_i - r_1P_m \sin\delta \qquad (4.16A)$$

Dividing by r_1P_m and introducing τ, the equation 4.16A becomes

$$\frac{d^2\delta}{d\tau^2} = p - \sin\delta \qquad (4.16B)$$

as in equation 4.14. Where δ is in electrical radian.

The equation 4.13, 4.14 and 4.16B are the differential equations which are independent of the inertia constant of the machine and of the constants of the network. The solution of the equations depend on the ratio of input to the amplitude of the power angle curve and on the initial angle δ_0 and initial angular speed ω_0

The amount of power that can be transmitted from one machine to the other in a two-machine system without loss of synchronism, when the system is subjected to a fault, depends on the duration of the fault. The power limit can be determined as a function of clearing angle by equal area criterion, and the relation between clearing angle and clearing time can be found by solving the differential equation(4.13) or (4.14) of the above.

4.2 Determination of initial operating voltage, power and angle:

a) Power at instantaneous clearing of the fault:

Practically, instantaneous clearing is never possible. Theoretically the zero or instantaneous clearing time can be assumed by switching out the faulted line from the existing system when there is no fault on that line. From the prefault and post-fault power angle equation, we can draw the pre-fault and post-fault power angle curves as in Fig. 4.3.

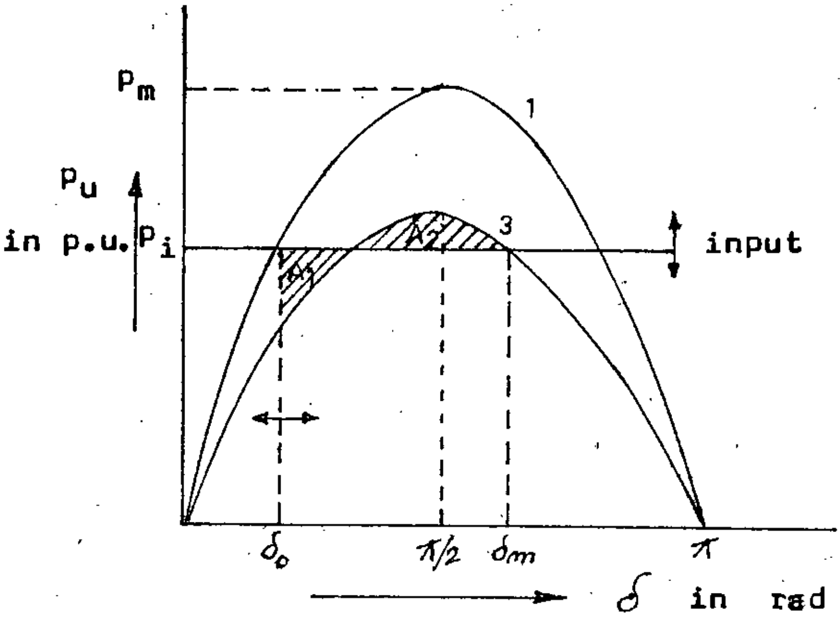


Fig. 4.3

Power-Angle Curve for Instantaneous clearing

Curve 1— pre-fault curve, $P_m \sin\delta$

Curve-3 Post fault curves $r_2 P_m \sin\delta$

Applying the equal area ceiterion method in Fig. 4.3 area of rectangle $= P_i(\delta_m - \delta_o) = P_m(\delta_m - \delta_o)\,\mathrm{Sin}\,\delta_o$ (4.17A)

Area under the power angle curve for post fault condition

$$= r_2 P_m \int_{\delta_o}^{\delta_m} \sin\delta \, d\delta = r_2 P_m(\mathrm{Cos}\,\delta_o - \mathrm{Cos}\,\delta_m) \quad (4.17B)$$

Equating the two areas, we get;

$$(\delta_m - \delta_o)\,\mathrm{Sin}\,\delta_o = r_2(\cos\delta_o - \cos\delta_m) \quad (4.18)$$

where $\delta_m = \pi - \sin^{-1}\left(\frac{\sin\delta_o}{r_2}\right)$

From the relation of r_2 and δ_o as in equation (4.18) the value of δ_o can be achieved by iterative method which determines the initial power flow at pre-fault condition as in $P_i = P_m \sin\delta_o$.

(b) Power-flow at sustained fault condition:

If a fault occurs on a power system and is never cleared at all then it will be called sustained fault condition and it is assumed that the fault is cleared after infinite time. As there is no clearing of the fault, there is no clearing angle. From the pre-fault and during fault power-angle equations we can draw the pre-fault and during fault power angle curves as in fig. 4.4.

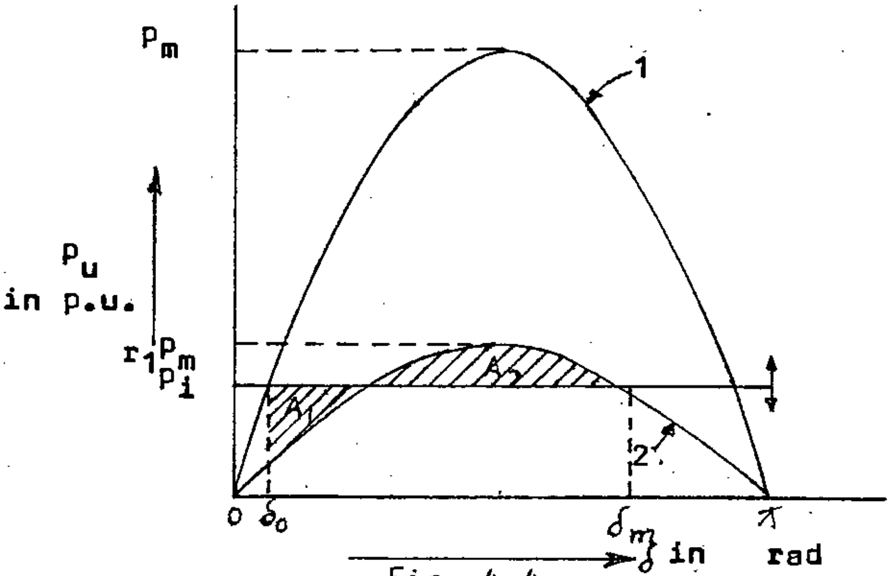


Fig. 4.4

Power-Angle Curve for Sustained Fault.

Curve - 1 — Prefault curve, $P_m \sin\delta$

Curve - 2 — Fault curve, $r_1 P_m \sin\delta$

Then applying the equal area criterion method in Fig. 4.4 the area of the rectangle $= Pi(\delta_m-\delta_o) = Pm(\delta_m-\delta_o) \sin\delta_o$ (4-19A)

the area under the power angle curve for faulted condition

$$= r_1 Pm \int_{\delta_o}^{\delta m} \sin\delta \, d\delta = r_1 Pm(\cos\delta_o - \cos\delta_m) \qquad (4.19B)$$

Equating the two areas, we get,

$$(\delta_m - \delta_o) \sin\delta_o = r_1(\cos\delta_o - \cos\delta_m) \qquad (4.20)$$

where, $\delta m = \pi - \sin^{-1}\left(\frac{\sin\delta_o}{r_1}\right)$

From the relation of r_1 and δ_o as in equation (4.20) the value of δ_o can be determined by iterative method which determines the initial power flow between the two mechines. This power will be the maximum powerflow between the machines for sustained fault condition.

If $r_1 = o$, for the adverse location of fault, the transfer impedence between the two machines will be such that there is no connection between them and virtually no power will be transferred from one machine to another.

4.3 Intermediate clearing angle and clearing time:

It is apparant that if the internal voltages E_1 & E_2 should vary, the amplitudes of all three power angle curves would change proportionately, but the ratios r_1 and r_2 would not be affected. The three power-angle curves and the input line Pi are drawn in Fig. 4.5. Then applying the equal-area criterion method, the rectangular area under the input line,

$$= Pi(\delta_m - \delta_o) = Pm\ (\delta_m - \delta_o)\ \sin\delta_o \qquad (4.21)$$

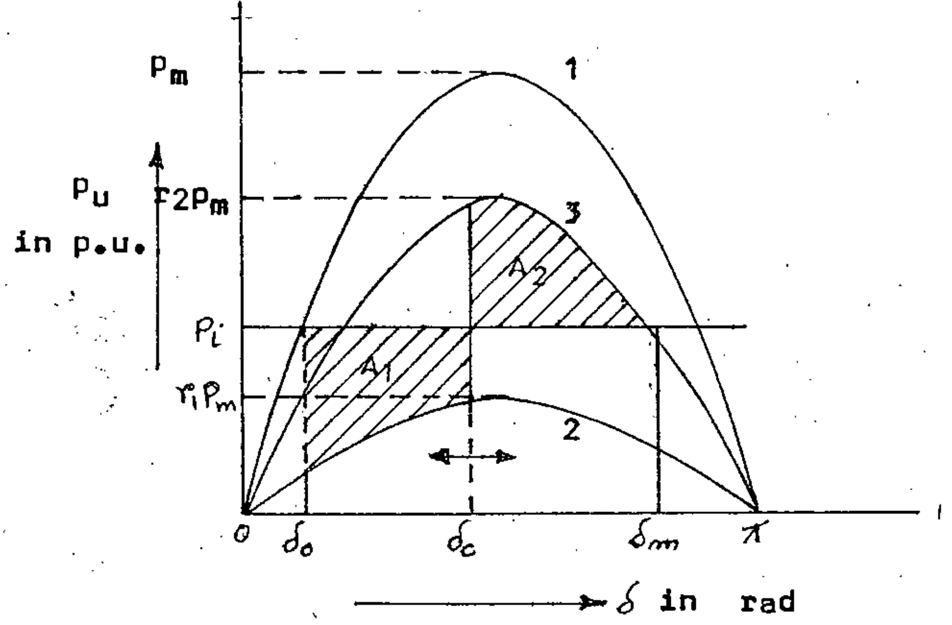


Fig. 4.5

Power-Angle Curve for Intermediate Clearing

Curve - 1 Pre-fault curve, Pm sin δ

Curve - 2 Fault-curve, $r_1 P_m \sin\delta$

Curve - 3 Post-fault curve, $r_2 P_m \sin\delta$

The area under the fault power-angle curve from angle δ_o to $\delta_c = r_1 P_m \int_{\delta_o}^{\delta_c} \sin\delta \, d\delta = -r_1 P_m(\cos\delta_c - \cos\delta_o)$ (4.22A)

The area under the post-fault power-angle curve from angle δ_c to $\delta_m = r_2 P_m \int_{\delta_c}^{\delta_m} \sin\delta \, d\delta = -r_2 P_m (\cos\delta_m - \cos\delta_c)$ (4.22B)

Equating the equations 4.21 with 4.22A and 4.22B , we get,

$$P_m(\delta_m - \delta_o)\sin\delta_o = -r_1 P_m(\cos\delta_c - \cos\delta_o) - r_2 P_m(\cos\delta_m - \cos\delta_c)$$

which yields, $$\cos\delta_c = \frac{(\delta_m - \delta_o)\sin\delta_o - r_1\cos\delta_o + r_2\cos\delta_m}{r_2 - r_1} \qquad (4.23)$$

where, $\delta_m = \pi - \sin^{-1}\left(\frac{\sin\delta_o}{r_2}\right)$

This angle, δ_c, will be the clearing angle for which the system will be stable for its output power equal to the input power P_i. The corresponding clearing time can be obtained by putting the value of δ_c in equation (4.14) and by solving it by Range-kutta method with several iterations. Then the clearing time in seconds can be achieved by putting the value of τ_c, obtained from Range-kutta method, in equation 4-12;

$$t = \tau\sqrt{\frac{GH}{\pi f r_1 P_m}} \qquad (4.24)$$

where, G = rating of the machine

H = Inertia constant

f = System frequency

P_m = maximum amplitude of prefault power angle curve.

Again, by setting a new value of initial angle δ_o in the power-angle curve, we can set a new value of input power P_i and a new value of clearing angle δ_c can be obtained. Similarly, for this new power P_i, the new value of clearing time can be obtained for this new clearing angle, δ_c. Thus a set of input power and the corresponding clearing time can be obtained by the method as stated above.

If the fault location is near any bus point 1 or 2, the transfer reactance during fault is infinity and the ratio r_1 becomes zero, i.e. the power transfer between the machines during fault period will be zero. In that case, the clearing time calculation as stated earlier will fail. For $r_1 P_m = 0$, τ_c will be zero for any value of t_c. In this case a new medified time ρ_t is introduced and related to the actual time by the equation;

$$t_c = \rho_c \sqrt{\frac{GH}{\pi f P_m}} \qquad (4.25)$$

This modified time ρ_c is differing from earlier modified time τ_c, in equation 4.24, in that P_m, the amptitude of pre-fault power-angle curve, is used instead of $r_1 P_m$, the amplitude of during fault power-angle curve. Since r_1 is zero, the negative part of the right hand side of equation 4.16A is zero. We may rewrite the equation 4.16B as,

$$M \frac{d^2\delta}{d\tau^2} = P_m \sin\delta_0 \qquad (4.26)$$

Now dividing the equation 4-26 by P_m and introducing ρ as in equation 4.25, the equation 4-26 becomes,

$$\frac{d^2\delta}{d\rho^2} = \sin\delta_0 \qquad (4.27)$$

where δ is in electrical radians.

Solving equation 4-27 , we get ,

$$\rho = \sqrt{\frac{2(\delta - \delta_0)}{\sin\delta_0}} \qquad (4.28)$$

If δ is equal to δ_c clearing angle, then ρ will be ρ_c and and t_c the clearing time, will be calculated by substituting the value of ρ_c in equation 4.25. Thus a set of input power and its corresponding clearing time can be calculated for various values of $\sin\delta_0$'s

Then a curve can be drawn with the input power Pi as a function of clearing time t_c & this curve is the stability limit curve.

CHAPTER – V

ASSUMPTIONS AND APPROXIMATIONS

Throughout this research, a number of assumptions and approximations have been made as follows:

a. Transient Saliency Neglected:

Because of the many factors involved in the stability limit study, it is not desirable to include those factors which would unduly complicate the study and have only secondary effect. An approximate method has been developed to establish a practical procedure. One of the approximations assumes that under transient conditions a synchrouous machine can be represented by a single transient reactance and a single voltage source behind the transient reactance. During transient swing the voltage behind the transient reactance is assumed to represent an equivalent constant field flux linkages. This approximation is reasonable within the normal operating range of the machine.

b. Damping Torque Neglected:

In Transient stability study the damping torque has the secondary influence on it during first and subsequent swing which occurs within one second. But in dynamic stability, the damping torques due to primermover, generator, and system do exist and have a significant influence. So, the damping torque is totally neglected in this study.

c. Constant Input Power During Swing:

The mechanical input is initially equal to the electrical output. When disturbance occurs, the output power is decreased suddenly but the input power remains unchanged. The input to a generating unit is controlled by the governor of its primemover. The governor will not act until the speed change exceeds a certain amount (usually 1% of normal speed)(2,8,17) depending on the adjustment of the governor and even then there is a time lag before the governor changes the input. During swings of the snchronous machines the percentage change in speed is very small until after synchronism is actually lost. Therefore, the governor action as well as effect of voltage regulator are neglected during transient condition and the input power is kept constant during the entire period of the swing curve.

d. Resistance Neglected:

Since the resistances are very small in comparison with the reactances, its effect are of secondary nature in transient stability study.

So, the resistances are neglected to simplify the calculations.

e. Saturation Approximated:

Because of saturation during transient condition, the equivalent transient reactance of a synchronous machine is slightly lower than the unsaturated value. The reactance representing a machine under a transient disturbance has a value of approximately 90 percent of that at rated current value (4,9,18). However, this small variation in transient reactance has a minor effect on transient stability limits and use of rated current value gives a slightly conservative result.

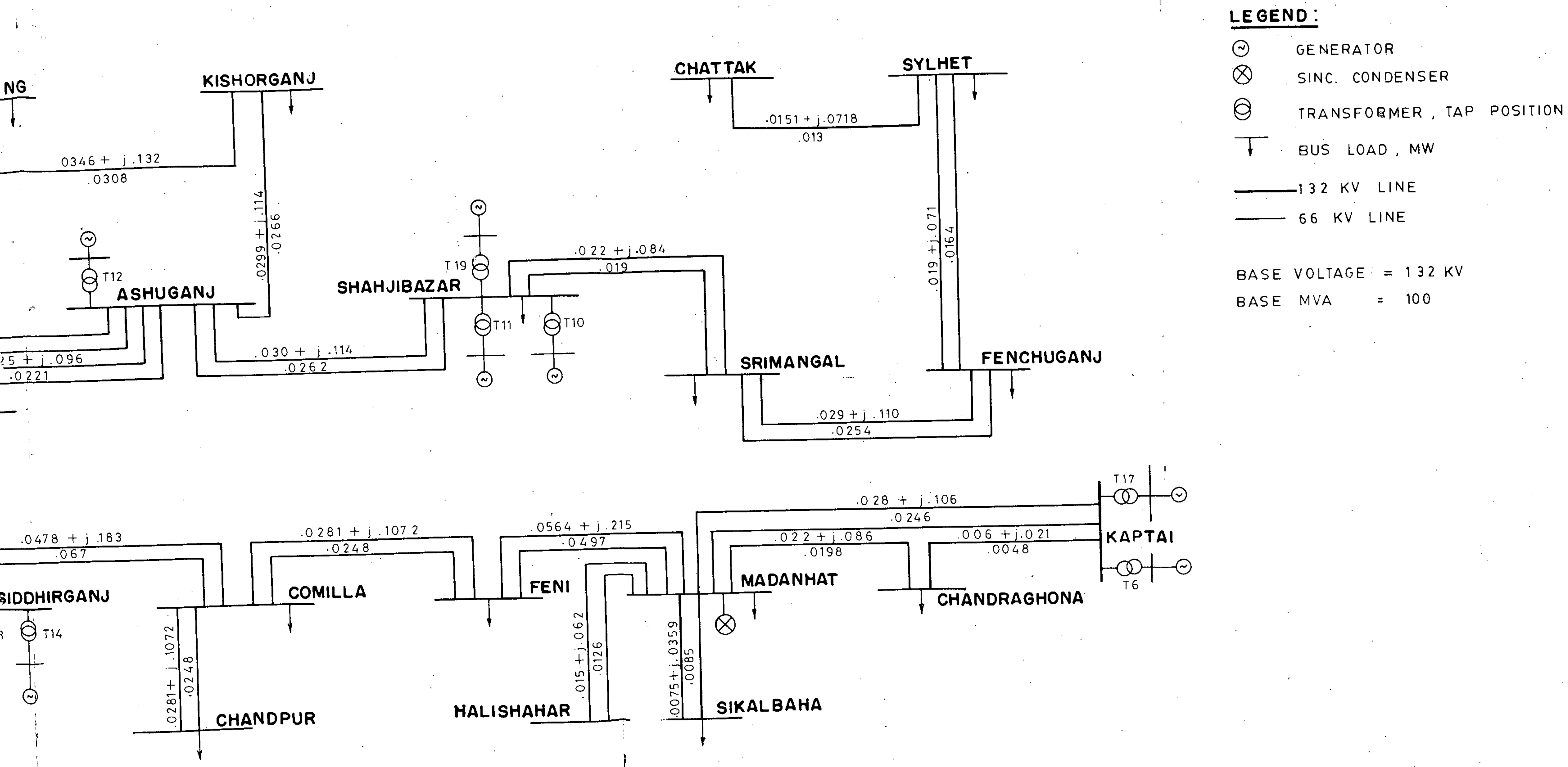
Generator saturation also increases the steady-state pull-out power over that which would exist if there were no saturation. An equivalent synchronous reactance equal to the reciprocal of short-circuit ratio has been assumed to approximate saturation effect under steady-state condition. In the over excited region this gives very conservative results. However, this has no significance, since transient stability is limiting in the overexcited region.

f. Power Trnasfer During Fault Neglected:

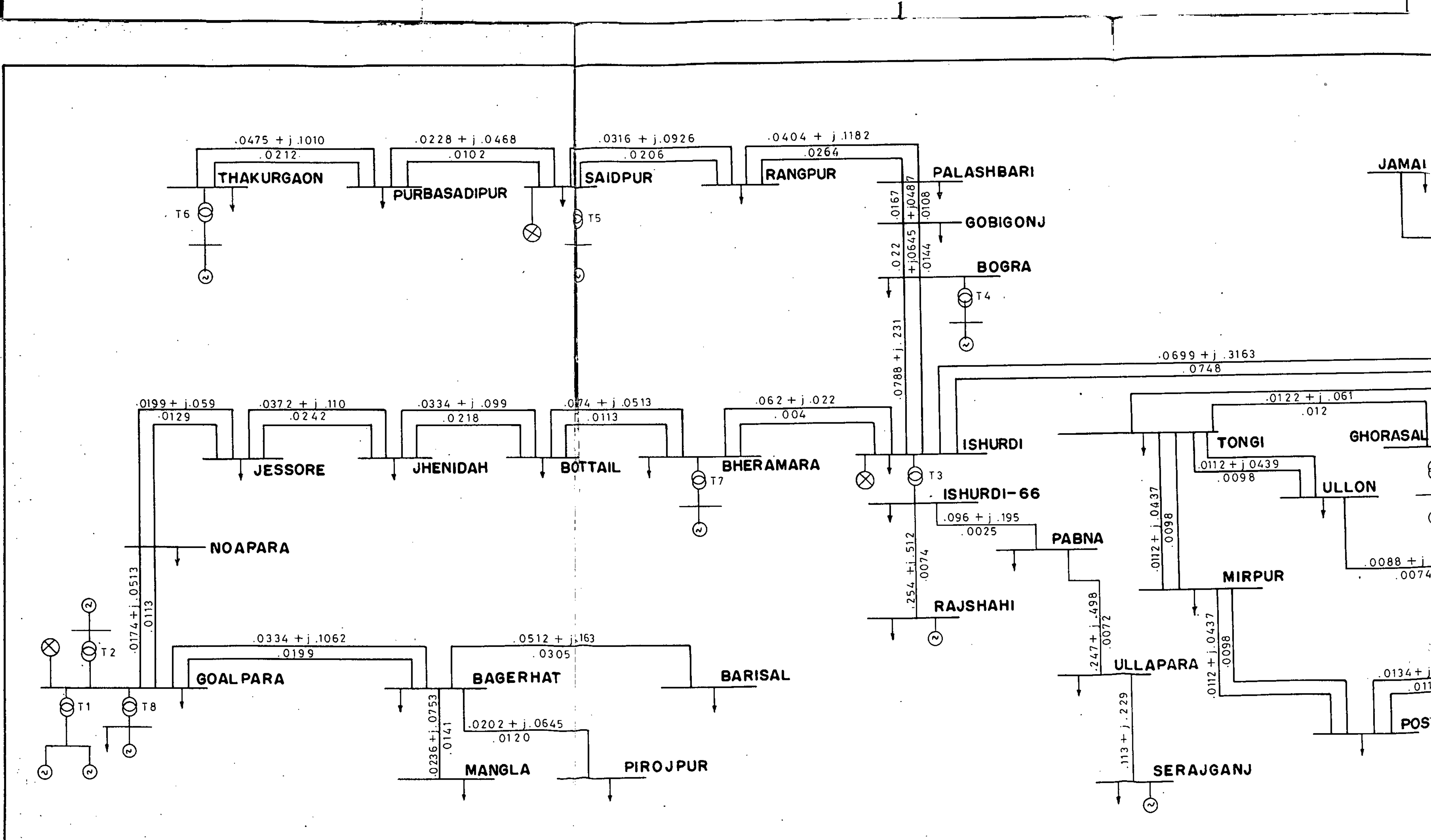
For most fault there will be some power transfer during fault. For all faults there will be resistance losses which is supplied by the generator. Both power transfer and losses will have the effect of providing some decelerating power during the fault. So the machine will not swing ahead quite as far as the calculations indicate. The result of losses and power transfer during fault will be to make the machine more stable than calculated.

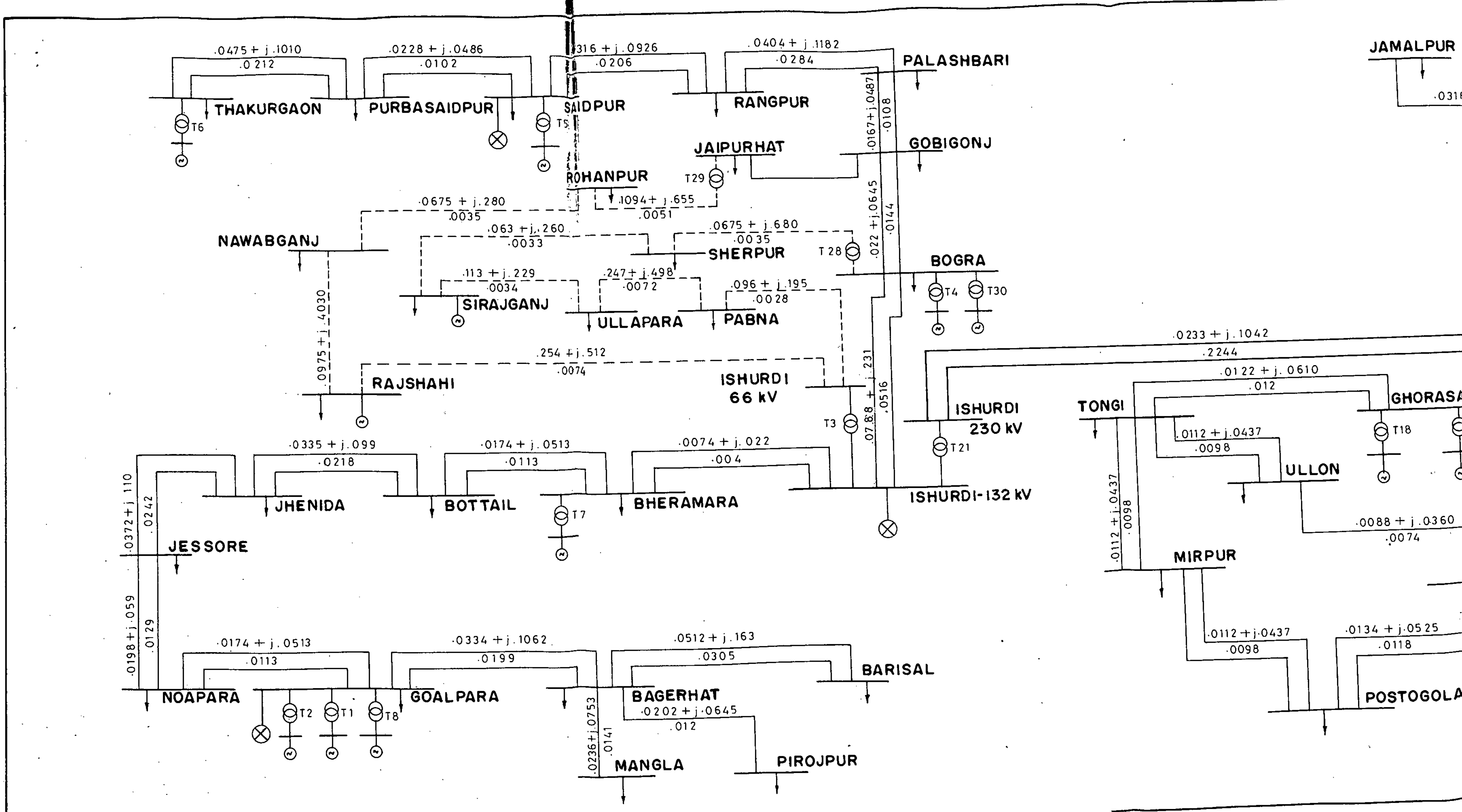
g. Simultaneous Operation of Circuit Breaker:

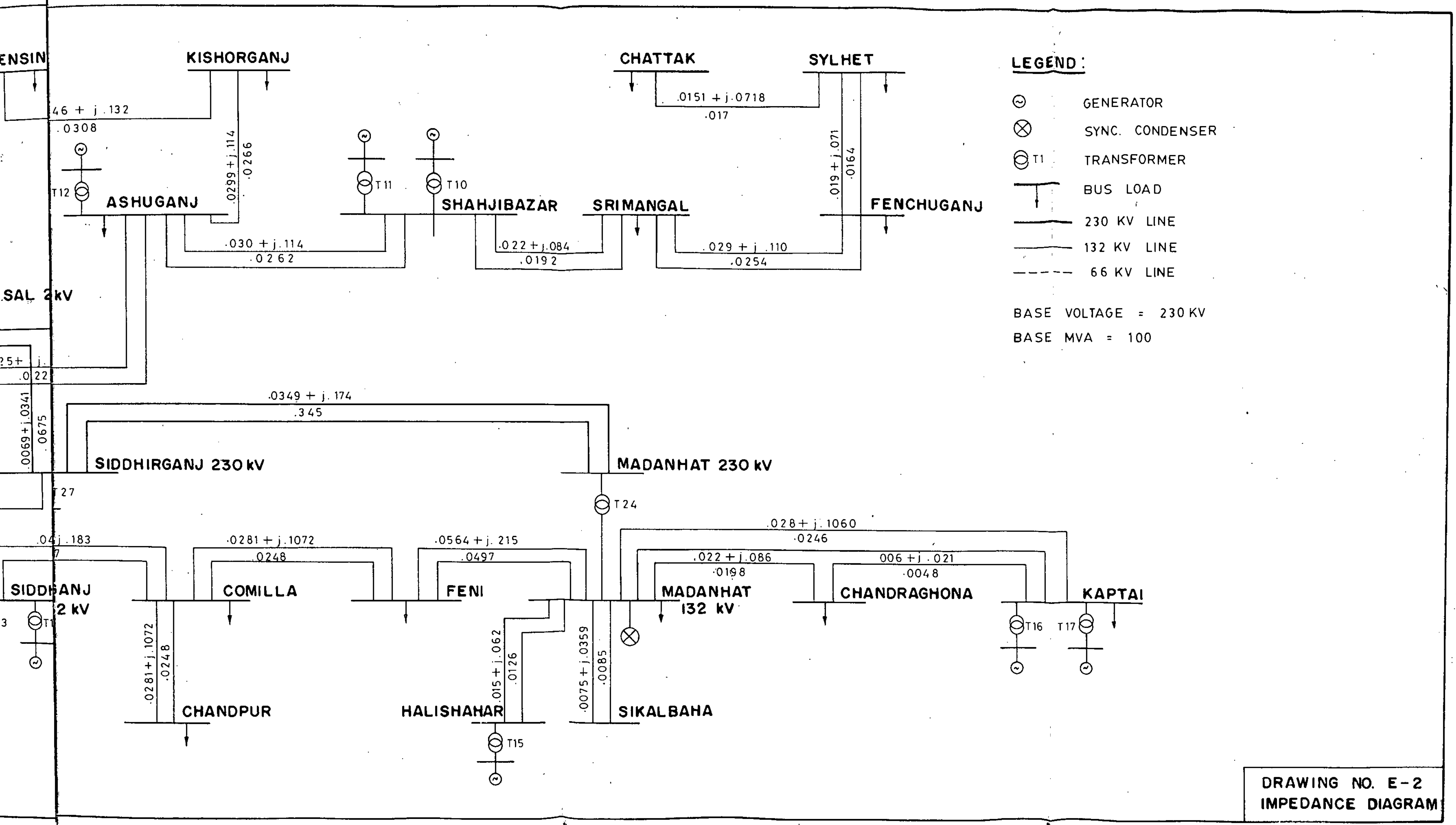
All the circuit breakers, which may open at different locations to interrupt the short circuit current due to any fault at any location ,are assumed to operate simultaneously to clear the fault. Auto reclosure is not included here.



DRAWING NO. E-1
IMPEDANCE DIAGRAM


1
.0475 + j .1010
.0212
THAKURGAON
T6
.0228 + j .0468
.0102
PURBASADIPUR
.0316 + j .0926
.0206
SAIDPUR
T5
.0404 + j .1182
.0264
RANGPUR
PALASHBARI
.0167
+ j.0487
.0108
GOBIGONJ
.022
+ j.0645
.0144
BOGRA
T4
JAMAI
.0788 + j .231
.0699 + j .3163
.0748
.0122 + j .061
.012
TONGI
GHORASAL
.0199 + j .059
.0129
JESSORE
.0372 + j .110
.0242
.0334 + j .099
.0218
JHENIDAH
.074 + j .0513
.0113
BOTTAIL
.062 + j .022
.004
BHERAMARA
T7
ISHURDI
T3
ISHURDI-66
.0112 + j .0439
.0098
ULLON
.096 + j .195
.0025
PABNA
NOAPARA
.254 + j .512
.0074
RAJSHAHI
.0112 + j .0437
.0098
MIRPUR
.0088 + j
.0074
.0174 + j .0513
.0113
T2
.0334 + j .1062
.0199
GOALPARA
.0512 + j .163
.0305
BAGERHAT
BARISAL
.247 + j .498
.0072
ULLAPARA
.0112 + j .0437
.0098
.0134 + j
.011
POS
T1
T8
.0236 + j .0753
.0141
.0202 + j .0645
.0120
MANGLA
PIROJPUR
.113 + j .229
SERAJGANJ


THAKURGAON
PURBASAIDPUR
SAIDPUR
RANGPUR
PALASHBARI
JAMALPUR
GOBIGONJ
JAIPURHAT
ROHANPUR
NAWABGANJ
SHERPUR
BOGRA
SIRAJGANJ
ULLAPARA
PABNA
RAJSHAHI
ISHURDI 66 kV
ISHURDI 230 kV
ISHURDI-132 kV
TONGI
GHORASA
ULLON
MIRPUR
POSTOGOLA
JHENIDA
BOTTAIL
BHERAMARA
JESSORE
NOAPARA
GOALPARA
BAGERHAT
BARISAL
MANGLA
PIROJPUR
T1
T2
T3
T4
T5
T6
T7
T8
T18
T21
T28
T29
T30
.0475 + j .1010
.0 212
.0228 + j .0486
.0102
.0316 + j .0926
.0206
.0404 + j .1182
.0284
.0167+j.0487
.0108
.022 +j.0645
.0144
.0318
.0675 + j.280
.0035
.1094+ j.655
.0051
.063 +j.260
.0033
.0675 + j.680
.0035
.113 + j.229
.0034
.247+ j.498
.0072
.096 + j.195
.0028
.0975 + j.4030
.254 + j.512
.0074
.07.8 + j.231
.0516
.0233 + j.1042
.2244
.0122 + j.0610
.012
.0112 + j.0437
.0098
.0088 + j.0360
.0074
.0112 + j.0437
.0098
.0112 + j.0437
.0098
.0134 + j.0525
.0118
.0335 + j.099
.0218
.0174 + j.0513
.0113
.0074 + j.022
.004
.0372 + j.110
.0242
.0198+j.059
.0129
.0174 + j.0513
.0113
.0334 + j.1062
.0199
.0512 + j.163
.0305
.0202 + j.0645
.012
.0236+j.0753
.0141



DRAWING NO. E-2
IMPEDANCE DIAGRAM

CHAPTER - VI

SYSTEM STUDY AND RESULTS

Bangladesh national grid system for operation at 132KV and 230KV levels has been considered as the model of this study. The East -West Interconnector is presently energized at 132KV and is expected to operate at 230KV level by 1987. Therefore this study has considered both the voltage levels to determine the transient stability limit. In existing network system, there are twelve number of different power stations delivering the load at the time of peak load period. In the expansion scheme, some new power stations are added with the old ones. For example, power stations at Halishahar, Ghorasal 230KV, Siddirganj 230KV , Bogra and Goalpara are added in the new scheme. The system configurations are given in drawing E-1 and drawing E-2 according to Acres International(Canada) Ltd. The line datas are given in resistance, inductive reactance and distributed capacitive susceptance in the drawings E-1 and E-2 . The generator rating in MW and in MVA , engine type, direct axis transient reactance and inertia constant are given in Table 6.1 & 6.4. The transformer rating in MVA, voltage ratios and impedance in per unit are given in Table No. 6-2 & 6.5. The tap positions of all the transformers are assumed to be unity. The data, for the planned generators and transformers, which are not available, are assumed standard values.

TABLE No- 6.1

Generator data for 132KV System

Name of the Power Station	Total No.of Generators	Generator No.	Rated MW	Rated MVA	Engine Type	Direct axis transient reactance in % on M/c. base	Inertia Constant (M) on M/c base
Kaptai	3	G_1, G_2	40	50.0	Hydro	30.0	3.861
		G_3	50	62.5	Hydro	30.0	4.00
Halishahar	1	G_1	10	12.5	G.T.	20.0	7.00
Ashugonj	5	G_1	64	90.0	S.T.	20.0	4.90
		$G_2 - G_5$	20	25.0	G.T.	24.0	6.00
Ghorasal	4	G_1, G_2	55	68.7	S.T.	20.2	4.425
		G_3	250	312.5	S.T.	20.2	2.25
		G_4	72	90.0	S.T.	21.5	5.10
Siddirgonj	4	G_1	50	62.5	S.T.	29.0	4.60
		$G_2 - G_4$	8	11.6	S.T.	22.0	4.40
Shaji bazar	10	$G_1 - G_3$	9	18.5	G.T.	18.0	6.50
		$G_4 - G_6$	9	20.0	G.T.	16.5	6.50
		G_7, G_8	10	12.5	G.T.	18.0	6.50
		G_9, G_{10}	50	62.5		29.0	4.60

contd----p

Table No. 6.1 (contd)

Name of the Power station	Total No. of Generators	Generator No.	Rated MW	Rated MVA	Engine Type	Direct axis transient reactance in % on M/c. base	Inertia Constant (M) on M/c. base
Goalpara	5	G_1	60	75.0	S.T.	21.9	5.5
		G_2, G_3	28	35.0	BMGT	22.0	5.0
		G_5, G_6	10	15.9	G.T.	23.5	6.5
Bheramara	3	$G_1 - G_3$	20	25	G.T.	21.5	4.5
Bogra	1	G_1	5	8.9	RMGT	20.6	7.0
Saidpur	3	$G_1 - G_3$	3.5	4.7	Diesel	30.55	3.85
Thakurgaon	1	G_1	10.0	12.5	Diesel	20.2	6.5
Serajgonj	1	G_1	4.3	5.4	Diesel	22.4	8.0
Rajshahi	1	G_1	4.2	5.25	Diesel	22.4	8.0

Contd----P

Table 6.1 (contd)
Condensor data for 132 KV System

Location	No. of condenser	Rated MVA	Direct axis transient reactance in %	Inertia constant (H)
Madan hat	1	50.0	15.7	5.0
Ishurdi	1	70.0	15.5	6.5
Goalpara	1	50.0	15.7	5.0
Saidpur	1	50.0	15.7	5.0

TABLE No. 6.2

Transformer data for 132KV System

Location	Transformer Number	No.	MVA Rating	Voltage Raging	Impedence Voltage in %
Kaptai	T_{16}	2	43.2/57.6	11KV/132KV	9.6
Kaptai	T_{17}	1	62.5	11KV/132KV	11.6
Halishahar	T_{15}	1	25/33.3/41.7	11KV/132KV	7.1
Ashugonj	T_{12}	2	80	11KV/132KV	12.0
Shahji bazar	T_{10}	2	45/60	11KV/132KV	11.9
Shahji bazar	T_{11}	1	15	11KV/132KV	10.5
Shahji bazar	T_{19}	2	62.5	11KV/132KV	8.75
Ghorasal	T_{18}	2	69	11KV/132KV	12.0
Ghorasal	T_{20}	1	90.0	11KV/132KV	10.0
Ghorasal	T_{25}	2	156.5	11KV/132KV	12.5
Siddirgonj	T_{13}	2	25/333	11KV/132KV	9.2
Siddirgonj	T_{14}	1	36/48/60	11KV/132KV	11.5
Goalpara	T_{1}	1	72	11KV/132KV	10.5
Goalpara	T_{2}	4	15		10.5
Goalpara	T_{8}	2	37.5	11KV/132KV	10.5
Bheramara	T_{7}	2	37.5	11KV/132KV	10.5
Ishurdi	T_{3}	2	12.5/16.7		10.6
Bogra	T_{4}	2	10/13.3		7.5
Saidpur	T_{5}	1	10/13.3		9.0
Thakurgaon	T_{6}	2	10/13.3	11KV/132KV	7.3

Table No. 6.3

Transient reactance and Inertia constant of Generators & Condensors on System base. For 132 KV System

Location	Transient reactance including transformer	Inertia Constant,H
Kaptai	j0.27243	6.361
Halishahar	j0.77026 1.813	0.875
Ashugonj	j0.19745	9.920
Ghorasal	j0.05976	16.295
Siddirgonj	j0.34788	4.410
Shahjibazar	j0.11928	14.883
Goalpara	j0.19044	9.692
Bheramara	j0.42667	3.380
Bogra	j2.59656	0.623
Saidpur	j2.84336	0.543
Thakurgaon	j1.89044	0.813
Sirajgonj	j5.16700	0.430
Rajshahi	j5.26700	0.420
	Condensers	
Madanhat	j0.5700	2.500
Ishurdi	j0.3643	4.550
Goalpara	j0.5700	2.500
Saidpur	j0.5700	2.500

Table No. 6.4

Generator data for 230KV System

Name of the Power Station	Total no.of Generators	Generator Number	Rated MW	Rated MVA	Engine Type	Direct axis Transient Reactance in % on m/c base	Inertia constant (H) on Machine base
Kaptai	5	G_1,G_2	40	50.0	Hydro	30.0	3.861
		G_3-G_5	50	62.5	Hydro	30.0	4.000
Halishahar	1	G_1	10	12.5	G.T.	20.0	7.000
Ashugonj	5	G_1	64	9.0	S.T.	20.0	4.900
		G_2-G_5	20	25.0	G.T.	24.0	6.000
Ghorasal-132KV	3	G_1,G_2	55	68.7	S.T.	20.20	4.425
		G_3	250	312.5	S.T.	20.2	2.250
Ghorasal-230KV	1	G_1	250	312.5	S.T.	20.2	2.250
Shahjibazar	8	G_1-G_3	9	18.5	G.T.	18.0	6.500
		G_4-G_6	9	20.0	G.T.	16.5	6.500
		G_7-G_8	10	12.50	G.T.	18.0	6.500
Siddirgonj-132KV	4	G_1	50	62.50	S.T.	29.0	4.600
		G_2-G_4	8	11.60	S.T.	22.0	4.400
Siddirgonj-230KV	1	G_1	250	312.5	S.T.	20.2	2.250

Contd---P

Table No. 6.4(Contd)

Name of the Power station	Total No.of Generators	Generator Number	Rated MW	Rated MVA	Engine Type	Direct axis Transient Reactance in % on m/c base	Inertia consta (H) on Machine ba
Goalpara	6	G_1	60	75.0	S.T.	21.9	5.500
		G_2, G_3	28	35.0	BMGT	22.0	5.000
		G_4, G_5	10	15.9	G.T.	23.5	6.500
		G_6	110	137.5	S.T.	20.2	5.000
Bheramara	3	G_1-G_3	20	32.0	S.T.	21.50	4.500
Bogra	2	G_1	5	8.9	RMGT	20.60	7.000
		G_2	100	125.0	S.T.	20.20	4.500
Saidpur	3	G_1-G_3	3.5	4.7	Diesel	30.55	3.850
Thakurgaon	1	G_1	10.0	12.5	Diesel	20.20	6.500
Sirajgonj	1	G_1	4.3	5.375	Diesel	22.40	8.000
Rajshahi	1	G_1	4.2	5.45	Diesel	22.40	8.000

Table No. 6.4 (contd)

Condensor data for 230KV System

Location	No. of condenser	Rated MVAR	Direct axis transient reactance in %	Inertia constant (H)
Madanhat	1	50.00	15.7	5.00
Ishurdi	1	200.00	10.0	2.22
Goalpara	1	100.00	14.5	4.50
Saidpur	1	70.00	15.5	6.50

Table No. 6.5

Transformer data for 230KV system

Location	Transformer No.	No.	MVA Rating	Voltage Rating	Impedance Voltage in %
Kaptai	T16	2	43.2/57.6	11KV/132KV	9.6
Kaptai	T17	3	62.5	11KV/132KV	11.6
Halishahar	T15	1	25/33.3/41.7	11KV/132KV	7.1
Ashugonj	T12	2	80	11KV/132KV	12.0
Shajibazar	T10	2	45/60	11KV/132KV	11.9
Shahjibzaar	T11	1	15	11KV/132KV	10.5
Ghorasal-132KV	T18	2	69	11KV/132KV	12.0
Ghorasal-132KV	T25	2	156.5	11KV/132KV	12.5
Ghorasal-230KV	T26	4	156.5	11KV/230KV	12.5
Siddirgonj-132KV	T13	2	25/33.3	11KV/132KV	9.2
Siddirgonj-132KV	T14	1	36/48/60	11KV/132KV	11.5
Siddirgonj-230KV	T27	2	156.5	11KV/250KV	12.5
Goalpara	T1	1	72.0	11KV/132KV	10.5
Goalpara	T2	4	15.0		10.5
Goalpara	T8	2	37.5	11KV/132KV	10.5
Goalpara	T9	1	125	11KV/132KV	8.0
Bheramara	T7	2	37.5	11KV/132KV	10.5
Ishurdi 132KV	T3	2	12.5/16.7	66KV/132KV	10.6
Bogra	T4	2 1	10/13.3 125.0	 11KV/132KV	7.5 9.0
Bogra	T28	1	10		10.0
Saidpur	T5	1	10/13.3		9.0
Thakurgaon	T6	2	10/13.3	11KV/132KV	7.3
Jaipurhat	T29	1	10		10.0

Table No. 6.5 (contd)

Location	Transformer Number	No.	MVA Rating	Voltage Rating	Impedance Voltage in %
Madanhat	T24	2	100	132KV/230KV	10.0
Siddirgonj	T23	1	100	132KV/230KV	10.0
Ghorasal	T22	1	100	132KV/230KV	10.0
Ishurdi	T21	3	250	132KV/230KV	10.0

Table No- 6.6

Transient reactance and inertia constant of generators and condensers on system base.

For 230KV System.

	Location	Transient reactance including transformer on system base in p.u.	Inertia constant on system base
1.	Kaptai	j0.14810	11.36100
2.	Halishahar	j1.62481 1.813	0.87500
3.	Ashugonj	jo.18205	9.92000
4.	Ghorasal-132KV	j0.07227	13.02188
5.	Ghorasal-230KV	j0.09502	6.93750
6.	Siddirgonj-132KV	j0.34785	4.41000
7.	Siddirgonj-230KV	j0.10458	6.93750
8.	Shahji bazar	j0.21020	8.20625
9.	Goalpara	j0.09450	15.69200
10.	Bheramara	j0.42667	3.38000
11.	Bogra	j0.20007	5.62300
12.	Saidpur	j2.84336	0.54285
13.	Thakurgaon	j1.82444	0.81250
14.	Sirajgonj	j5.16700	0.43000
15.	Rajshahi	j5.26700	0.42000
	Condensers:		
1.	Madanhat	j0.57000	2.50000
2.	Ishurdi-132KV	j0.09000	4.44000
3.	Goalpara	j0.28500	4.50000
4.	Saidpur	j0.36450	4.55000

The generators operating in a power station are combined together and replaced by a single equivalent unit and represented by the voltage behind transient reactance in series with an equivalent transient reactance, X'_d, which is the parallel combination of all the individual transient reactnaces of the machine and the reactances of its connecting transformer in a power station, shown in Table No-6.3 & 6.6.

For example in Ghorasal 132KV power station there are two generators and two transformers connecting the generators with the system network as in figure 6.1.

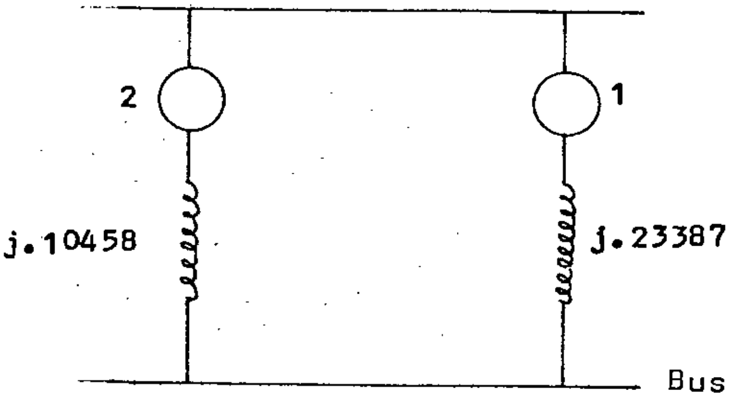


Fig. 6.1

Equivalent Generator connection diagram

The reactance on the system base MVA is obtained by the formula $X'd \text{ (system base)} = \frac{X'd \text{ machine base}}{m/c \text{ rating in MVA}} \times \text{System base MVA}$

In Fig. 6.1 reactances of generators and transformers are

$$X'd_1 = \frac{.202}{2\times68.75} \times 100 + \frac{.12\times100}{2\times69} = j.23387 \text{ p.u.}$$

$$\text{and } X'd_2 = \frac{.202\times.8}{1\times250} \times 100 + \frac{.125}{2\times156.5} \times 100 = j.10458 \text{ p.u.}$$

Then the equivalent reactance will be the parallel combination of the two and equal to j.07227 p.u.

The inertia constants of each of the generators in a power station are combined to a single equivalent inertia constant on the same system base MVA. For example, in Ghorasal 132KV station, $He = \frac{4.425 \times 68.75}{100} \times 2 + \frac{2.22\times250}{100\times .8} = 13.02188$. The equivalent inertia constant of the machine in a group is the summation of inertia constants of all the individual machines in the group.

Since resistance and distributed capacitance of transmission lines have little effect on transient stability studies, these two quantities have been omitted for simplification of calculations.

At normal operation, the torque angle between two machines and the voltages behind their transient reactances depend on the load flow between them. At different load conditions the torque angle between the machines and the voltages behind transient reactnace are obtained from the reference voltage at bus 1 and bus 2 of the inter-grid system with the help of trigonometrical relations as in Fig. 6.2. The reference voltage at the two ends are taken either nominal voltages or from actual load flow studies.

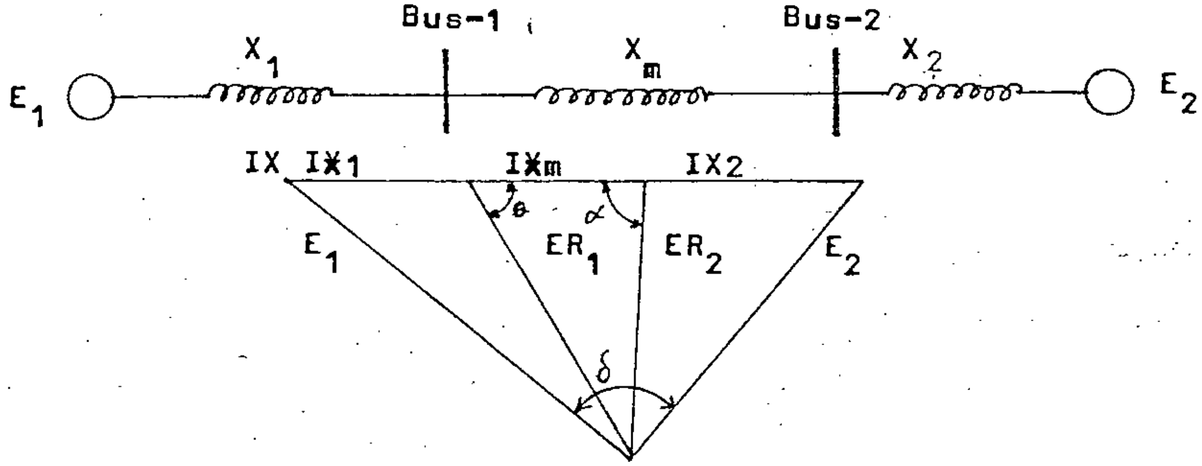


Fig. 6.2

Reactance and Voltage Vector Diagram

From the relation of trigonometry, the angle θ and α are calculated as in equation;

$$\cos A = (b^2+c^2-a^2)/2bc \tag{6.1}$$

Whereas a, b & c are known values and the machine voltages behind transient reactance E1 & E2 are calculated as in equation

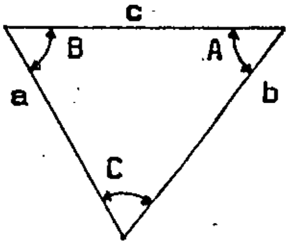


Fig. 6.3

Trigonometrical Relation of a Triangle

$$a = \sqrt{b^2+c^2-2bc \ \cos A} \qquad (6.2)$$

according to Fig. 6.3 , where, b, c and A are known values. The boundary value (i.e. the value at the two extreme moment at instantenous clearing and sustained fault condition) of the internal angular differences are calculated by iterative method and the corresponding voltages behind transient reactance and power transfer are calculated as in equations 6.1, 6.2 , 4.15 and 4.16 . The system is simulated with a three phase fault at the middle point and near bus point 1 or 2 on the East-West interconnector. For both of the fault conditions the system is studied for different clearing time from instantaneous clearing condition to sustained fault condition.

The swing equation for each of the fault condition from initial angle, δo to the clearing angle, δ_c is sloved by Runge-Kutta fourth order approximation (22, 23).

A computer programm has been developed to solve all the equations required for obtaining the maximum power trsnsfer for different clearing time of the breaker and plot power transfer as a function of clearing time. There are five subroutine programs for solving the boundary values of initial angular difference between machines, for calculating the value of clearing angle, δc and for calculating clearing time etc. The input datas given to the program are (i) various load values(2) reference voltages of the two buses (3) inertia constants of the machines and (5) the transfer reactances of the machines.

The final results obtained from the computer are the curves of input maximum power Pi, Vs. clearing time t_c along with the values of Pi in p.u. and t_c in seconds.

The results obtained from the output curves are tabulated in Table No. 6.7 and Table No. 6.8.

In the power system study done by Acres international, they found the safe limit of power transfer to be 180 MW at 132KV level operation and 500MW at 230KV level operation. Results obtained by this algorithm are in agreement and this proves the accuracy of the algorithm.

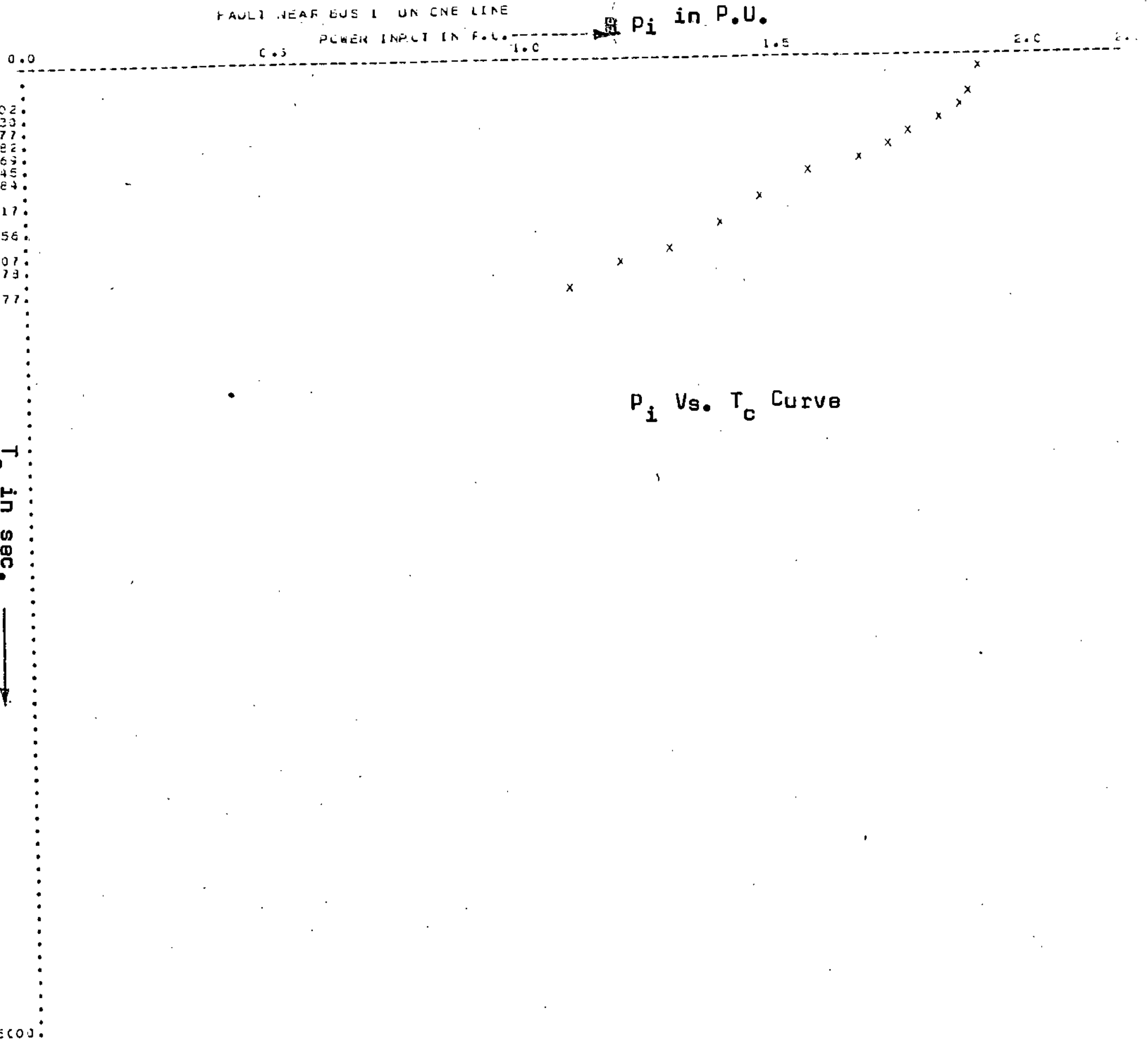
```
   AI          E1          E2          DELTA       SIN(DELTA)      FI         FM

 1.94875    1.035736    1.060626    38.797775    0.626573    1.925467    3.073013
 1.92000    1.034708    1.059094    38.255905    0.619174    1.897738    3.064951
 1.90000    1.034000    1.057963    37.878250    0.613935    1.878432    3.059410
 1.85000    1.032262    1.054974    36.931259    0.600836    1.830091    3.045807
 1.80000    1.030567    1.052115    35.980789    0.587513    1.781674    3.032570
 1.75000    1.028915    1.049327    35.026398    0.573963    1.733157    3.019684
 1.70000    1.027308    1.046610    34.068558    0.560184    1.684563    3.007161
 1.60000    1.024227    1.041393    32.142456    0.532026    1.587137    2.983198
 1.50000    1.021324    1.036469    30.202927    0.503064    1.489408    2.960675
 1.40000    1.018600    1.031640    28.250334    0.473328    1.391391    2.939595
 1.30000    1.016058    1.027513    26.285904    0.442850    1.293104    2.919959
 1.20000    1.013699    1.023489    24.309875    0.411671    1.194574    2.901771
 1.10000    1.011522    1.019773    22.323135    0.379835    1.095818    2.885028
 1.00000    1.005532    1.016369     0.0         0.0         0.0         2.869740
   AI    CLEARING ANGLE   ROWC      CLEARING TIME    POWER INPUT
 1.94875    0.67715     0.0            0.0           1.92547
 1.92000    0.68675     0.24612        0.04028       1.89774
 1.90000    0.69378     0.32629        0.05302       1.87843
 1.85000    0.71300     0.47725        0.07773       1.83009
 1.80000    0.73442     0.60194        0.09825       1.78167
 1.75000    0.75792     0.71472        0.11690       1.73316
 1.70000    0.78336     0.82091        0.13455       1.68456
 1.60000    0.83962     1.02344        0.16842       1.58714
 1.50000    0.90241     1.22145        0.20177       1.48941
 1.40000    0.97113     1.42126        0.23562       1.39139
 1.30000    1.04538     1.62764        0.27074       1.29310
 1.20000    1.12490     1.84492        0.30784       1.19457
 1.10000    1.20962     2.07752        0.34772       1.09582
 1.00000    SUSTND      INFINI         INFINT        0.0
```

GRAPH NO.

132 KV SYSTEM
REF. VOLTS. IN P.U. 1.000 & 1.000

FAULT NEAR BUS 1 ON ONE LINE

PI	TC
1.92347	0.0
1.89774	0.0402
1.87843	0.0530
1.83009	0.0777
1.78167	0.0982
1.73316	0.1169
1.68456	0.1345
1.58714	0.1684
1.48941	0.2017
1.39139	0.2356
1.29310	0.2707
1.19457	0.3073
1.09982	0.3477



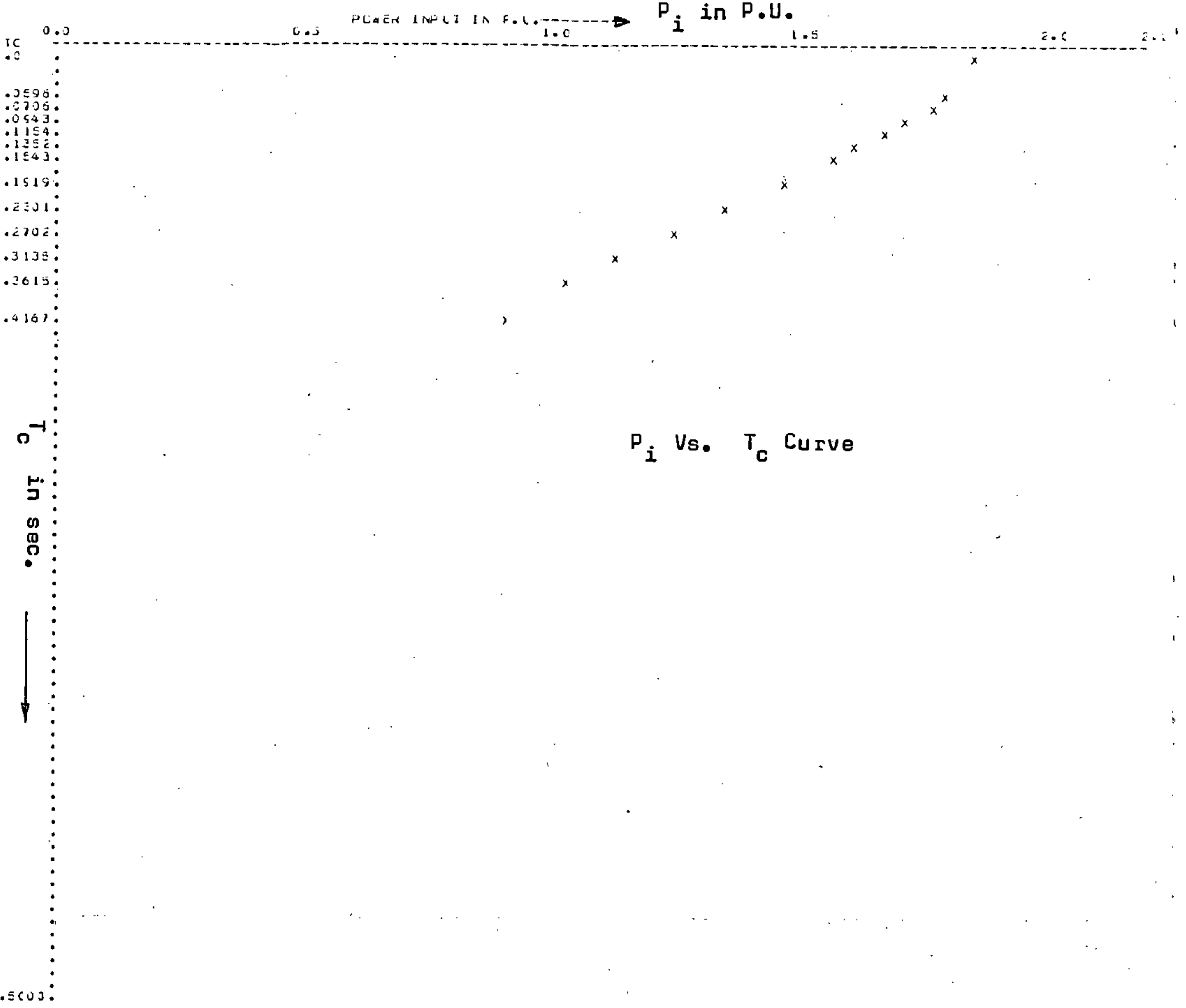
```
   AI          E1          E2         DELTA      SIN(DELTA)      FI          FM

1.97452     1.121026    0.944255    38.795396    0.626602    1.855103    2.960577
1.92000     1.119211    0.940527    37.690372    0.611400    1.800050    2.944143
1.90000     1.118557    0.939195    37.281738    0.605714    1.779783    2.939225
1.85000     1.116950    0.935894    36.253494    0.591358    1.728949    2.923691
1.80000     1.115383    0.932670    35.217392    0.576680    1.677868    2.909533
1.75000     1.113858    0.929524    34.173203    0.561696    1.626533    2.895753
1.70000     1.112373    0.926456    33.120345    0.546395    1.574911    2.882347
1.60000     1.109529    0.920558    30.987885    0.514857    1.470777    2.856674
1.50000     1.106849    0.914964    28.816391    0.482034    1.365284    2.832517
1.40000     1.104337    0.909737    26.600922    0.447773    1.258190    2.809885
1.30000     1.101993    0.904626    24.334152    0.412057    1.145138    2.788784
1.20000     1.099817    0.900254    22.005219    0.374691    1.037600    2.769217
1.10000     1.097812    0.896026    19.597350    0.335413    0.922784    2.751185
1.00000     1.095978    0.892151     0.0         0.0         0.0         2.734710
   AI    CLEARING ANGLE   RUKC      CLEARING TIME    POWER INPUT
1.97452     0.67719      0.0            0.0            1.85510
1.92000     0.69741      0.35962        0.05960        1.80005
1.90000     0.70563      0.42552        0.07063        1.77970
1.85000     0.72806      0.56779        0.09438        1.72895
1.80000     0.75306      0.69283        0.11545        1.67767
1.75000     0.78049      0.80955        0.13522        1.62653
1.70000     0.81025      0.92169        0.15434        1.57491
1.60000     0.87631      1.14155        0.19197        1.47078
1.50000     0.95068      1.36502        0.23019        1.36528
1.40000     1.03314      1.59401        0.27029        1.25819
1.30000     1.12389      1.84217        0.31359        1.14514
1.20000     1.22362      2.11691        0.36158        1.03760
1.10000     1.33376      2.43175        0.41671        0.92278
1.00000     SUSTND       INFINT         INFINT         0.0
```

GRAPH NO.

132 KV SYSTEM
REF. VOLTS. IN P.U. 1.043 & 0.950

FAULT NEAR BUS 1 ON ONE LINE

PI	TC
1.85510	0.0
1.80005	0.0596
1.77978	0.0706
1.72895	0.0943
1.67787	0.1154
1.62653	0.1352
1.57491	0.1543
1.47078	0.1919
1.36528	0.2301
1.25819	0.2702
1.14914	0.3135
1.03760	0.3615
0.92278	0.4167



P_i Vs. T_c Curve

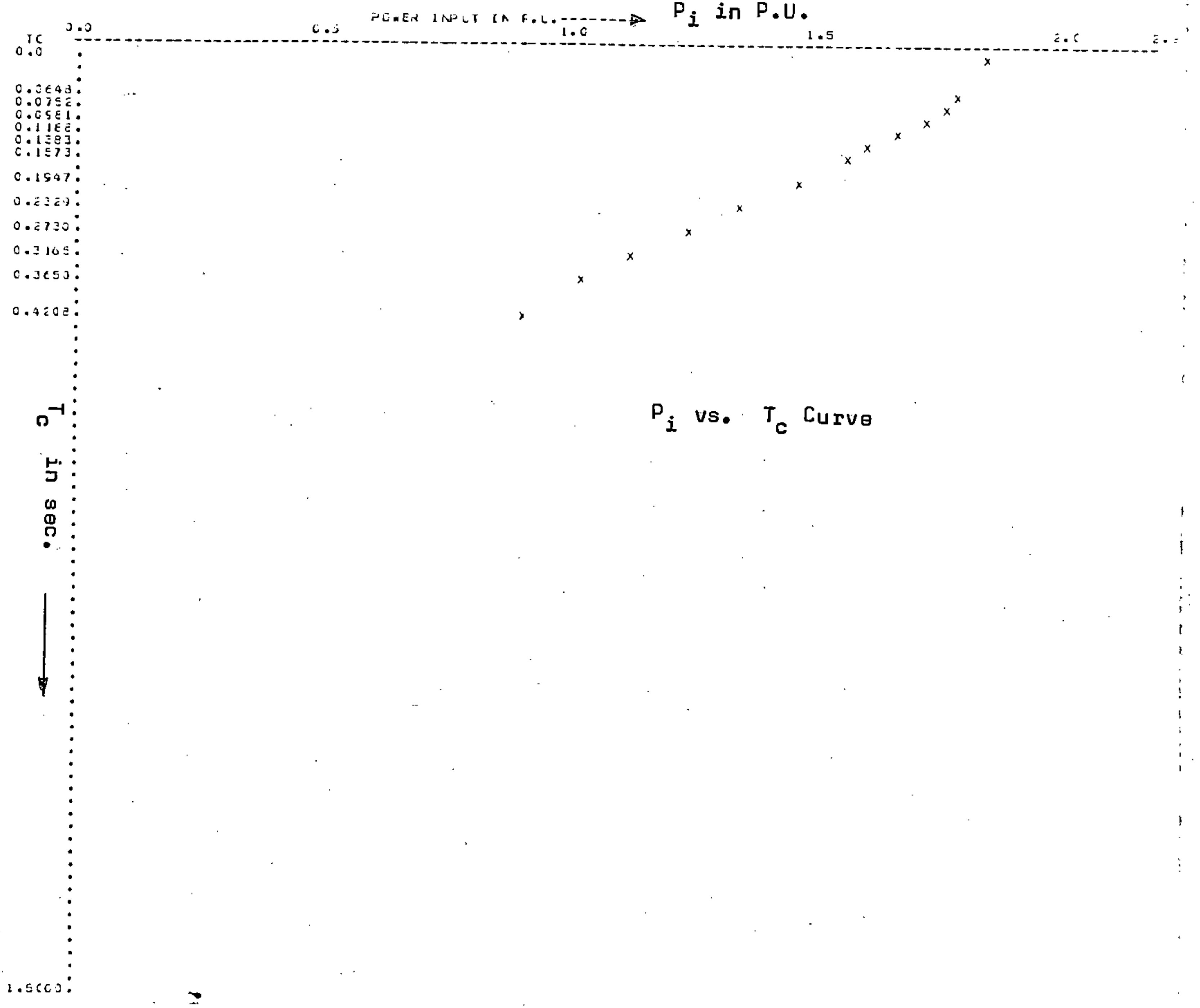
```
    AI          E1          E2         DELTA      SIN(DELTA)      FI          FM

 1.98467     1.127092    0.946066    38.807770    0.626709    1.869077    2.982368
 1.92000     1.124944    0.941670    37.493652    0.608673    1.803370    2.962790
 1.90000     1.124293    0.940331    37.084579    0.602993    1.782968    2.956863
 1.85000     1.122695    0.937054    36.056656    0.588534    1.731796    2.942308
 1.80000     1.121137    0.933614    35.020523    0.573865    1.680362    2.928126
 1.75000     1.119619    0.930671    33.976181    0.558848    1.628662    2.914323
 1.70000     1.118142    0.927667    32.923050    0.543512    1.576671    2.900896
 1.60000     1.115312    0.921717    30.785352    0.511893    1.471753    2.875177
 1.50000     1.112646    0.916149    28.615555    0.478930    1.365419    2.850980
 1.40000     1.110147    0.910910    26.396378    0.444578    1.257403    2.828308
 1.30000     1.107815    0.906005    24.123901    0.408711    1.147321    2.807170
 1.20000     1.105651    0.901439    21.786880    0.371155    1.034619    2.787565
 1.10000     1.103656    0.897218    19.367035    0.331618    0.918419    2.769509
 1.00000     1.101832    0.893347     0.0         0.0         0.0         2.753003
    AI    CLEARING ANGLE   HGWC     CLEARING TIME    POWER INPUT
 1.98467     0.67732     0.0           0.0           1.86908
 1.92000     0.70132     0.39270       0.06485       1.80337
 1.90000     0.70974     0.45527       0.07525       1.78297
 1.85000     0.73264     0.59254       0.09615       1.73180
 1.80000     0.75807     0.71539       0.11863       1.68036
 1.75000     0.78591     0.83090       0.13834       1.62866
 1.70000     0.81604     0.94255       0.15730       1.57667
 1.60000     0.88282     1.16177       0.19475       1.47175
 1.50000     0.95789     1.38365       0.23292       1.36542
 1.40000     1.04107     1.61562       0.27305       1.25740
 1.30000     1.13262     1.86663       0.31657       1.14732
 1.20000     1.23331     2.14400       0.36500       1.03462
 1.10000     1.34470     2.46401       0.42084       0.91842
 1.00000     SUSTND      INFINT        INFINT        0.0
```

GRAPH NO.

132 KV SYSTEM
REF. VOLTS. IN P.U. 1.048 & 0.953

FAULT NEAR BUS 1 ON ONE LINE

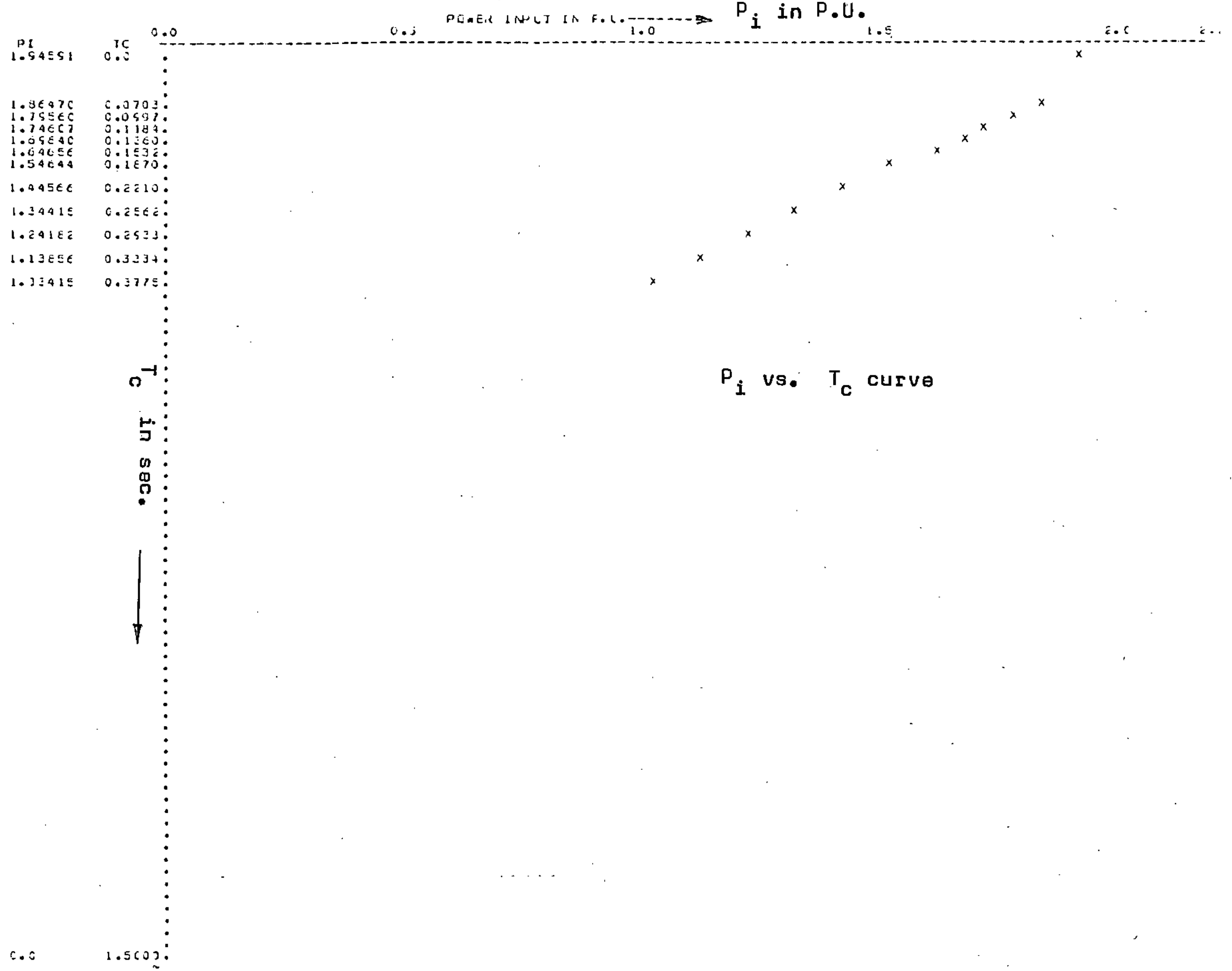
PI	TC
1.86508	0.0
1.80337	0.0648
1.78297	0.0752
1.73180	0.0981
1.68036	0.1182
1.62866	0.1383
1.57667	0.1573
1.47175	0.1947
1.36542	0.2329
1.25740	0.2730
1.14732	0.3165
1.03462	0.3650
0.91642	0.4202



P_i vs. T_c Curve

```
   AI          E1          E2          DELTA       SIN(DELTA)     FI          FM

2.00260     0.981134    1.131669    38.800323    0.626608    1.945906    3.105461
1.92000     0.977964    1.126952    37.224319    0.604937    1.864701    3.082475
1.90000     0.977215    1.125833    36.640373    0.596796    1.844968    3.077055
1.85000     0.975376    1.123061    35.879242    0.586078    1.795601    3.063756
1.80000     0.973582    1.120395    34.912933    0.572331    1.746069    3.050806
1.75000     0.971834    1.117778    33.942032    0.558353    1.696398    3.038217
1.70000     0.970132    1.115227    32.966187    0.544144    1.646564    3.025973
1.60000     0.966868    1.110333    31.000275    0.515042    1.546443    3.002560
1.50000     0.963792    1.105715    29.014389    0.485029    1.445656    2.980557
1.40000     0.960906    1.101378    27.007360    0.454108    1.344148    2.959976
1.30000     0.958211    1.097324    24.978165    0.422273    1.241822    2.940809
1.20000     0.955708    1.093558    22.923981    0.389509    1.138559    2.923063
1.10000     0.953400    1.090081    20.841171    0.355778    1.034151    2.906732
1.00000     0.951288    1.086697     0.0         0.0         0.0         2.891822
   AI    CLEARING ANGLE   ROWC      CLEARING TIME    POWER INPUT
2.00260     0.67719     0.0             0.0            1.94591
1.92000     0.70682     0.43400         0.07036        1.86470
1.90000     0.71494     0.48986         0.07938        1.84499
1.85000     0.73683     0.61440         0.09977        1.79560
1.80000     0.76084     0.72759         0.11840        1.74607
1.75000     0.78685     0.83458         0.13609        1.69640
1.70000     0.81477     0.93804         0.15327        1.64656
1.60000     0.87590     1.14029         0.18705        1.54644
1.50000     0.94362     1.34272         0.22106        1.44566
1.40000     1.01754     1.55095         0.25623        1.34415
1.30000     1.09747     1.77007         0.29338        1.24182
1.20000     1.18349     2.00560         0.33343        1.13856
1.10000     1.27596     2.26450         0.37753        1.03415
1.00000     SUSTND      INFINT          INFINT         0.0
```

```
GRAPH NO.

        132 KV SYSTEM
REF. VOLTS. IN P.U.  0.972 & 1.030

FAULT NEAR BUS 1  ON ONE LINE
```



```
  PI           TC
1.94591      0.0

1.86470      0.0703.
1.79560      0.0997.
1.74607      0.1184.
1.69640      0.1360.
1.64656      0.1532.
1.54644      0.1870.

1.44566      0.2210.

1.34415      0.2562.

1.24182      0.2933.

1.13856      0.3234.

1.03415      0.3775.
```

P_i vs. T_c curve

```
    AI          E1          E2         DELTA      SIN(DELTA)      FI          FV

 1.94375     1.035736    1.060626    38.797775    0.626573    1.925467    3.073013
 1.92000     1.034709    1.059054    38.255905    0.619174    1.897738    3.064551
 1.90000     1.034000    1.057903    37.878250    0.613935    1.876432    3.059410
 1.85000     1.032262    1.054974    36.931259    0.600856    1.830091    3.045807
 1.80000     1.030567    1.052115    35.980759    0.587513    1.781674    3.032570
 1.75000     1.028915    1.049327    35.026398    0.573953    1.733157    3.019684
 1.70000     1.027308    1.046610    34.068558    0.560134    1.684563    3.007161
 1.60000     1.024227    1.041393    32.142456    0.532026    1.587137    2.983198
 1.50000     1.021324    1.036469    30.202927    0.503034    1.489408    2.960675
 1.40000     1.018600    1.031840    28.250534    0.473328    1.391391    2.939595
 1.30000     1.016058    1.027513    26.285904    0.442830    1.293104    2.919959
 1.20000     1.013699    1.023489    24.309875    0.411671    1.194574    2.901771
 1.10000     1.011522    1.019773    22.323135    0.379825    1.095818    2.885028
 0.70078     1.004651    1.008071    14.300309    0.247034    0.699678    2.832661


    AI    CLEARING ANGLE   TCWC     CLEARING TIME    POWER INPUT
 1.94375     0.67715      0.0           0.0            1.92547
 1.92000     0.70255      0.22500       0.06570        1.89774
 1.90000     0.71588      0.29375       0.06585        1.87843
 1.85000     0.76427      0.42500       0.12449        1.83009
 1.80000     0.81178      0.53437       0.15687        1.78167
 1.75000     0.85992      0.63125       0.18570        1.73316
 1.70000     0.91212      0.72500       0.21372        1.68456
 1.60000     1.01995      0.90312       0.26730        1.58714
 1.50000     1.13453      1.08125       0.32123        1.48941
 1.40000     1.25400      1.26562       0.37735        1.39139
 1.30000     1.38640      1.47187       0.44032        1.29310
 1.20000     1.52625      1.70312       0.51109        1.19457
 1.10000     1.67673      1.97611       0.59534        1.09582
 0.70078     SUSTND       INFINT        INFINT         0.69968
```

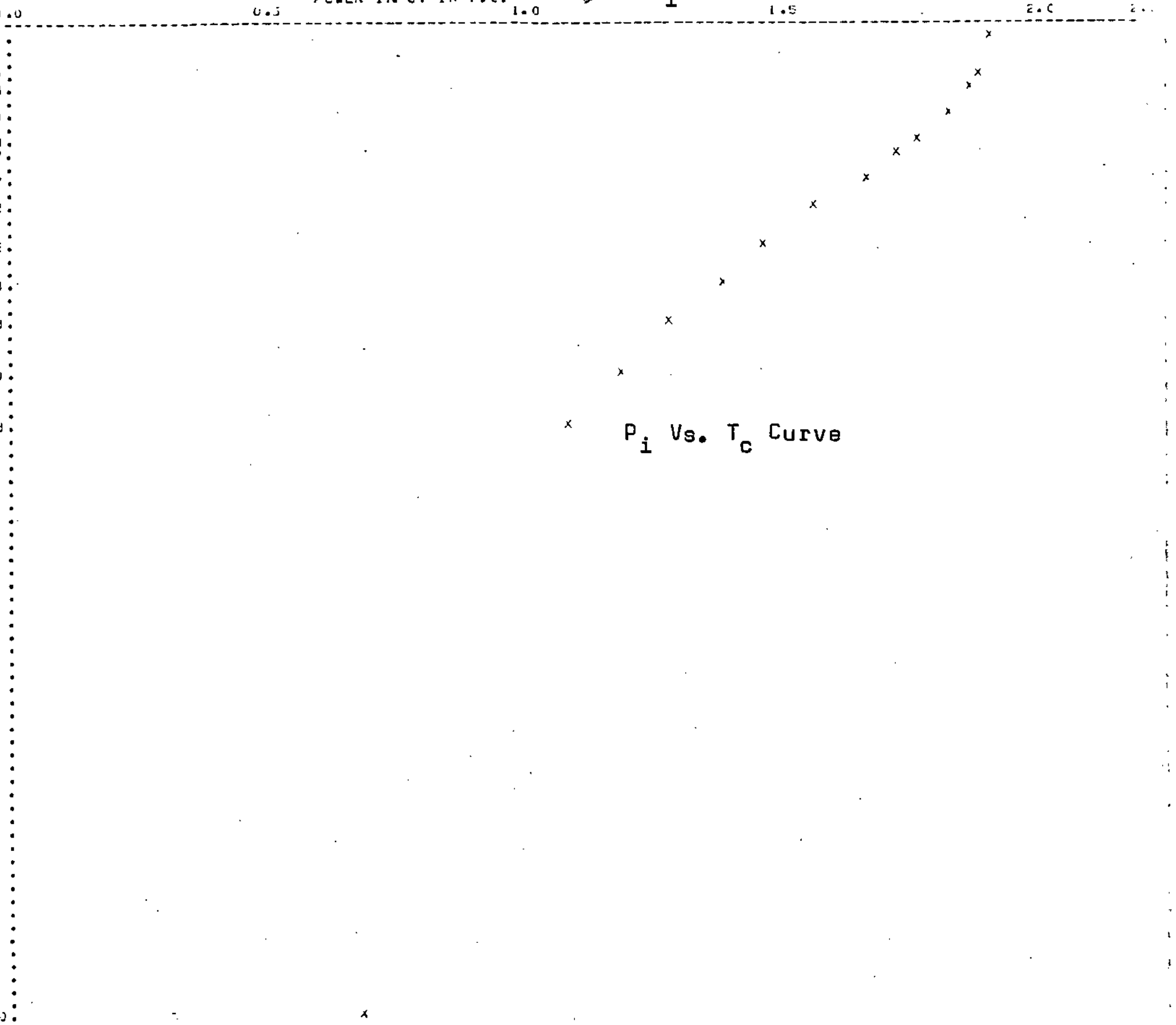
58052

GRAPH NO.

132 KV SYSTEM
REF. VOLTS. IN P.U. 1.000 & 1.000

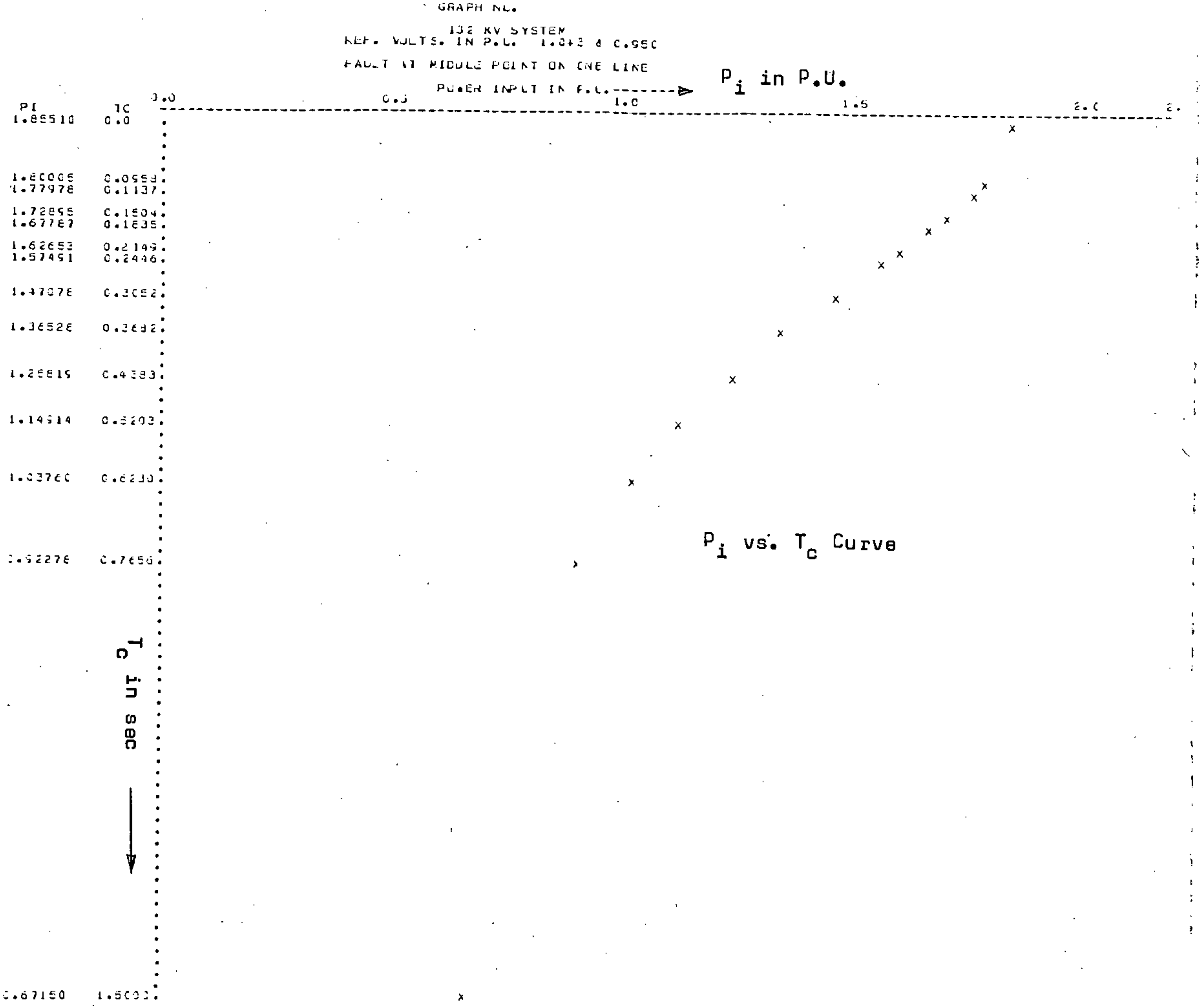
FAULT AT MIDDLE POINT ON ONE LINE

POWER INPUT IN P.U.



PI	TC
1.92547	0.0
1.89774	0.0657
1.87693	0.0658
1.83009	0.1249
1.76167	0.1568
1.73316	0.1657
1.66456	0.2137
1.58714	0.2673
1.48941	0.3212
1.39139	0.3773
1.29310	0.4403
1.19457	0.5110
1.09562	0.5553
0.65566	1.5000

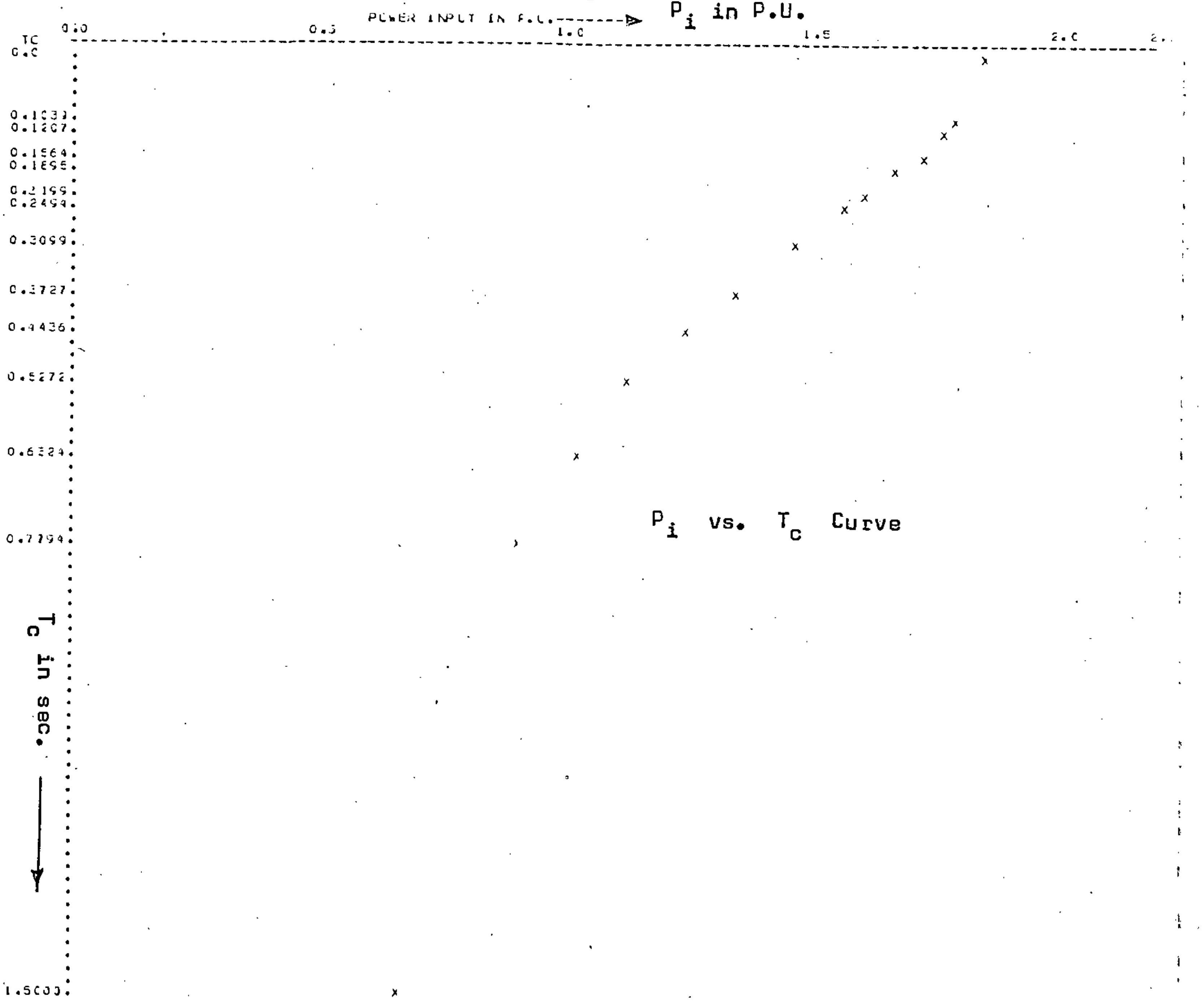
```
     AI          E1          E2         DELTA      SIN(DELTA)       FI          FM

  1.97452     1.121026    0.944255    38.799896    0.626602     1.855103    2.960577
  1.92000     1.119211    0.940557    37.690872    0.611400     1.800050    2.944143
  1.90000     1.118557    0.939195    37.281738    0.605734     1.779783    2.938225
  1.85000     1.116950    0.935694    36.253494    0.591358     1.728949    2.923691
  1.80000     1.115383    0.932670    35.217392    0.576630     1.677868    2.909533
  1.75000     1.113858    0.929524    34.173203    0.561696     1.626533    2.895753
  1.70000     1.112373    0.926456    33.120346    0.546399     1.574911    2.882347
  1.60000     1.109529    0.920558    30.587885    0.514857     1.470777    2.856674
  1.50000     1.106849    0.914964    28.816391    0.482004     1.365284    2.832517
  1.40000     1.104337    0.909727    26.600922    0.447773     1.258190    2.809885
  1.30000     1.101593    0.904826    24.334152    0.412057     1.149138    2.788784
  1.20000     1.099817    0.900254    22.005219    0.374691     1.037600    2.769217
  1.10000     1.097812    0.896028    19.597356    0.335413     0.922784    2.751189
  0.89570     1.094249    0.886466    14.297157    0.246951     0.671503    2.719179


     AI   CLEARING ANGLE   TUWC     CLEARING TIME    POWER INPUT
  1.97452     0.67719      0.0          0.0            1.85510
  1.92000     0.72802      0.32187      0.09569        1.80005
  1.90000     0.74801      0.38125      0.11370        1.77978
  1.85000     0.79709      0.50312      0.15042        1.72895
  1.80000     0.85025      0.61250      0.18356        1.67787
  1.75000     0.90680      0.71562      0.21498        1.62653
  1.70000     0.96352      0.81250      0.24465        1.57491
  1.60000     1.08804      1.00937      0.30529        1.47078
  1.50000     1.22034      1.21250      0.36828        1.36528
  1.40000     1.36503      1.43749      0.43838        1.25819
  1.30000     1.52443      1.70000      0.52039        1.14914
  1.20000     1.70311      2.02811      0.62302        1.03760
  1.10000     1.91053      2.46436      0.76567        0.92278
  0.89570     SUSTND       INFINT       INFINT         0.67150
```



PI	TC
1.85510	0.0
1.80065	0.0559
1.77978	0.1137
1.72855	0.1504
1.67787	0.1835
1.62653	0.2149
1.57451	0.2446
1.47078	0.3052
1.36526	0.3682
1.25815	0.4383
1.14914	0.5203
1.03760	0.6230
0.92278	0.7650
0.67150	1.5000

```
     A1          E1          E2          DELTA       SIN(DELTA)     PI          PM

  1.98467     1.127092    0.946086    38.807770     0.626705    1.869077    2.982266
  1.92000     1.124544    0.941070    37.493652     0.608673    1.803370    2.962790
  1.90000     1.124293    0.940331    37.084579     0.602993    1.782968    2.956863
  1.85000     1.122695    0.937034    36.036656     0.588534    1.731796    2.942308
  1.80000     1.121137    0.933814    35.020623     0.573869    1.680362    2.928126
  1.75000     1.119619    0.930671    33.976161     0.558848    1.628662    2.914323
  1.70000     1.118142    0.927617    32.923050     0.543512    1.576671    2.900856
  1.60000     1.115312    0.921717    30.789382     0.511603    1.471752    2.875177
  1.50000     1.112646    0.916149    28.615555     0.478930    1.365419    2.850980
  1.40000     1.110147    0.910910    26.396376     0.444576    1.257403    2.828208
  1.30000     1.107815    0.906005    24.123901     0.408711    1.147321    2.807170
  1.20000     1.105651    0.901439    21.786890     0.371155    1.034619    2.787569
  1.10000     1.103656    0.897216    19.367035     0.331618    0.918419    2.769509
  0.90595     1.100271    0.890020    14.301556     0.247023    0.676573    2.738883


    A1     CLEARING ANGLE    TOWC     CLEARING TIME    POWER INPUT
  1.98467     0.67732       0.0           0.0            1.86908
  1.92000     0.73694       0.35000       0.10395        1.80337
  1.90000     0.75713       0.40625       0.12077        1.78297
  1.85000     0.80706       0.52500       0.15646        1.73180
  1.80000     0.86223       0.63437       0.18951        1.68036
  1.75000     0.91753       0.73437       0.21991        1.62866
  1.70000     0.97496       0.85125       0.24949        1.57667
  1.60000     1.10016       1.02812       0.30995        1.47175
  1.50000     1.23229       1.23124       0.37276        1.36542
  1.40000     1.37883       1.45937       0.44360        1.25740
  1.30000     1.54129       1.72812       0.52726        1.14732
  1.20000     1.72251       2.06561       0.63244        1.03462
  1.10000     1.93267       2.53749       0.77945        0.91842
  0.90595     SUSTND        INFINT        INFINT         0.67657
```

```
GRAPH NO.

          132 KV SYSTEM
REF. VOLTS. IN P.U.  1.048 & 0.953

FAULT AT MIDDLE POINT ON ONE LINE

          POWER INPUT IN P.U.
```



```
   PI        TC
1.86508    0.0

1.80337    0.1033
1.76297    0.1207

1.73180    0.1564
1.68036    0.1895

1.62866    0.2199
1.57667    0.2494

1.47175    0.3099

1.36542    0.3727

1.25740    0.4436

1.14732    0.5272

1.03462    0.6324

0.91842    0.7794

0.67657    1.5000
```

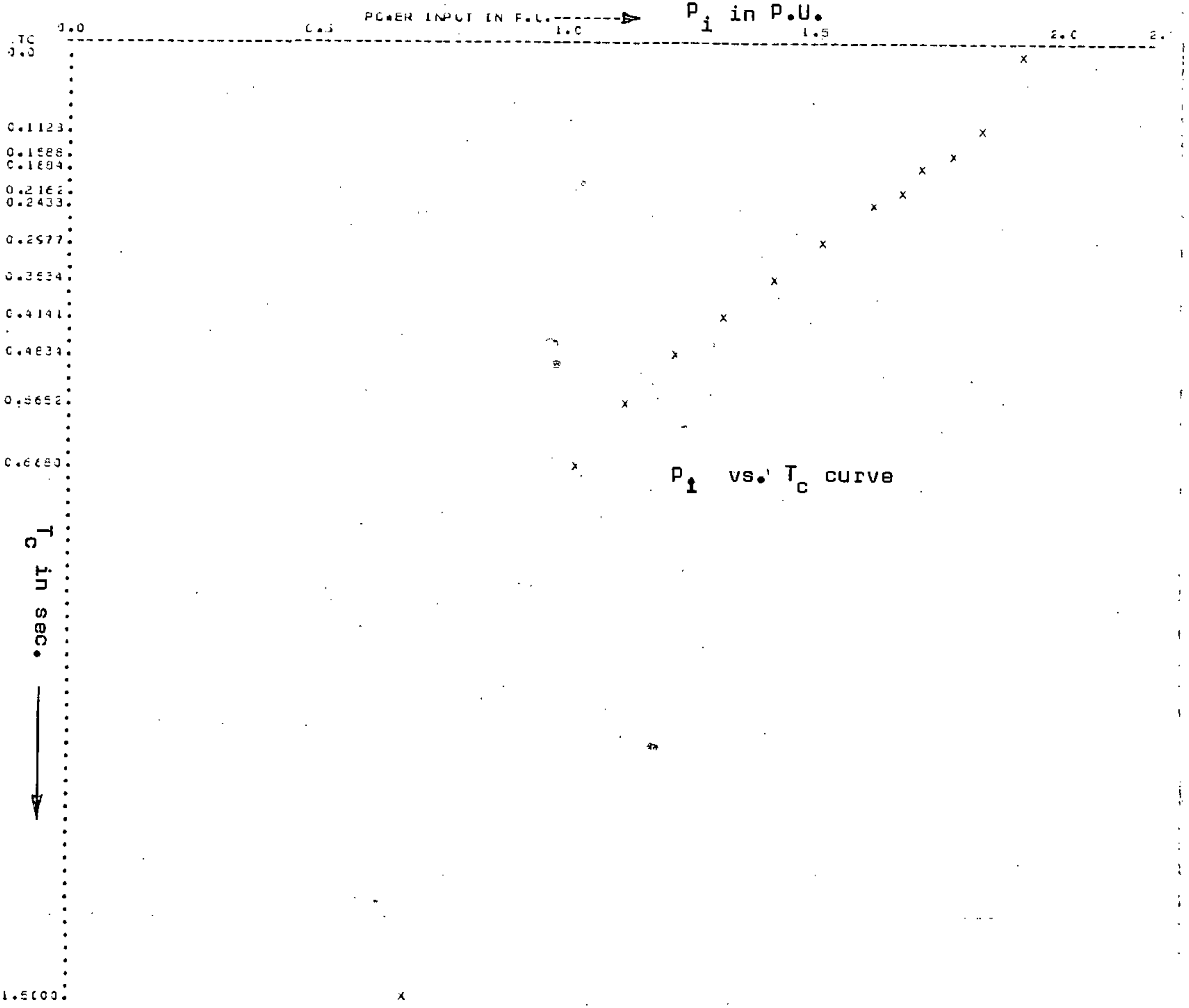
```
   AI         E1          L2         DELTA      SIN(DELTA)     FI          FM
 2.00263   0.981134   1.131669   38.800323   0.626608   1.945906   3.105461
 1.92000   0.977964   1.126952   37.224319   0.604937   1.864701   3.082475
 1.90000   0.977215   1.125833   36.840973   0.599596   1.844988   3.077055
 1.85000   0.975376   1.123061   35.879242   0.586078   1.795601   3.063756
 1.80000   0.973582   1.120395   34.912933   0.572331   1.746069   3.050606
 1.75000   0.971834   1.117778   33.942032   0.558353   1.696398   3.038217
 1.70000   0.970132   1.115227   32.966187   0.544144   1.646564   3.025973
 1.60000   0.966868   1.110333   31.000275   0.515042   1.546442   3.002560
 1.50000   0.963792   1.105715   29.014389   0.485029   1.445656   2.980557
 1.40000   0.960906   1.101376   27.007568   0.454108   1.344148   2.959976
 1.30000   0.958211   1.097324   24.978165   0.422273   1.241822   2.940809
 1.20000   0.955708   1.093558   22.923981   0.389505   1.138559   2.923063
 1.10000   0.953400   1.090061   20.841171   0.355778   1.034151   2.906732
 0.79804   0.947624   1.081309   14.303072   0.247051   0.708056   2.866035
```

```
   AI     CLEARING ANGLE    TOKC     CLEARING TIME   POWER INPUT
 2.00263      0.67719      0.0          0.0           1.94591
 1.92000      0.75003      0.38750      0.11283       1.86470
 1.90000      0.76952      0.43750      0.12750       1.84499
 1.85000      0.81585      0.54375      0.15880       1.79560
 1.80000      0.86692      0.64375      0.18841       1.74607
 1.75000      0.91940      0.73750      0.21629       1.69640
 1.70000      0.97352      0.82812      0.24336       1.64656
 1.60000      1.08832      1.00937      0.29778       1.54644
 1.50000      1.20821      1.19374      0.35347       1.44566
 1.40000      1.33734      1.39374      0.41412       1.34415
 1.30000      1.47861      1.62187      0.48347       1.24182
 1.20000      1.63142      1.89061      0.56529       1.13856
```

132 KV SYSTEM
REF. VOLTS. IN P.U. 0.972 & 1.030

FAULT AT MIDDLE POINT ON ONE LINE

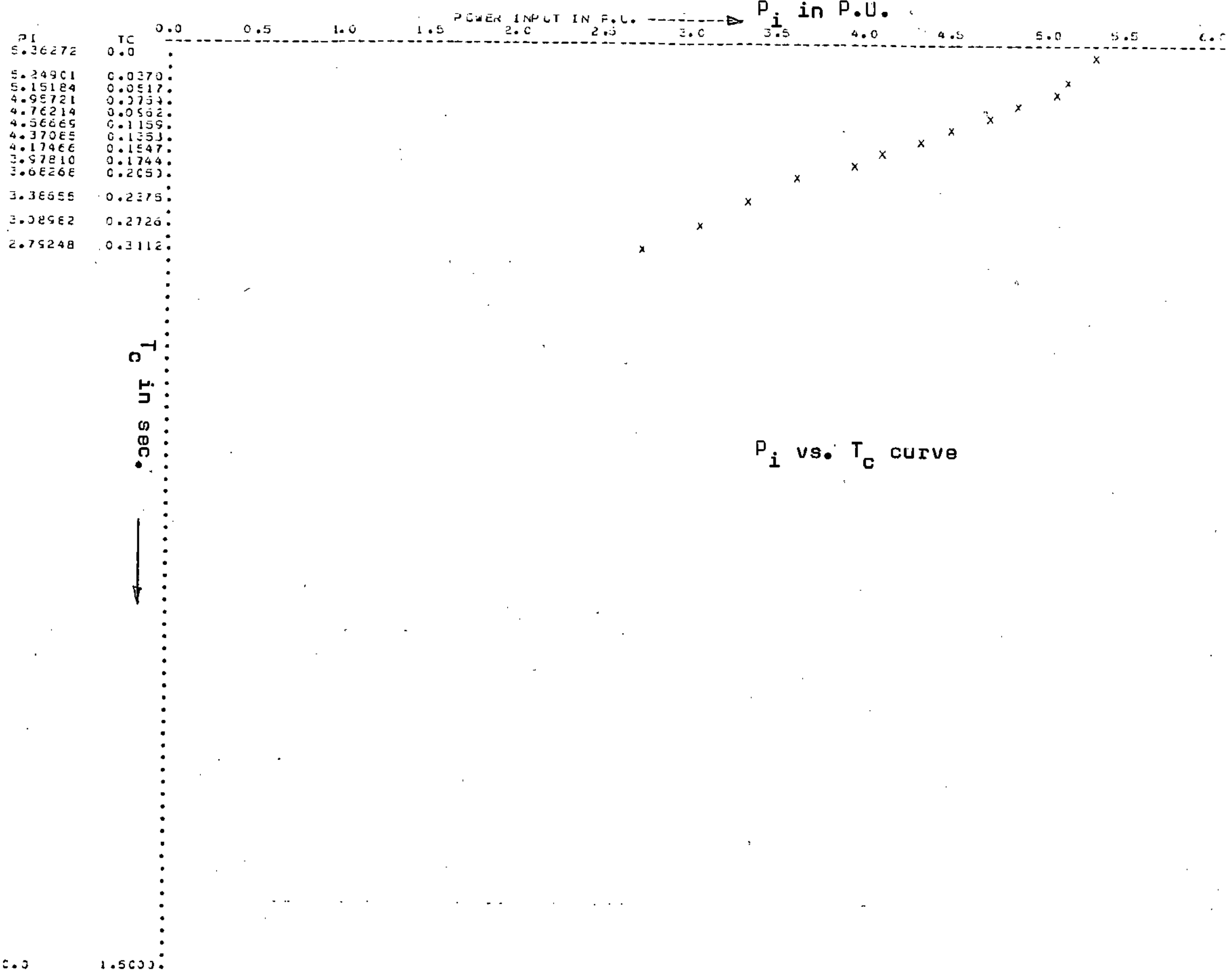
PI	TC
1.94591	0.0
1.86470	0.1123
1.79560	0.1588
1.74607	0.1884
1.69540	0.2162
1.64656	0.2433
1.54644	0.2577
1.44566	0.3534
1.34415	0.4141
1.24182	0.4834
1.13856	0.5652
1.03415	0.6680
0.70806	1.5000



```
   AI          E1          E2          DELTA      SIN(DELTA)      PI          PM

 5.41718    1.034879    1.090651    41.783351    0.666311    5.362718    8.048366
 5.30000    1.033410    1.087119    40.546365    0.655352    5.249010    8.009454
 5.20000    1.032181    1.083987    40.229235    0.645847    5.151842    7.976879
 5.00000    1.029788    1.077860    38.786560    0.625421    4.957207    7.913546
 4.80000    1.027483    1.071976    37.332657    0.606441    4.762138    7.852598
 4.60000    1.025269    1.066287    35.867889    0.585918    4.566689    7.794078
 4.40000    1.023144    1.060809    34.392487    0.564858    4.370852    7.737965
 4.20000    1.021109    1.055549    32.906754    0.543273    4.174661    7.684278
 4.00000    1.019164    1.050506    31.410828    0.521171    3.978102    7.633012
 3.70000    1.016419    1.043366    29.146395    0.487031    3.682675    7.560711
 3.40000    1.013882    1.036738    26.866043    0.451906    3.386546    7.493923
 3.10000    1.011554    1.030633    24.563356    0.415707    3.089821    7.432691
 2.80000    1.009436    1.025060    22.243164    0.378538    2.792479    7.377012
 2.50000    1.007528    1.020027     0.0         0.0         0.0         7.326930
   AI    CLEARING ANGLE    RUKC      CLEARING TIME    POWER INPUT
 5.41718    0.72925       0.0            0.0            5.36272
 5.30000    0.73825       0.26639        0.03705        5.24901
 5.20000    0.74737       0.37429        0.05178        5.15184
 5.00000    0.76932       0.54304        0.07542        4.95721
 4.80000    0.79599       0.69012        0.09622        4.76214
 4.60000    0.82713       0.82655        0.11595        4.56669
 4.40000    0.86247       0.96354        0.13533        4.37085
 4.20000    0.90179       1.09795        0.15474        4.17466
 4.00000    0.94487       1.23374        0.17446        3.97810
 3.70000    1.01612       1.44366        0.20508        3.68268
 3.40000    1.09495       1.66455        0.23756        3.38655
 3.10000    1.18108       1.90254        0.27264        3.08982
 2.80000    1.27448       2.16392        0.31127        2.79248
 2.50000    SUSTND        INFINT         INFINT         0.0
```

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.000 & 1.000

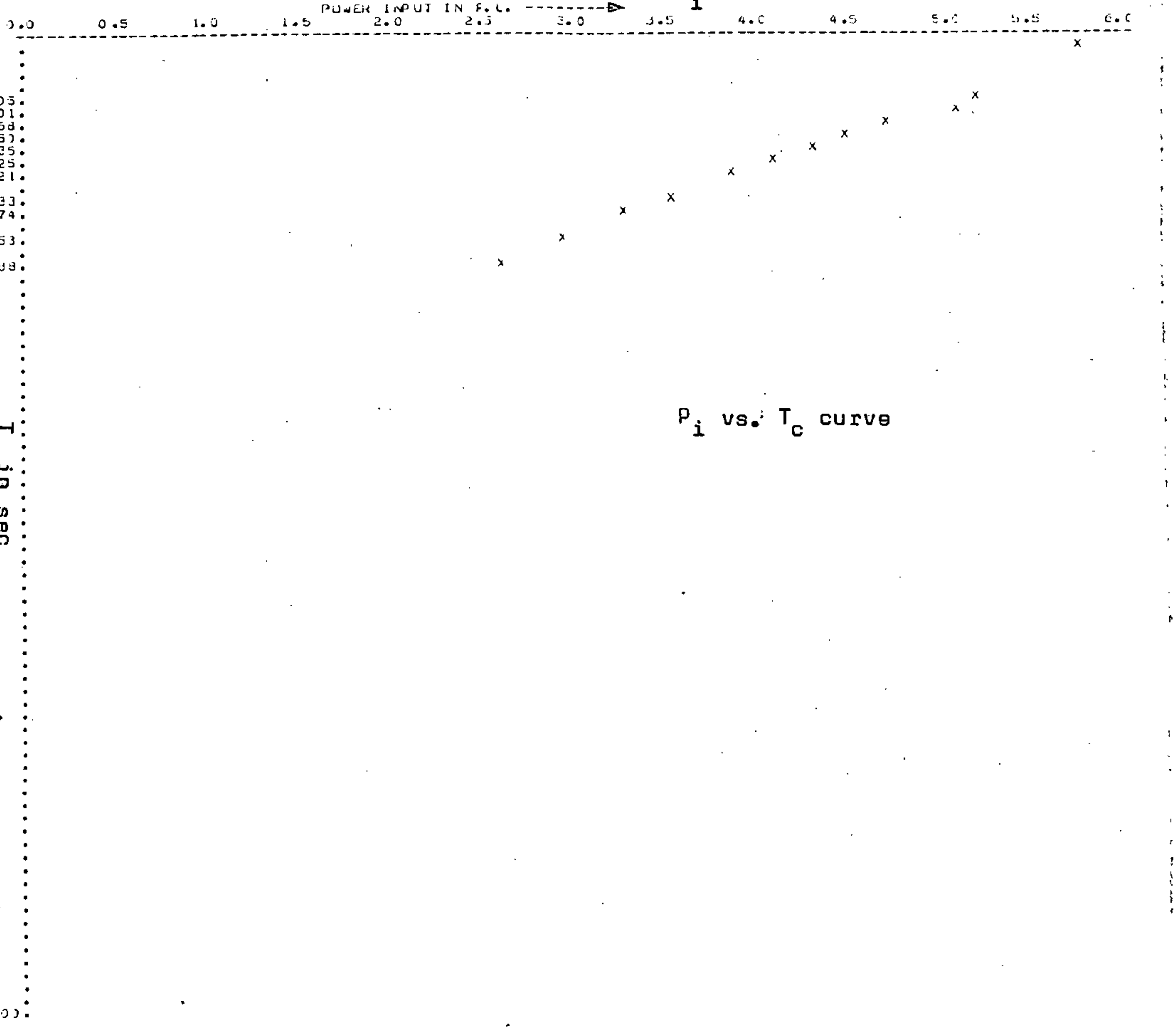
FAULT NEAR BUS 1 ON ONE LINE



PI	TC
5.36272	0.0
5.24901	0.0370
5.15184	0.0517
4.95721	0.0754
4.76214	0.0962
4.56665	0.1159
4.37065	0.1353
4.17466	0.1547
3.97810	0.1744
3.68268	0.2053
3.38655	0.2375
3.08962	0.2726
2.79248	0.3112

```
   AI          E1          E2         DELTA      SIN(DELTA)      PI          PM

 5.81092    1.009520    1.213167   41.781418    0.666270    5.817419    8.731059
 5.30000    1.002697    1.197666   38.205322    0.618431    5.296113    8.563100
 5.20000    1.001430    1.195025   37.496216    0.608709    5.193498    8.531994
 5.00000    0.998964    1.189467   36.068317    0.588756    4.987671    8.471543
 4.80000    0.996588    1.184142   34.628998    0.568260    4.781007    8.413417
 4.60000    0.994305    1.178953   33.176066    0.547222    4.573483    8.357637
 4.40000    0.992113    1.174042   31.711576    0.525643    4.365043    8.304196
 4.20000    0.990014    1.169290   30.233200    0.503523    4.155596    8.253087
 4.00000    0.988009    1.164742   28.741165    0.480853    3.945079    8.204330
 3.70000    0.985177    1.158305   26.476181    0.445825    3.627061    8.135612
 3.40000    0.982559    1.152337   24.175476    0.409532    3.305820    8.072183
 3.10000    0.980156    1.146648   21.834503    0.371927    2.980651    8.014084
 2.80000    0.977970    1.141842   19.444092    0.332902    2.650339    7.961303
 2.50000    0.976002    1.137326     0.0        0.0         0.0         7.913865
   AI    CLEARING ANGLE   RUNG     CLEARING TIME   POWER INPUT
 5.81092    0.72922      0.0          0.0           5.81742
 5.30000    0.77945      0.60354      0.08058       5.29611
 5.20000    0.79277      0.67419      0.09018       5.19350
 5.00000    0.82261      0.80590      0.10871       4.98767
 4.80000    0.85655      0.94207      0.12689       4.78101
 4.60000    0.89438      1.07355      0.14506       4.57348
 4.40000    0.93594      1.20633      0.16355       4.36504
 4.20000    0.98108      1.34200      0.18250       4.15560
 4.00000    1.02971      1.48265      0.20219       3.94508
 3.70000    1.10908      1.70564      0.23355       3.62706
 3.40000    1.19625      1.94459      0.26740       3.30582
 3.10000    1.29162      2.21276      0.30558       2.98065
 2.80000    1.39609      2.51962      0.34888       2.65033
 2.50000    SUSTND       INFINT       INFINT        0.0
```

```
                GRAPH NO.

                230 KV SYSTEM
      REF. VOLTS. IN P.U.  1.002 & 1.059

      FAULT NEAR BUS 1  ON ONE LINE

                POWER INPUT IN P.U. ---------->
```



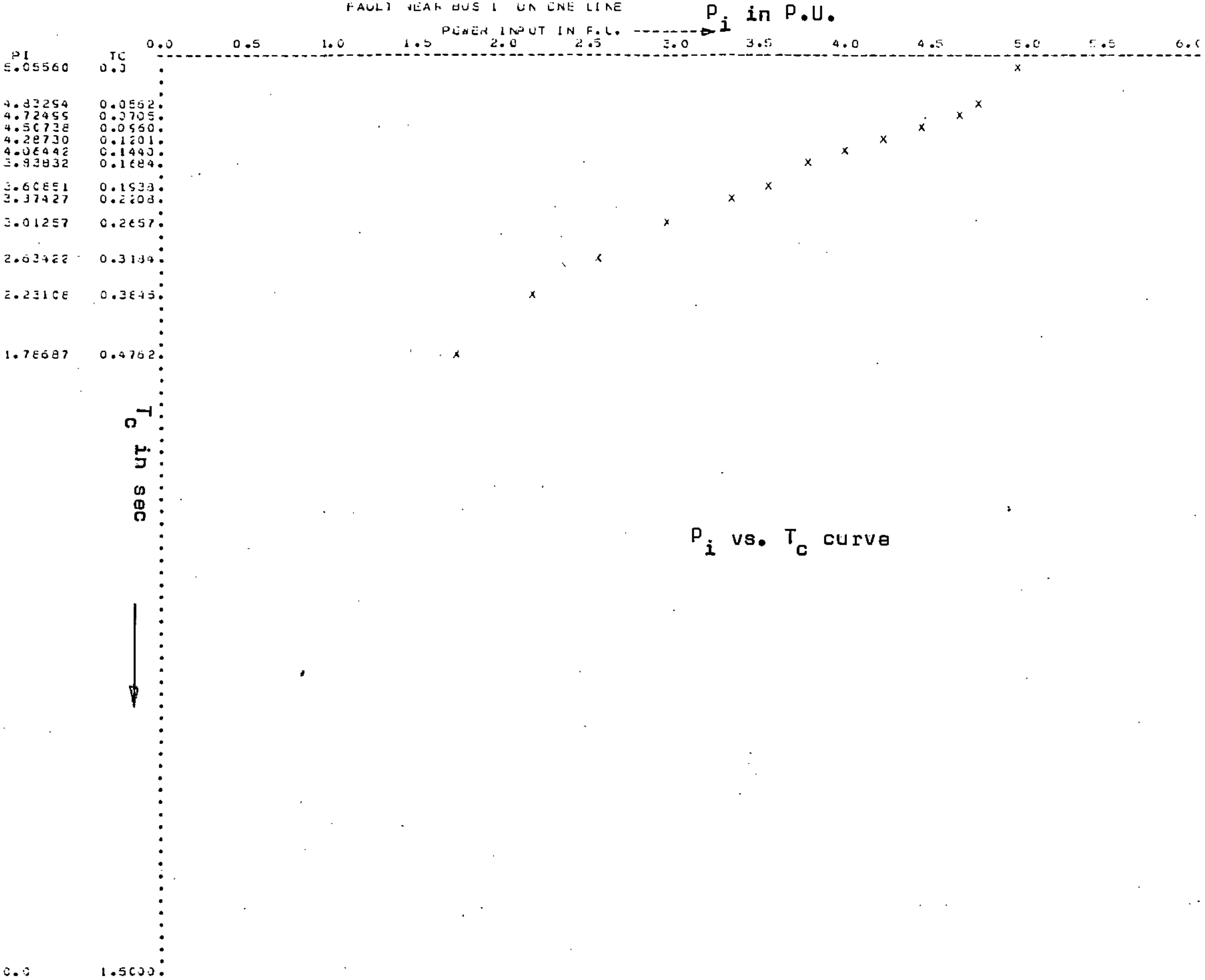
```
 PI          TC
5.81742     0.0


5.25611     0.0805
5.19350     0.0901
4.78101     0.1268
4.57348     0.1450
4.36504     0.1635
4.15560     0.1825
3.94508     0.2021

3.62706     0.2333
3.30582     0.2674

2.98365     0.3053

2.65033     0.3488











0.0         1.5000
```

```
    AI          E1          E2          DELTA      SIN(DELTA)      PI          PM

 5.50779    1.156154    0.920536    41.781464    0.665291    5.055604    7.587684
 5.30000    1.153802    0.912666    40.075027    0.643790    4.832940    7.507018
 5.20000    1.152701    0.908875    39.242004    0.632597    4.724989    7.469195
 5.00000    1.150558    0.901561    37.551019    0.609478    4.507383    7.395475
 4.80000    1.148497    0.894517    35.827454    0.585346    4.287299    7.324388
 4.60000    1.146516    0.887669    34.066269    0.560151    4.064422    7.255940
 4.40000    1.144616    0.881101    32.264633    0.533830    3.838322    7.190159
 4.20000    1.142797    0.874766    30.418350    0.506310    3.608508    7.127077
 4.00000    1.141061    0.868671    28.521454    0.477482    3.374267    7.066712
 3.70000    1.138609    0.860021    25.554056    0.431520    3.012571    6.981310
 3.40000    1.136345    0.851968    22.435944    0.381650    2.634218    6.902184
 3.10000    1.134268    0.844526    19.067356    0.326688    2.231079    6.829400
 2.80000    1.132380    0.837717    15.320126    0.264212    1.786874    6.763045
 2.50000    1.130680    0.831551     0.0         0.0         0.0         6.703154
    AI    CLEARING ANGLE   RCWC     CLEARING TIME   POWER INPUT
 5.50779     0.72922      0.0           0.0          5.05560
 5.30000     0.74949      0.39432       0.05623      4.83294
 5.20000     0.76189      0.49536       0.07053      4.72499
 5.00000     0.79169      0.66875       0.09608      4.50738
 4.80000     0.82804      0.83229       0.12013      4.28730
 4.60000     0.87080      0.99311       0.14404      4.06442
 4.40000     0.91987      1.15609       0.16644      3.83832
 4.20000     0.97526      1.32467       0.19389      3.60851
 4.00000     1.03712      1.50300       0.22089      3.37427
 3.70000     1.14286      1.79693       0.26570      3.01257
 3.40000     1.26647      2.14121       0.31842      2.63422
 3.10000     1.41326      2.57190       0.38450      2.23108
 2.80000     1.59520      3.17035       0.47628      1.78687
 2.50000     SUSTND       INFINT        INFINT       0.0
```

GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.055 & 0.952

FAULT NEAR BUS 1 ON ONE LINE



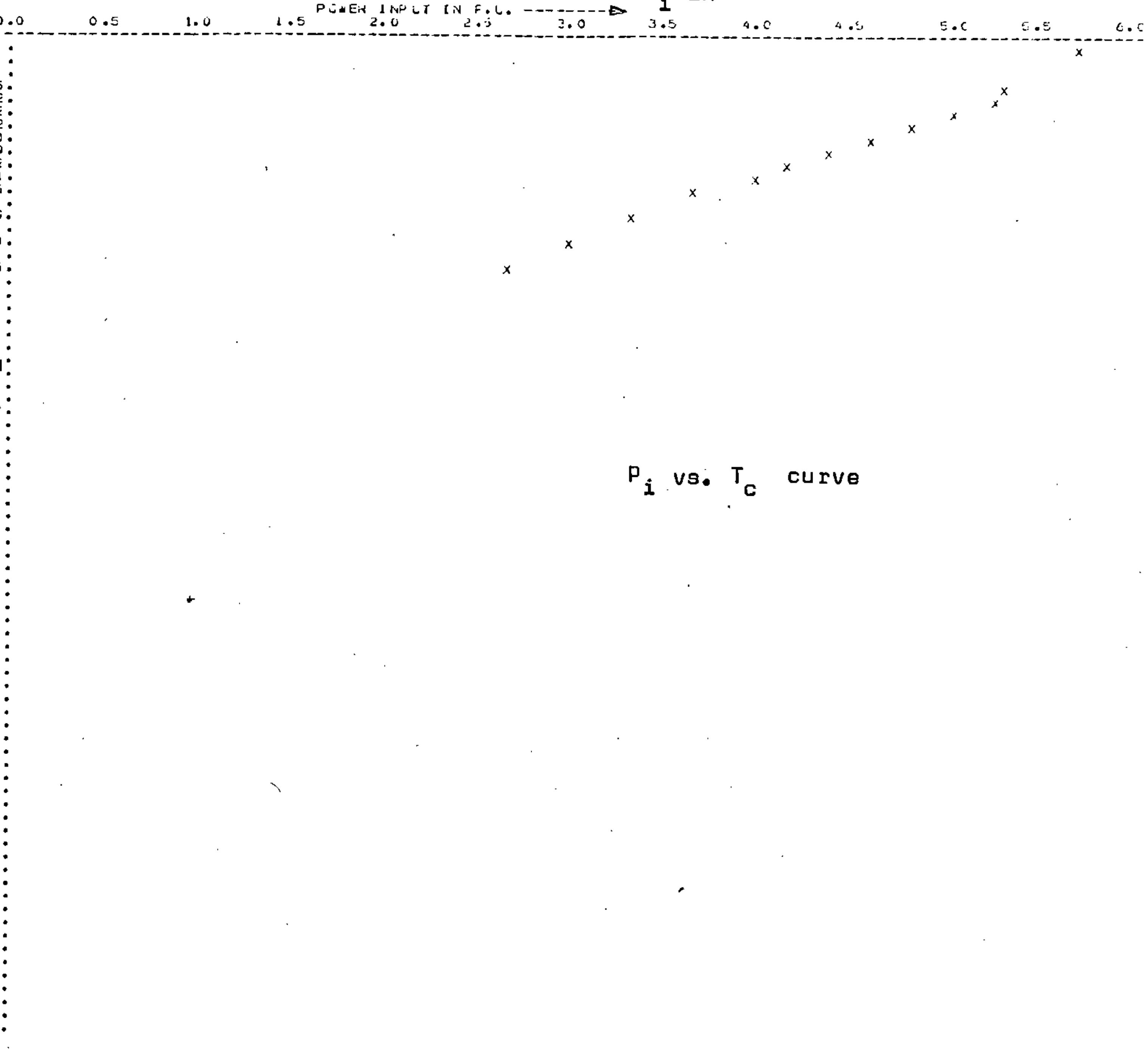
P_i vs. T_c curve

```
   AI          E1          E2         DELTA     SIN(DELTA)      FI          PM

5.63279     1.145975    1.058093    41.773605   0.666199    5.759029    8.644744
5.30000     1.142129    1.046916    39.403397   0.634776    5.411230    8.524631
5.20000     1.141017    1.043653    38.683319   0.625015    5.306297    8.489873
5.00000     1.138852    1.037306    37.232162   0.605046    5.095841    8.422242
4.80000     1.136769    1.031174    35.766235   0.584479    4.884566    8.357127
4.60000     1.134768    1.025257    34.285339   0.563314    4.672437    8.294548
4.40000     1.132848    1.019559    32.789032   0.541547    4.459363    8.234491
4.20000     1.131010    1.014084    31.277308   0.519176    4.245292    8.176984
4.00000     1.129255    1.008836    29.748871   0.496199    4.030150    8.122047
3.70000     1.126779    1.001396    27.424759   0.460583    3.705152    8.044483
3.40000     1.124491    0.994490    25.059494   0.423539    3.376937    7.972773
3.10000     1.122392    0.988124    22.647720   0.385094    3.044678    7.906942
2.80000     1.120482    0.982309    20.181641   0.344997    2.707210    7.847050
2.50000     1.118765    0.977050     0.0        0.0         0.0         7.793119
   AI     CLEARING ANGLE   RORC     CLEARING TIME    POWER INPUT
5.63279     0.72909      0.0          0.0             5.75903
5.30000     0.75936      0.47511      0.06357         5.41123
5.20000     0.77106      0.55400      0.07425         5.30620
5.00000     0.79799      0.69964      0.09421         5.09584
4.80000     0.82944      0.83755      0.11325         4.88457
4.60000     0.86519      0.97326      0.13203         4.67244
4.40000     0.90506      1.10600      0.15093         4.45936
4.20000     0.94888      1.24597      0.17023         4.24529
4.00000     0.99654      1.38765      0.19013         4.03015
3.70000     1.07504      1.60926      0.22167         3.70515
3.40000     1.16199      1.84575      0.25594         3.37694
3.10000     1.25772      2.11648      0.29406         3.04468
2.80000     1.36309      2.42076      0.33762         2.70721
2.50000     SUSTND       INFINT       INFINT          0.0
```

GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.081 & 1.024

FAULT NEAR BUS 1 ON ONE LINE

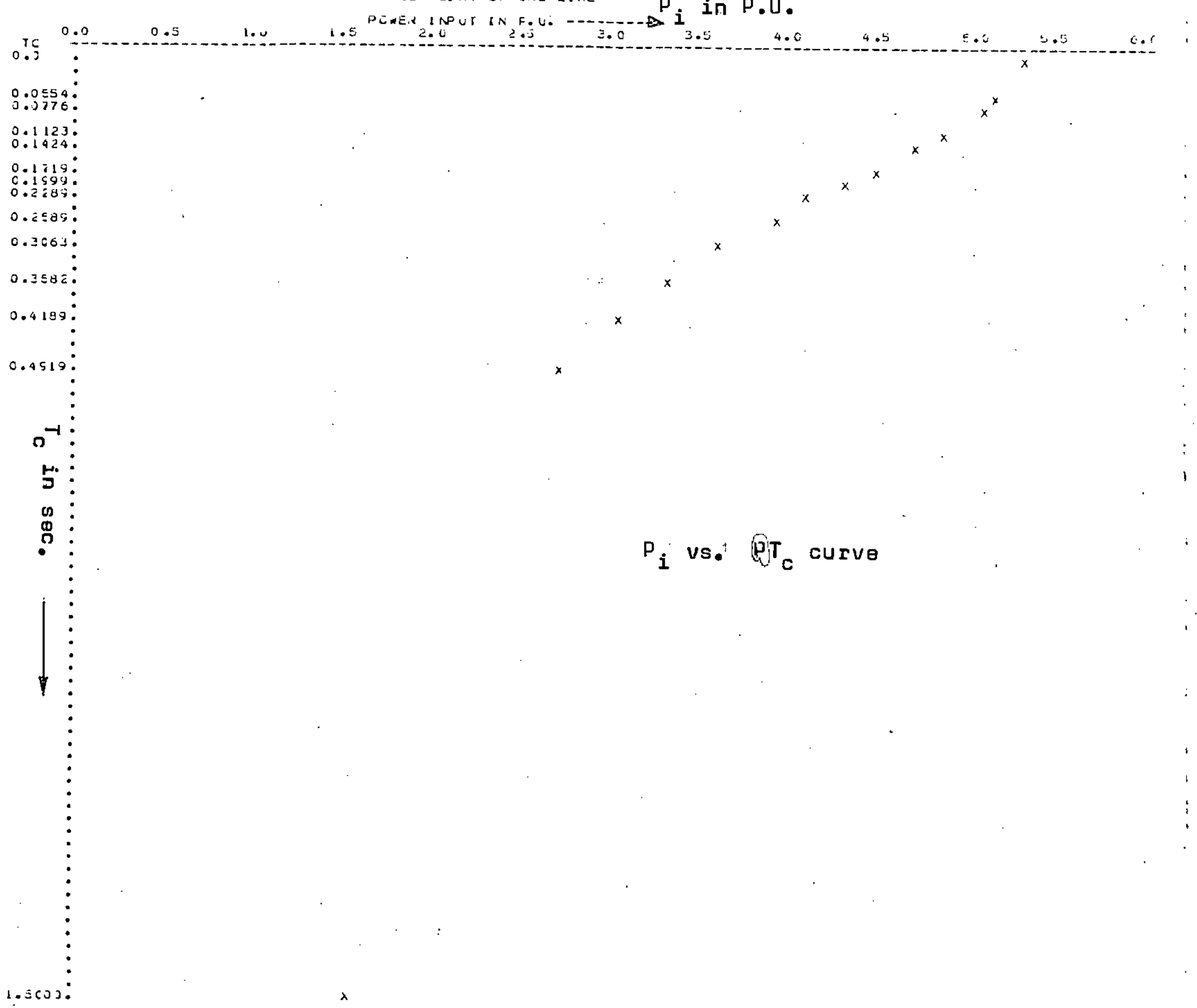


P_i vs. T_c curve

PI	TC
5.75903	0.0
5.41123	0.0635
5.30630	0.0742
5.09584	0.0942
4.88457	0.1132
4.67244	0.1320
4.45936	0.1509
4.24529	0.1702
4.03015	0.1901
3.70515	0.2216
3.37694	0.2559
3.04468	0.2940
2.70721	0.3376
0.0	1.5000

```
   AI          E1          E2          DELTA      SIN(DELTA)      PI          FM

 5.41713    1.034879    1.090651    41.783051    0.666311    5.362718    8.048366
 5.30000    1.033410    1.087119    40.946165    0.655352    5.249010    8.009454
 5.20000    1.032181    1.083967    40.229233    0.645847    5.151842    7.976879
 5.00000    1.029788    1.077860    38.786560    0.626421    4.957207    7.913546
 4.80000    1.027483    1.071976    37.332657    0.606441    4.762128    7.852598
 4.60000    1.025269    1.066287    35.867089    0.585918    4.566689    7.794078
 4.40000    1.023144    1.060609    34.392487    0.564858    4.370852    7.737965
 4.20000    1.021109    1.055549    32.906754    0.543273    4.174661    7.684278
 4.00000    1.019164    1.050506    31.410828    0.521171    3.978102    7.633013
 3.70000    1.016419    1.043566    29.148395    0.487031    3.682675    7.560711
 3.40000    1.013882    1.036736    26.866043    0.451906    3.386546    7.493923
 3.10000    1.011554    1.030633    24.563356    0.415707    3.089821    7.432691
 2.80000    1.009436    1.025060    22.243164    0.378538    2.792479    7.377012
 1.59843    1.003084    1.008234    12.796389    0.221437    1.596979    7.210271


   AI    CLEARING ANGLE    TUWC       CLEARING TIME    POWER INPUT
 5.41718    0.72925       0.0            0.0            5.36272
 5.30000    0.75256       0.21250        0.05545        5.24901
 5.20000    0.77485       0.29667        0.07762        5.15184
 5.00000    0.82285       0.42612        0.11238        4.95721
 4.80000    0.87921       0.54062        0.14246        4.76214
 4.60000    0.93553       0.65000        0.17193        4.56669
 4.40000    0.99711       0.75312        0.19992        4.37085
 4.20000    1.06555       0.85937        0.22892        4.17466
 4.00000    1.13936       0.96875        0.25892        3.97810
 3.70000    1.25654       1.14062        0.30632        3.68268
 3.40000    1.38113       1.32812        0.35625        3.38655
 3.10000    1.52178       1.54687        0.41898        3.08982
 2.80000    1.67966       1.80936        0.45192        2.79248
 1.59843    SUSTND        INFINT         INFINT         1.59698
```

```
GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U.  1.000 & 1.000

FAULT AT MIDDLE POINT ON ONE LINE

POWER INPUT IN P.U.
```



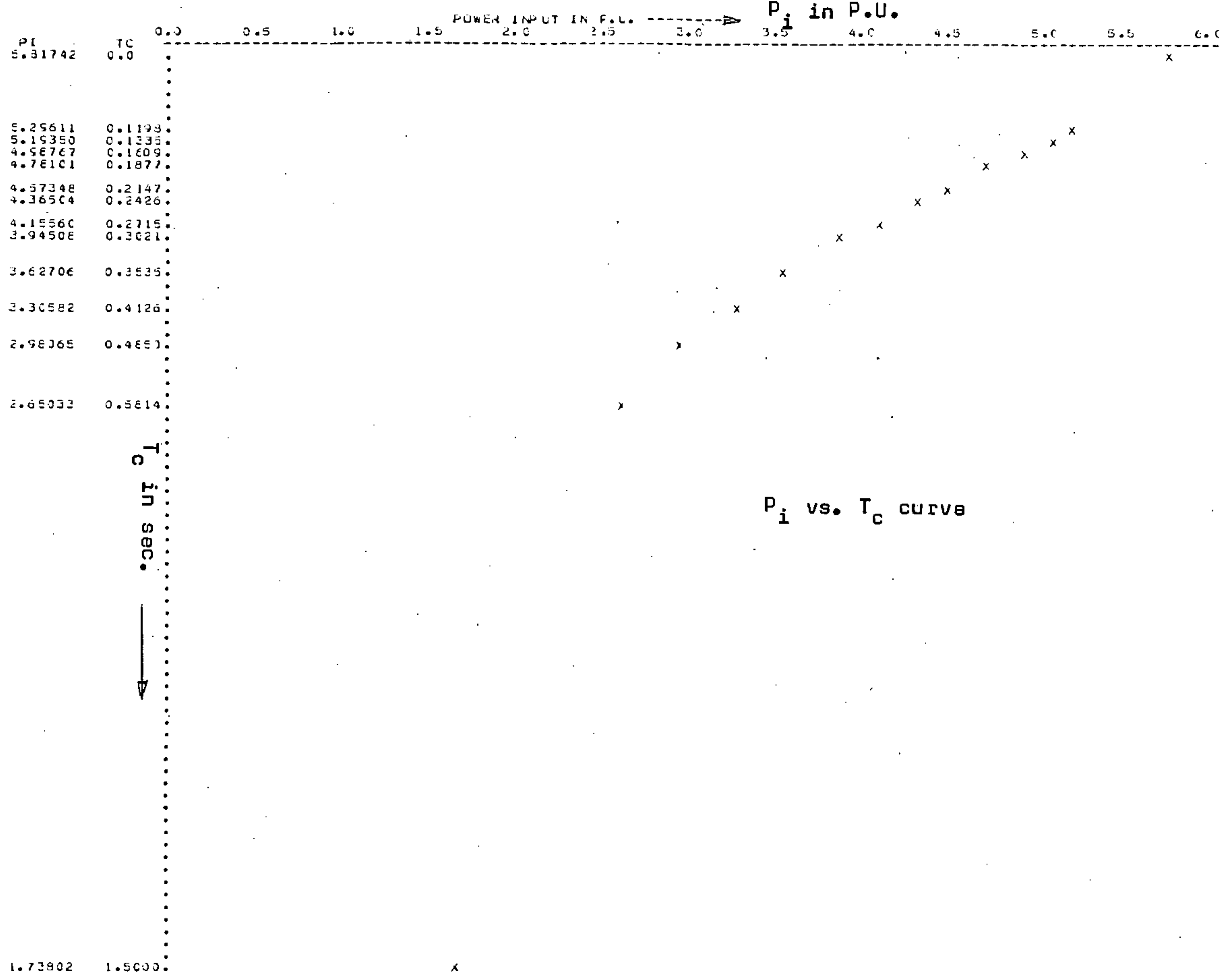
```
   PI        TC
5.36272    0.0
5.24901    0.0554
5.15184    0.0776
4.95721    0.1123
4.76214    0.1424
4.56669    0.1719
4.37085    0.1999
4.17466    0.2289
3.97210    0.2589
3.68268    0.3063
3.38655    0.3582
3.08982    0.4189
2.79248    0.4519
1.55696    1.5000
```

```
      AI          E1           E2         DELTA      SIN(DELTA)      FI          FM

   5.81092     1.009520     1.213137    41.781418    0.666293     5.817419    8.721059
   5.30000     1.002697     1.197866    38.205322    0.618431     5.296113    8.563100
   5.20000     1.001430     1.195025    37.496216    0.608709     5.193498    8.531994
   5.00000     0.998964     1.189487    36.066817    0.588756     4.987671    8.471543
   4.80000     0.996588     1.184142    34.628996    0.568260     4.781007    8.413417
   4.60000     0.994305     1.178993    33.176066    0.547222     4.573483    8.357637
   4.40000     0.992113     1.174042    31.711578    0.525643     4.365043    8.304196
   4.20000     0.990014     1.169256    30.233200    0.503520     4.155596    8.253087
   4.00000     0.988009     1.164742    28.741165    0.480853     3.945079    8.204330
   3.70000     0.985177     1.158315    26.476181    0.445825     3.627061    8.135612
   3.40000     0.982559     1.152337    24.175476    0.409532     3.305820    8.072183
   3.10000     0.980156     1.146846    21.834303    0.371927     2.980651    8.014084
   2.80000     0.977970     1.141842    19.444992    0.332912     2.650330    7.961303
   2.01092     0.973264     1.131050    12.794835    0.221450     1.738015    7.847975


      AI    CLEARING ANGLE    TOKC      CLEARING TIME    POWER INPUT
   5.81092     0.72922       0.0            0.0            5.81742
   5.30000     0.84351       0.47500        0.11986        5.29611
   5.20000     0.86875       0.52612        0.13351        5.19350
   5.00000     0.92616       0.63437        0.16094        4.98767
   4.80000     0.98782       0.73750        0.18775        4.78101
   4.60000     1.05356       0.84062        0.21472        4.57348
   4.40000     1.12460       0.94667        0.24263        4.36504
   4.20000     1.19860       1.05625        0.27150        4.15560
   4.00000     1.27676       1.17187        0.30211        3.94508
   3.70000     1.40732       1.36862        0.35354        3.62706
   3.40000     1.54648       1.58749        0.41260        3.30582
   3.10000     1.70151       1.85936        0.46501        2.98065
   2.80000     1.88279       2.22186        0.56148        2.65033
   2.01092     SUSTNO        INFINT         INFINT         1.73802
```

GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.002 & 1.059

FAULT AT MIDDLE POINT ON ONE LINE



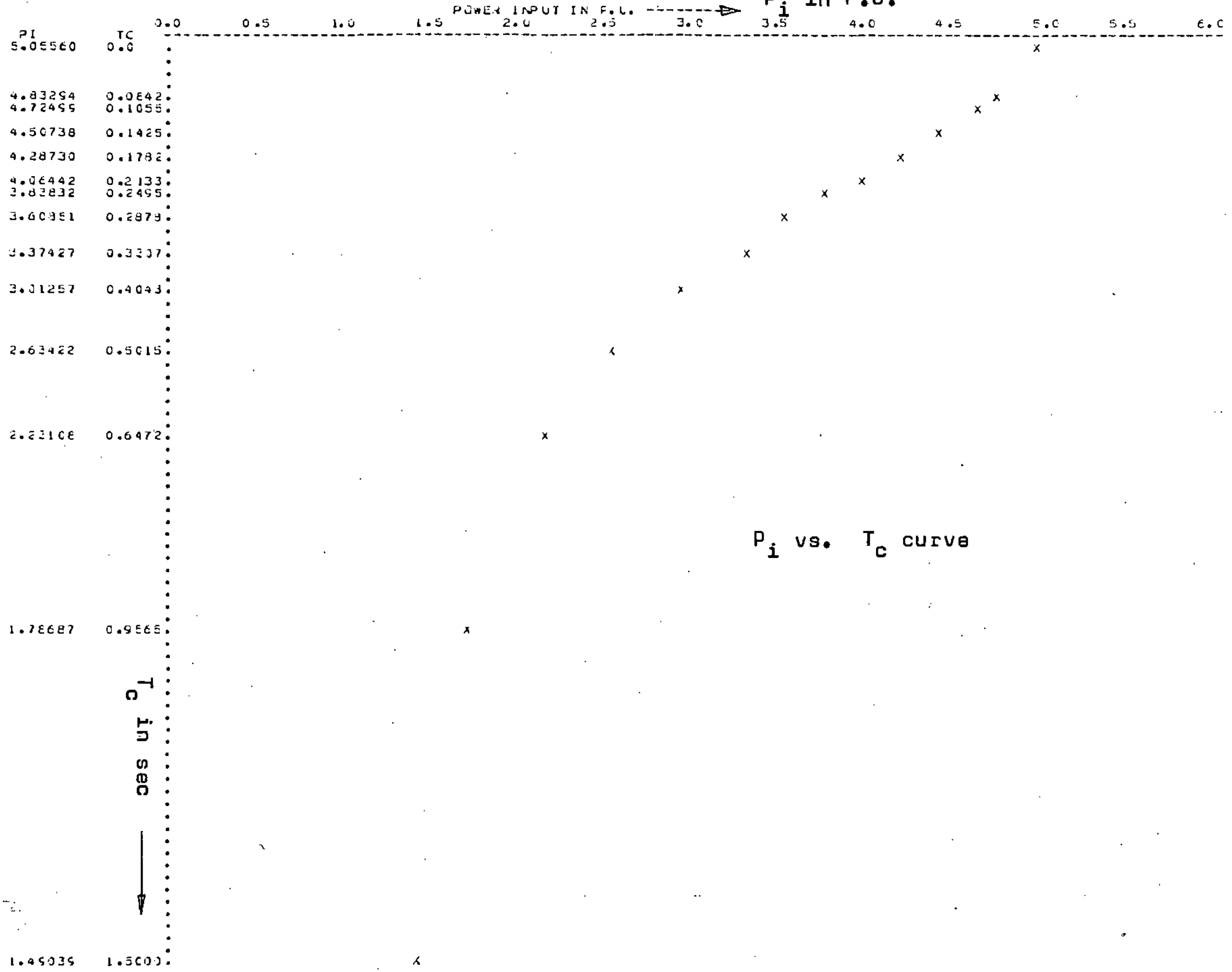
```
    AI          E1          E2          DELTA       SIN(DELTA)      PI          PM

 5.50779     1.156154    0.920536    41.781464    0.666291     5.055604    7.587684
 5.30000     1.153802    0.912666    40.075027    0.643790     4.832940    7.507018
 5.20000     1.152701    0.908675    39.242004    0.632597     4.724989    7.469195
 5.00000     1.150558    0.901561    37.551319    0.609478     4.507383    7.395479
 4.80000     1.148497    0.894517    35.827454    0.585346     4.287299    7.324388
 4.60000     1.146516    0.887669    34.066269    0.560131     4.064422    7.255940
 4.40000     1.144616    0.881101    32.264633    0.533830     3.838322    7.190159
 4.20000     1.142797    0.874760    30.418350    0.506310     3.608508    7.127077
 4.00000     1.141061    0.866671    28.521454    0.477438     3.374267    7.066712
 3.70000     1.138609    0.860021    25.564056    0.431520     3.012571    6.981310
 3.40000     1.136345    0.851968    22.435944    0.381650     2.634218    6.902184
 3.10000     1.134268    0.844528    19.067056    0.326688     2.231079    6.829400
 2.80000     1.132380    0.837717    15.320126    0.264212     1.786874    6.763045
 2.62262     1.131351    0.833592    12.800590    0.221568     1.490392    6.726864
```

```
   AI     CLEARING ANGLE    TOWC      CLEARING TIME    POWER INPUT
 5.50779     0.72922        0.0           0.0            5.05560
 5.30000     0.77974        0.31250       0.08422        4.83294
 5.20000     0.80773        0.39062       0.10554        4.72499
 5.00000     0.86755        0.52500       0.14256        4.50738
 4.80000     0.93740        0.65312       0.17821        4.28730
 4.60000     1.01367        0.77812       0.21331        4.06442
 4.40000     1.09697        0.90625       0.24957        3.83832
 4.20000     1.18730        1.04062       0.28784        3.60851
 4.00000     1.29021        1.19062       0.33073        3.37427
 3.70000     1.45747        1.44687       0.40436        3.01257
 3.40000     1.66114        1.78437       0.50153        2.63422
 3.10000     1.91353        2.29061       0.64725        2.23108
 2.80000     2.26608        3.30873       0.95654        1.78687
 2.62232     SUSTND         INFINT        INFINT         1.49039
```

GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.065 & 0.952

FAULT AT MIDDLE POINT ON ONE LINE



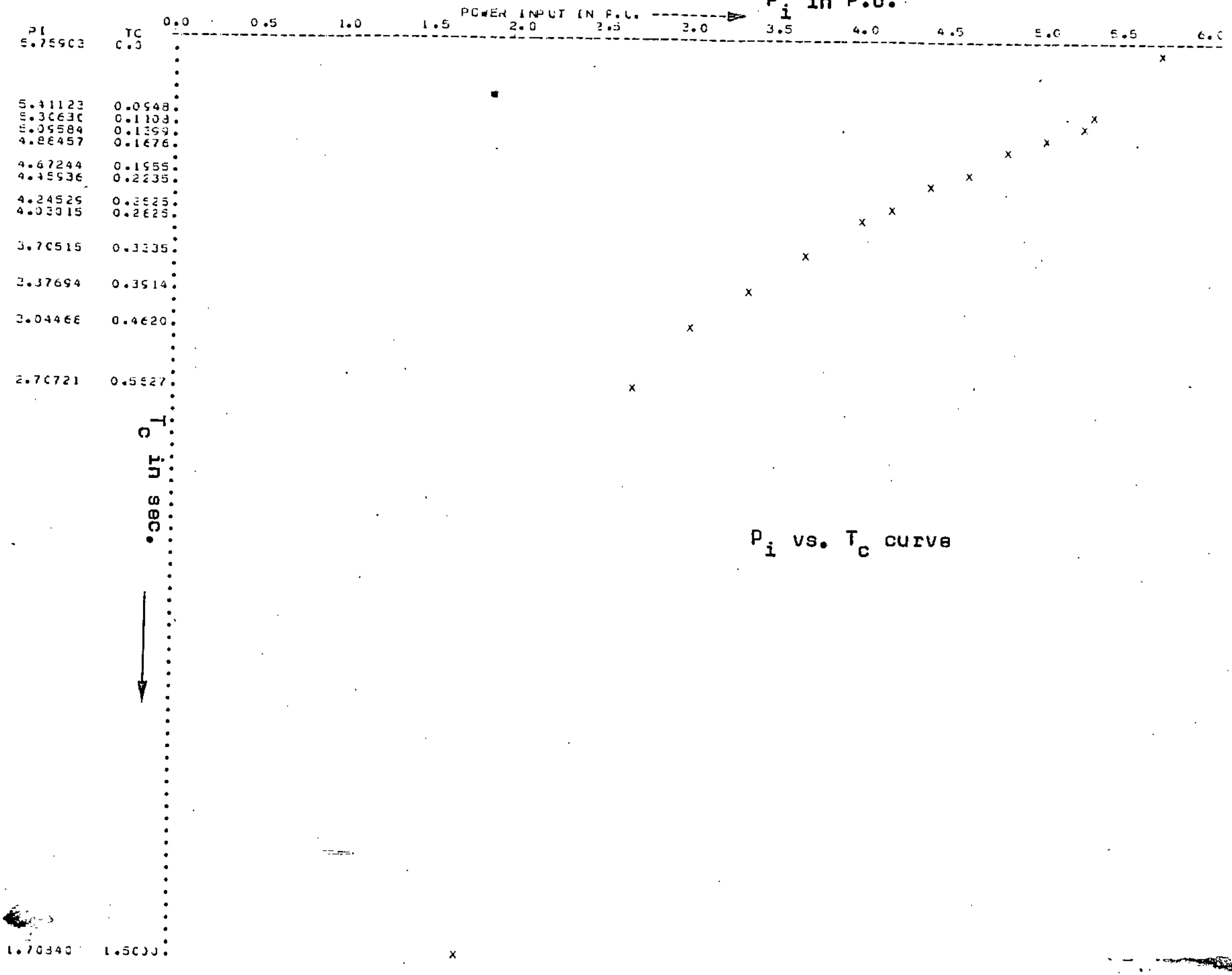
PI	TC
5.05560	0.0
4.83294	0.0842
4.72499	0.1055
4.50738	0.1425
4.28730	0.1782
4.06442	0.2133
3.83832	0.2495
3.60851	0.2879
3.37427	0.3337
3.01257	0.4043
2.63422	0.5015
2.22108	0.6472
1.78687	0.9565
1.49039	1.5000

```
     AI          E1          E2          DELTA       SIN(DELTA)     FI          FM
  5.63279     1.145975    1.058093    41.773605    0.666139    5.759029    8.644744
  5.30000     1.142129    1.046966    39.403397    0.634776    5.411230    8.524631
  5.20000     1.141017    1.043653    38.683319    0.625015    5.306297    8.489873
  5.00000     1.138852    1.037308    37.232162    0.605046    5.095841    8.422242
  4.80000     1.136769    1.031174    35.766235    0.584479    4.884566    8.357127
  4.60000     1.134768    1.025257    34.285339    0.563314    4.672437    8.294546
  4.40000     1.132848    1.019559    32.789032    0.541547    4.459363    8.234491
  4.20000     1.131010    1.014064    31.277008    0.519176    4.245292    8.176984
  4.00000     1.129255    1.008636    29.748371    0.496199    4.030150    8.122047
  3.70000     1.126779    1.001398    27.424759    0.460583    3.705152    8.044483
  3.40000     1.124491    0.994450    25.059494    0.423559    3.376937    7.972773
  3.10000     1.122392    0.988124    22.647720    0.385054    3.044678    7.906943
  2.80000     1.120482    0.962309    20.181641    0.344997    2.707210    7.847050
  1.95777     1.116149    0.969016    12.800432    0.221556    1.708396    7.710917


     AI      CLEARING ANGLE    TOWC      CLEARING TIME    POWER INPUT
  5.63279      0.72909        0.0          0.0            5.75903
  5.30000      0.80135        0.37500      0.09484        5.41123
  5.20000      0.82700        0.43750      0.11068        5.30630
  5.00000      0.88045        0.55000      0.13995        5.09584
  4.80000      0.93696        0.65625      0.16763        4.88457
  4.60000      1.00362        0.76250      0.19550        4.67244
  4.40000      1.07224        0.86675      0.22356        4.45936
  4.20000      1.14553        0.97812      0.25258        4.24529
  4.00000      1.22068        1.09062      0.28259        4.03015
  3.70000      1.35079        1.28124      0.33367        3.70515
  3.40000      1.49013        1.49667      0.39146        3.37694
  3.10000      1.64808        1.75936      0.46202        3.04468
  2.80000      1.82283        2.09666      0.55275        2.70721
  1.95777      SUSTND         INFINT       INFINT         1.70840
```

GRAPH NO.

230 KV SYSTEM
REF. VOLTS. IN P.U. 1.031 & 1.024

FAULT AT MIDDLE POINT ON ONE LINE



P_i vs. T_c curve

Table No. 6.7

Interconnector energized with 132KV

Fault Location	Reference bus voltage in p.u.		Clearing time in cycles	Maximum Power transfer in MW
	ER_1	ER_2		
Near the Bus- 1 or Bus- 2 of one line.	1.0	1.0	3	186
			5	178
			8	160
	1.043	0.950	3	180
			5	171
			8	156
	1.048	0.953	3	181
			5	172
			8	157
	0.972	1.030	3	187
			5	179
			8	162.5
Middle Point of one line.	1.0	1.0	3	190
			5	186
			8	178
	1.043	0.950	3	182
			5	179.5
			8	171
	1.048	0.953	3	183
			5	180
			8	172
	0.972	1.030	3	190
			5	185
			8	179

Table No. 6.8

Interconnector energized with 230KV

Fault location	Reference Bus voltages in p.u.		Clearing time in cycles	Maximum Power transfer in MW
	ER_1	ER_2		
Middle point of one line.	1.0	1.0	3	523
			5	502
			8	471
	1.002	1.059	3	550
			5	535
			8	499
	1.065	0.952	3	490
			5	474
			8	439
	1.081	1.024	3	550
			5	537.5
			8	494
Near the Bus-1 or Bus-2 of one line.	1.0	1.0	3	508
			5	472
			8	411
	1.062	1.059	3	540
			5	508
			8	439
	1.065	0.952	3	480
			5	447
			8	390
	1.081	1.024	3	543
			5	503
			8	435

CHAPTER - VII

FACTORS AFFECTING TRANSIENT STABILITY LIMIT

From the knowledge of the methods of analyzing the transient stability of a system, we can draw a number of general conclusions regarding the effect on stability limit of certain features of apparatus design, system layout and operation. The effect of each feature must be considered under all three conditions viz. before fault, during fault and after fault is cleared. Some features of layout or design promote stability during all conditions, whereas other are beneficial during one condition but detrimental during another. The factors which generally affect transient stability limit are listed below and described elaborately.

1) Inertia constant of synchronous machine.
2) Mutual reactance.
3) No. of parallel transmission lines and location of fault.
4) System voltage and effect of excitation,
5) Clearing time.
6) Number of intermediate high tension buses.
7) Breaking resistor,
8) Short circuit ratio (SCR) .
9) Saturation .
10) Saliency .

1. Inertia Constant:

The power angle curves for each of the three conditions are used in equal-area-criterion method of stability study. The relative sizes of the areas A_1 & A_2 (Fig. 4.5) are dependent on (1) the clering angle δc, (2) the amplitudes of the three power angle curves P_m, $r_1 P_m$ and r_2 P_m and (3) the input power P_i. Stability may be improved by decreasing the area A_1 and/ or by increasing the area A_2. For a given input power P_i, this may be accomplished chiefly by decreasing the clearing angle and increasing the amptitudes of the during fault and post-fault power-angle curves r_1 P_m and r_2 P_m. The critical clearing time t_c required to clear the fault depends on the clearing angle. Higher the critical clearing angle, δc, larger will be the time t_c required to clear the system. Now for a particular clearing angle δc, the modified clearing time τc is constant irrespective of the inertia constant . But the actual clearing time, t_c in second is dependent on inertia constant and it will be higher if the inertia constant is higher as in equation $t_c = \tau_c \sqrt{GH/\pi f r_1 P_m}$. So , for higher inertia constant of the machine, a system requires more time to reach critical clearing angle. We can explain it in another way that for a particular accelerating power the angular displacement will be lower for higher value of inertia constant and vice-versa.

2) Mutual reactance:

The critical clearing angle δc may be increased (i) if the amptitude of the output power-angle curve for fault condition $r_1 Pm$ increases, or (ii) if the amptitudes of the output power-angle curves for during fault $r_1 Pm$ and post-fault r_2 Pm increase simultaneously or (iii) if the amplitudes of prefault, during fault and post-fault power angle curves increase simultaneously. But due to increase of amplitude of only prefault and post-fault power angle curves the initial angle δo decreases and the maximum angle δmax increases. So for a particular initial power Pi, an increase in amplitudes of prefault and post-fault power angle curves, the critical clearing angle δc may or may not increase. But still the effect will be beneficial to the system because of the increased difference between δc and δo due to a lower value of δo and the system will take a larger time to change its torque angle from δo to δc.

The amplutide of all the power-angle curves may be increased by decreasing the mutual reactance. This mutual reactance consists principally of the reactances of the synchronous machines, transformer reactances, and line reactances. The large part of it is in the machines. The transient reactance of each class of large synchronous machines has a characteristics value and does not vary much in normal design. A lower value of reactance may be obtained by building a larger machine and under-rating it. The reactances of transformers also have, for a given size and voltage, normal values. Only the reactance of an overhead transmission line may slightly be varied by changing the spacing and size of the conductors. Also the reactance of the transmission line can be reduced by reducing the system frequency. A frequency of 25 cps. is preferable to 50 or 60 cps. from the stand point of stability. Nevertheless, because of other advantages, 50 or 60 cps. has become the standard power system frequency.

The most important means of reducing the line reactnace are (a) to increase the transmission voltage and (b) to connect more lines in parallel. Higher transmission line voltage reduced the line current and the flux is reduced proportionately. Since the reactance is the effect of flux-linkage of the line, reactance of the line reduced by increasing the transmission voltage.

3) No. of parallel transmission lines and location of fault:

The ratio, r_1 of the amplitude of the during fault power-angle curve to the amplitude of the pre-fault power-angle curve, depends upon the type and location of the fault and number of parallel lines . Here the effect of the location of fault and the number parallel lines will be discussed. A fault on a bus or on a line close to a bus is more severe than a fault of the same type near the middle of the line. Most severe of all is a three phase short circuit on a bus, where it entirely blocks the power transfer between the points: i.e. in that case $r_1 = 0$ and $r_2=0$.

Although the fault on a line close to the bus and on the middle of a line are equally probable, the more severe case is usually assumed in stability studies for conservative results.

The ratio, r_2 of the amplutude of the post-fault power-angle curve to the amplitude of the pre-fault power angle curve also depends on the number and location of the lines which are opened to clear the fault, i.e. it depends upon the fault location and the relaying scheme. As the number of lines will be more the value of r_2 will approach 1. In practice, the value of r_2 may be 1 only if a fault occurs on an unloaded radial feeder and is cleared by disconnection of that feeder. It may also be attained with quick-reclosing schemes which restores the faulted line in service. Again the value of r_2 may be zero if a fault occurs on a bus. Although a fault on a bus is electrically equivalent, before clearing, to a fault on a line adjacent to a bus, it is more severe in its effect after clearing as because more lines are to be opened to clear the fault.

A large number of lines, having same equivalent reactance, are preferable to a small number of lines from the stand-point of stability. To clear the fault requires the opening of one line in either case, but one line is a small fraction of the entire number of lines when this total number will be a large and r_2 will be large.

4) System voltage and effect of excitation:

The power-angle curves can also be increased if the system voltage is increased . In case of two-machine system, the amplitude of the power-angle curve is $P_m = E_1E_2/X_{12}$. An increase in E_1 & E_2 do not increase the initial power flow. The initial power flow rather is determined by the factor $\sin\delta_o$, the initial torque angle between the two machines.

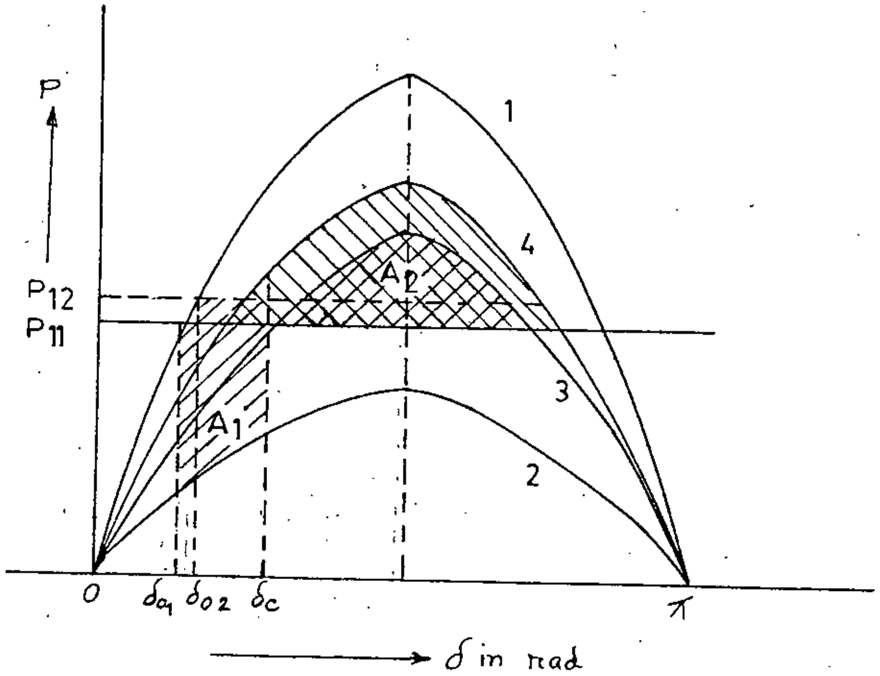


Fig. 7.1

Power Angle Curves Showing the Effect of Excitation.

Curve - 1 Pre-fault power angle curve
Curve - 2 Fault power angle curve
Curve - 3 Post-fault, power-angle curve without excitation
Curve - 4 Post-fault power angle curve with excitation.

If a synchronous generator has an automatic voltage regulator and excitation control system with very short time delay, the generator voltage behind transient reactance increases thus stability limit is improved as explained in Fig. 7.1, where the pre-fault, during fault and two post-fault curves are drawn. Consider a two-machine-system with automatic voltage regulator and excitation control system. The area A_1 is equal to area A_2 for critical clearing angle δc when the generators are without AVR and excitation control system. In this case, the power, Pi_1 can be transferred if the clearing angle lies within δc. Since the AVR and excitation control gives higher generator voltage behind transient reactance, the post-fault power-angle curve will be higher than that without excitation and the area A_2 will be larger. Then for same clearing angle δc the power transfer can be increased to ao higher value Pi_2 to make the area A_1 equal to area A_2. Thus the stability limit can be improved with the help of AVR and excitation control provided the time delay of AVR and excitation systems are short.

In 1950, C. Concordia (13) has shown that the exciter response required to give the same stability limit as that obtained with constant flux-linkage is not constant but increases with increasing switching time. In other words, the required exciter time constant decreases with the increase of switching time. A result calculated for a 200-mile transmission system is listed below(13).

Table No. 7.1

Switching time (in sec.)	Exciter time constant (in sec.)
0.02	2.7
0.06	0.7
0.10	0.3

This results indicate that the effect of fault-clearing time is even more important than is indicated by the usual transient stability studies in which constant flux linkages are assumed.

5) Clearing time, t_c :

In the equal area criterion method of stability study, it is observed that the compared area A_2 can be made larger than area A_1 by reducing the clearing angle δ. This clearing angle δ depends on the clearing time of the relaying scheme and circuit-breaker arrangement of the faulted line. The clearing time includes the relay sensing and operating time plus circuit breaker operating time (7). So the stability limit is increased as the clearing-time is reduced i.e. if for a 5 cycle breaker, the power transfrer limit is say, 0.8 p.u. then for a 3-cycle-breaker the power transfer limit will be higher than that .

6. Number of intermediate high tension buses.

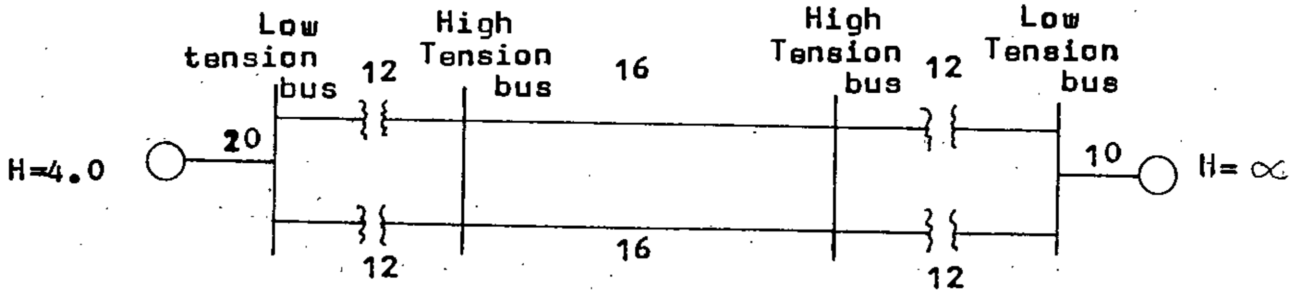


Fig. 7.2
One line Diagram Showing High Tension Buses

When two or more parallel high tension lines are used, the number of intermediate bus affects the stability limit. Some time it may be beneficial or detrimental to stability. In Fig. 7.2 , if the high voltage bus and circuit breakers are provided, a line fault can be cleared by switching out one line leaving all the transformers in service, whereas ,without high voltage buses, the transformers would be switched out with the line. Thus the high voltage buses increase the value of r_2.

On the other hand, during the fault the value of r_1 is decreased. Therefore, the high tension buses help system stability after clearing the fault but as detrimental during the fault period i.e. we may conclude that system stability can be improved by increasing the number of buses provided fast acting circuit breakers are used.

7. Braking resister:

Another method of improving the stability is to connect a resistive load, called breaking resistor at or near the generating bus. This breaking resistor may be in series or in shunt with the bus(7.16). It is connected generally in line after fault occurs and switched off at some definite time in its back swing so that a severe oscillation will not result. The use of braking resistors increase the synchrnous machine output power and thus the acceleration of the machine becomes lower and makes the system more stable for even a delayed clearing. In the otherhand, we may conclude that the system may be stable for an increased power flow and the stability limit increases. Present-day quick operating circuit breakers and relays leave little gain to be realized by braking resistors.

8. Short circuit ratio (SCR):

The short circuit ratio of a synchronous machine may be defined as the ratio of the field current, I_{f_1} required to generate rated voltage at no-load and at rated speed to the field current, I_{f_2} required to produce rated armature current under a sustained three phase short circuit at the terminal. i.e. SCR = I_{f_1} / I_{f_2} as in Fig. 7.3 shown below:

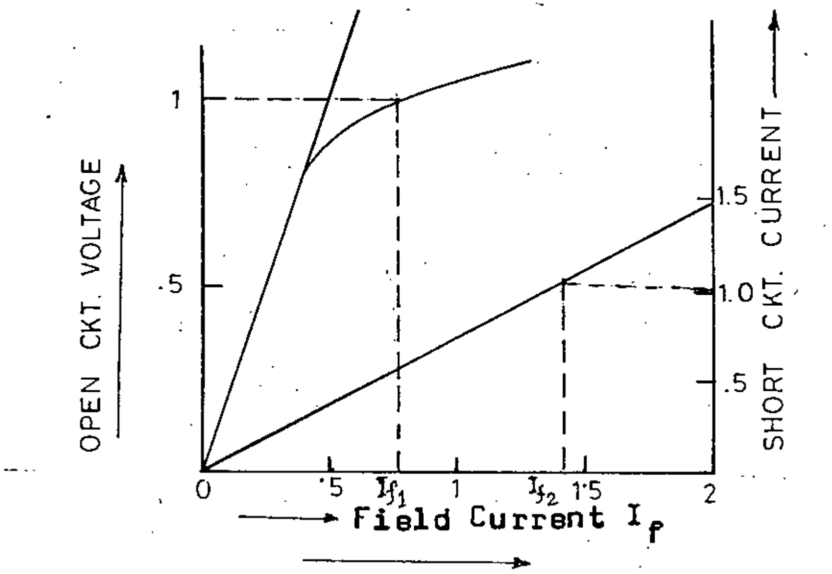


Fig. 7.3

Open Circuit Voltage and Short-Circuit Current Characteristics Curve.

The direct axis synchronous-reactance (x_d) as well as direct-axis transient reactance (x'_d) are inversely proportional to SCR if there is no saturation in the synchronous machine,Higher the SCR , lower is the transient reactance. It is also seen from the Fig.7.3. that the SCR will be higher for a machine running with saturated field current. If there is no saturation ,the SCR is lower and a greater change in field current is required to maintain a constant terminal voltage for a given load change. So a machine with lower SCR requires an exciter control system with quick response and providing large changes in field current. The SCR of a machine is also directly proportional to the machine cost and weight. Higher the SCR, higher the cost and weight of the machine. A too bulky machine is also restricted for higher speed. Hence, as a result of improvements in the excitation system, there has been a trend towards the use of generators of lower SCR and conseqeutnly of lower cost.

The range of short-circuit ratio for steam-turbine-driven generators are 0.5 to 1.1. Most modern generators of this type have ratio in the range of 0.8 to 1.0, but it appears likely that 0.7 will become more generally used. Water-wheel-driven generators usually have higher SCR upto 2.0 whereas synchronous condensers may have SCR as low as 0.4

for higher excitation the reactance will be lower and for

lower excitation the reactance will be higher. The rated

9. Saturation:

The effect of saturation has an important role in the analysis of steady-state stability. Though the saturation has a little effect on transient stability, still it is necessary to include saturation for more accurate result during transient disturbance. During any fault or transient disturbance, the current flowing through the armature is much more higher than the normal rated value. This current, during disturbance increases the saturation in the leakage paths aswell as in the main flux paths. The increased saturation in the leakage paths decreases the effective leakage reactance while the increased saturation in the main flux paths increases the effective fictitious reactance. The net effect is a lower value of transient reactance than would occur if there is no saturation. Usually two values of transient reactances are available in machine-specification: namely (1) reactance at rated current value and (2) reactance at rated voltage value. The reactance at rated current value is offered by the machine at reduced excitation and with rated short-circuit armature current. The reactance at rated voltage value is offered by the machine during short-circuit with an excitation required to produce rated no-load voltage. The difference in the two reactances results from the differences in excitation. For higher excitation the reactance will be lower and for lower excitation the reactance will be higher. The rated voltage value of transient reactnce of a salient pole synchronous machine is 85 to 90% of that of rated current value. Nevertheless, this difference is little for the range of currents encountered during normal operation and usually the rated current value of transient reactance is used in stability study.

10. Saliency:

The inclusion of the effect of synchronous machine saliency increases the complexity in stability analysis, but it is necessary to include it for obtaining more accurate result when excitation response and saturation are considered.

In a salient-pole machine the field winding in each pole is concentrated at the throat of the pole and it has no quadrature axis field circuit, i.e. the field current in the quadrature axis, Ig is zero and the exciting voltage in direct axis, Ed = 0. So the only direct axis field current producing the excitation voltage $E = jEq$ always lies on the quadrature axis in the transient state as well as in steady state as does Eqd, the voltage behind x_q as shown in Fig. 7.4 . Furthermore since $x'_q = x_q$, $E'_d = Ed = 0$, the voltage behind direct axis transient reactance,

$E' = jE'_q$, lies on the quadrature axis.

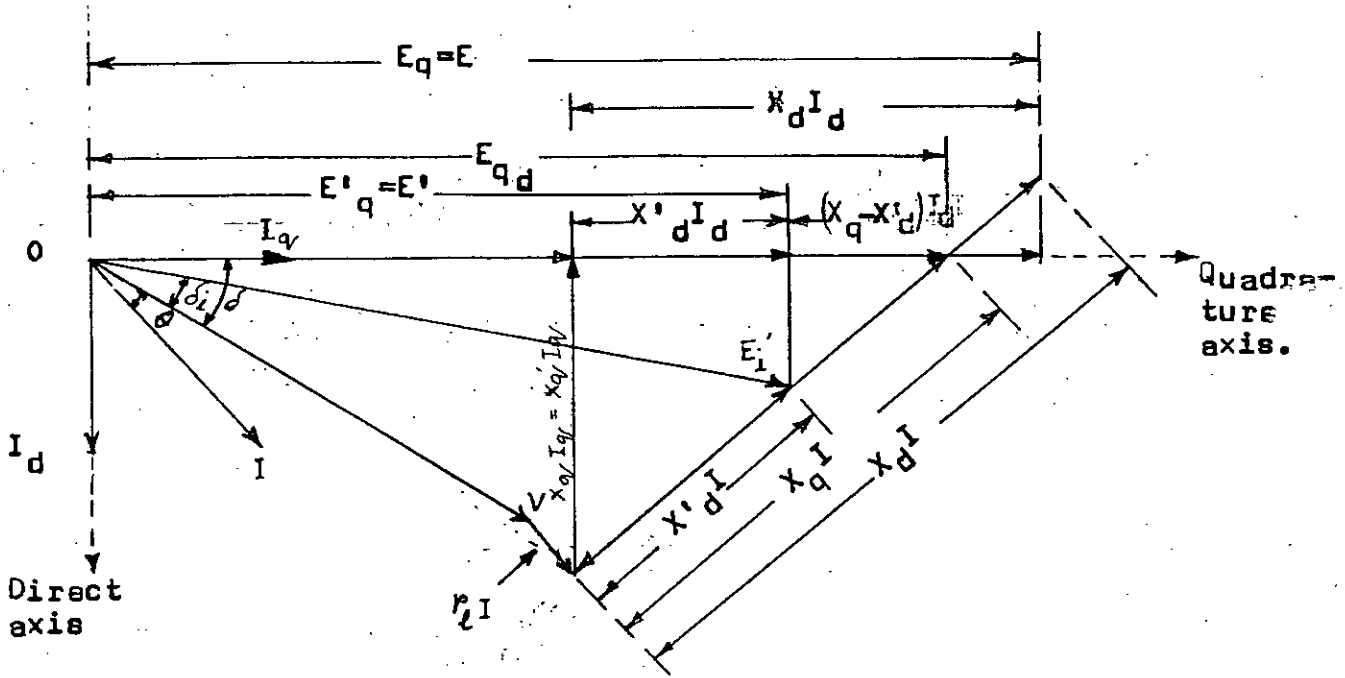


Fig. 7.4

Vector Diagram of Salient-Pole Synchronous Machine

The electric power output of a salient pole synchronous machine at steady-state may be expressed interms of the terminal voltage v, the excitation voltage Eq, the angle δ between the two voltages and x_d and x_q as$^{(9,18)}$

$$p = \frac{E_q\ V \sin\delta}{x_d} + v^2 \frac{(x_d - x_q)}{2x_d\ x_q} \sin 2\delta \qquad (7.1)$$

a combination of fundamental frequency and its 2nd harmonic, where x_d is direct axis synchronous reactance & x_q is quadrature axis synchronous reactance. The power equation at transient condition can be achieved from that of the steady-state condition by simply replacing E'_q for E_q, X'_d for x_d and x'_q for x_q and δ is same for both the condition i.e. at transient condition the power equation becomes;

$$p = \frac{E'_q v \sin\delta}{x'_d} + \frac{v^2(x'_d - x'_q)}{2x'_d x'_q} \sin 2\delta \qquad (7.2)$$

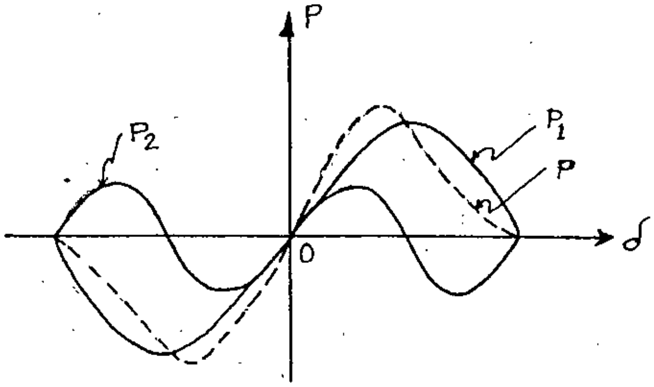
But since at transient condition $x'_d < x'_q$, the equation may be written as

$$p = \frac{E'_q v}{x'_d} \sin\delta - \frac{v^2(x'_q - x'_d)}{2x'_q x'_d} \sin 2\delta \qquad (7.3)$$

$$= p_1 - p_2$$

where, $p_1 = \frac{E'_q v}{x'_d} \sin\delta$ and $p_2 = \frac{v^2(x'_q - x'_d)}{2x'_q x'_d} \sin 2\delta$

From the power-angle curves shown in fig. 7.5a and fig. 7.5b it is observed that the smooth sine wave is deviated due to its 2nd harmonic term and attains a peak value before the angle δ reaches 90^0 for steady-state condition but attains a peak value after the angle δ exceeds 90^0 for transient condition.



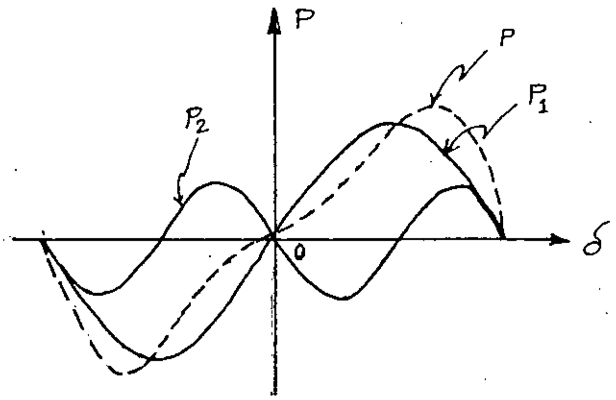


Fig. 7.5a.a. Fig. 7.5b. b.

For steady-state condition For Transieent Condition

Power-Angle Curves including Saliency Effect.

It is rather very much difficult to carry out the analytical calculations where a number of salient-pole machines exist. Therefore for the simplicity of calculation the 2nd harmonic term in power equation is omitted due to its very small amplitude and the power equation becomes $p = \frac{E'_q\ v}{x'_d} \sin\delta$, which is equivalent to the power equation computed for in case of non-salienet pole machine.

CHAPTER - VIII

CONCLUSION, SUGGESTION FOR IMPROVING SYSTEM STABILITY AND SUGGESTION FOR FURTHER WORK

8.1 Conclusion:

The study of stability limit is essential for any grid for the selection of proper circuit breaker arrangement on it. The method has been applied here for determination of Transient stability limit of the East-West Interconnector.

This method of stability limit study is fast and efficient. For any fault location, when the system becomes unstable, the multimachine system can be split in to two groups of machines which go out of synchronism with each other, while the machine within each group stay in synchronism (2, 5). This grouping may differ with the fault location. But still , for a given fault location the behabiour of the multi-machine system is similar to that of a two-machine system. It could be analyzed as a two-machine system except that the machines within a group may swing so far with respect to each other, without going out of step, as to have a marked effect on the relations between the two groups.

At normal operating condition the two machine voltages behind transient reactance and their relative rotor angle depends on the load transfer between the machines. The relative rotor angle between the machines and their voltages are found out by trigonometrical relations for different loading conditions, keeping the two inter-grid bus voltages as the constant reference values related to the system base value.

Earlier, the transient stability limit was studied with the help of (i) equal area-criterion method in conjunction with (2) Pre-calculated swing curve and(3) the curve-determining critical clearing time and an analog computer was used as the computing device(2,3). In this study all equations, required for determination of stability limit, have been solved by digital computer IBM-370. The main program alongwith five subprograms are used to solve all the equations without any manual intervention.

The multimachine system is reduced to a two-machine system by star-mesh conversion principle. The equivalent transfer reactance of the two machines for pre-fault condition is used as the input data in the analysis. Therefrom, the transfer reactances for during-fault and post-fault conditions are calculated by the Computer Program. The time taken for all calculations by the Computer for one complete run is about 200 seconds.

Two types of fault locations are assumed one at the middle point and another near the bus terminal of one of the double circuit line of the interconnector. For two types of fault locations one computer run is sufficient, i.e. with one Computer run we can have two number of stability limit curves. The results obtained for the two different fault locations are different. It is found that the fault near the bus is more restrictive and the transient stability limit is lower than that for the fault at the middle of the interconnector. For the East-West interconnector, the safe limit of power transfer, from the view point of transient stability limit, is 180 MW at 132 KV operation and about 500 MW at 230 KV operation. This result agrees with the results of 'ACRES' study of the interconnector.

8.2 Suggestions for improving system stability:

The transient stability limit is the maximum allowable power flow through any point under transiently stable condition of a power system while it undergoes large disturbance or any fault. This stability limit is a function of (1) clearing time(2) Machine, transformer & line reactances; (3) governor and AVR and excitation control system of the machine and (4) Damper winding of the machine.

(1) The power limit can be made larger if the clearing time of the relay and circuit breaker are reduced i.e. if a 3-cycle breaker is used in place of a 5-cycle breaker, the power limit will increase. Further improvement of power limit may be possible by using circuit breaker with auto-reclosing arrangement.

(2) The power flow of the machines will be higher if the prefault and post-fault swing curves become larger. The amptitudes of the pre-fault and post-fault swing curves;

$(P_m = E_1 E_2/X_{12}$(pre-fault) & $r_2 P_m = E_1 E_2/X_{12}$(Post fault) depend on the reactances of prefault and post-fault conditions.

The pre-fault reactance comprises of the direct axis transient reactance of synchronous machines, transformer reactance and line reactance. The machine reactance can be reduced by using larger machines and under-rating it. The transformer reactance can be reduced by using larger autotransformer. The line reactance can be reduced by either energizing with higher voltage or by paralleling it or by changing the system frequency. A system frequency of 25cps is preferable to 50cps or 60 cps in stability point of view. But 50 cps or 60 cps are suitable considering other aspects. If the lines are parallel , the pre-fault reactance as well as post fault reactance becomes lower for any fault on a line at any location. The ratio, $r_2 = \frac{X_{12}(\text{prefault})}{X_{12}(\text{post fault})}$ will be higher.

The power transfer will be higher if initial operating angle δo be higher. This initial operating angle δo also depends on the ratio r_2. Higher the ratio, r_2, higher will be the operating angle at instantaneous clearing and larger will be the amplitude of post-fault power angle curve. If the interconnector could be paralleled by another double-circuit line or one sub-station could be arranged in between Tongi and Ishurdi, the ratio r_2 would be increased resulting in a higher power transfer.

3) Usually turbines are provided with governor and generators are provided with AVR and field excitation control system. In this study, governor action of the turbine and AVR and field

excitation of generator are neglected as their corrective action in the first one second is negligible because of their slow response. If the governor has a quick response both of acceleration and retardation of the machine will be slower which makes the machine more stable. Similarly the excitation control system and AVR, if included in calculation of power-angle equation, can help to make a further improvement in stability limit.

4) Damper windings are used on each of the generator poles. This damper winding produces some stabilizing torque at the time of acceleration and/or retardation of the machine and makes it to run in synchronous speed in a short time. The effectiveness of the damper winding depends on its winding resistance which may be reduced to make the machine more stable.

8.3 Suggestion for further work:

Further research in this field can be done with the following topics included:

1) The line resistance can be included in the calculation of transfer impedances. The necessary changes are to be made to solve the complex quantities.

2) The governor action and excitation control system can be incorporated in future study. The input power calculation and electrical output power calculation can be done by two more separate subroutine programs.

3) Equation for damping effect can be added in the swing equation for further work.

4) The calculation of network reduction can be done by adding one more sub-routine program.

REFERENCES:

1. Miller, R.H., Power System Stability, McGraw-Hill Book Company, New York.

2. Kimbark, E.W., Power System Stability, Vol. I, John Wiley & Sons Inc., New York.

3. Crary, S.B., Power System Stability, Vol-II, John Wiley & Sons, Inc., New York.

4. Shackshaft, G. & Aldred, A.S., Effect of Clearing time on Synchronous machine transient Stability, AIEE Vol. 76, Part-III, PAS, pp. 633-37. 1957.

5. Kimbark, E.W., Power System Stability, Vol-II, John Wiley & Sons Inc., New York.

6. Saline, L.E., Power limits of transmission lines, AIEE, Vol. 71, Part- III, PAS, pp. 709-719 , Aug. 1952.

7. Stevenson, W.D., Elements of Power System Analysis, Third Edition , Mc Graw-Hill, Kogakusha Ltd., Tokyo.

8. Butler, R.M. and Hopkins, D.L., Transient Stability Limits and Their Effects on the choice of Conductor size, AIEE, Volt-73, Part-III B, PAS ,pp.996-1003, Aug. 1954.

9. Crary, S.B., Power System Stability, Vol. I, John Wiley & Sons Inc. , New York.

10. Westing House Electrical Corporation, Electrical Transmission & Distribution Reference Book, Oxford & IBH Publishing Company, Calcutta.

11. Dyrkacz, M.S. Young, C.C. & Maginess, F.J., A Digital Transient Stability Program Including the Effect of Regulator, Exciter and Governor Response, AIEE Vol. 79, Part-III PAS, pp-1245-56, 1960.

12. Stagg, G.W. & El-Abiad, A.H., Computer Method in Power System Analysis, International Student Ediction Mc. Graw Hill Kogakusha, Ltd., Tokyo.

13. Kimbark, E.W., Power System Stability, Vol. III, John Wiley & sons Inc., New York.

14. Hannakam. L. & Concordia, C., Stability Limits of Synchronous Motors During Power System Disturbances, AIEE , Vol. 81, No. 58, Part- III pAS, pp-1136-41, Feb. 1962.

15. Rindt, L.J. , Long , R.W., & Byerly, R.T. Transient Stability Studies, Part-III, Improved Computational Techniques, AIEE, Vol. 78, Part-IIIB, .PAS , pp-1673-77, 1959.

16. Stevenson, W.D., Elements of Power System Analysis, Mc.Graw-Hill, Book Company , Inc. New York, 1955.

17. Haque, M.H., Transient Stability Study of Multi-machine System, An M.Sc.Thesis, submitted to Electrical Engineering Deptt. BUET, Dhaka, June, 1983.

18. Anderson, H.C., Simmons, JX., H.O. & Woodraw, C.A., System Stability Limitations and Generator Loading, AIEE, Volt-72, Part-III, PAS, pp-406-22, June, 1953.

19. Elgerd, O.I. Electric Energy Systems Theory: An introduction, Tata Mc-Braw-Hill Publishing Company Ltd., New Delhi.

20. Dyrkacz. M.S. & Lewis, D.G., A New Digital Transient Stability Program, AIEE, Vol. 78, Part-III B., PAS pp. 913-18 Oct.1959.

21. Haq, E., Stability Studies on a Power System including some Future Expansion programs. A Thesis submitted to EEE Deptt. BUET , Dhaka, August, 1977.

22. KUO-Shan . S., Numerical Method and Computers, Addison-Wesley Publishing Company, London.

23. Scarborough, J.B., Numerical Mathematical Analysis, Sixth edition, Oxford and IBH publishing Co., New Delhi.

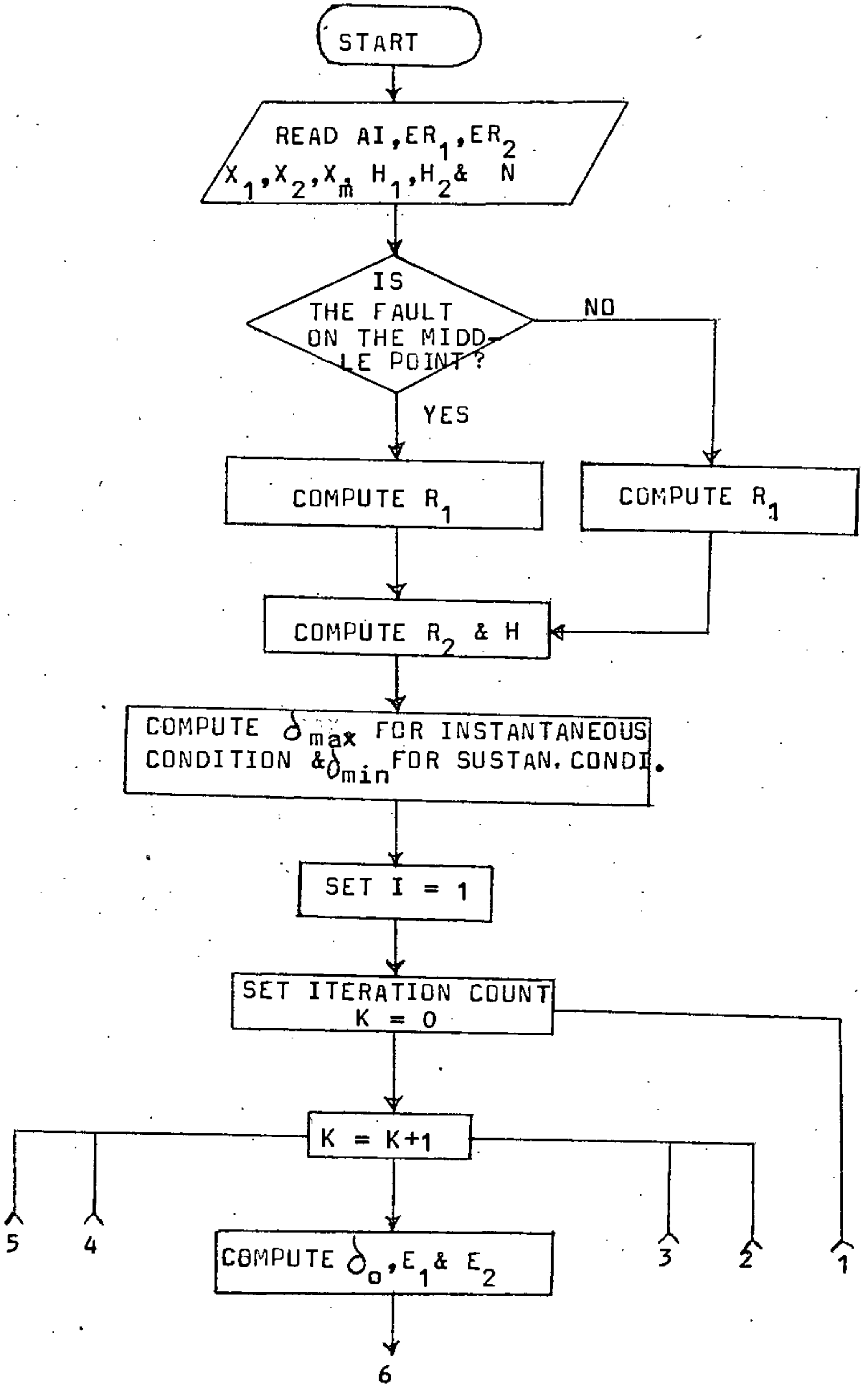
24. KUO, Shan, S., Computer Applications of Numerical Method, Addison-Wesley Publishing Company, California, London.

25. Acres International(Canada) Ltd., A Study Report on Transient Stability of BPDB national Power System network, 1968.

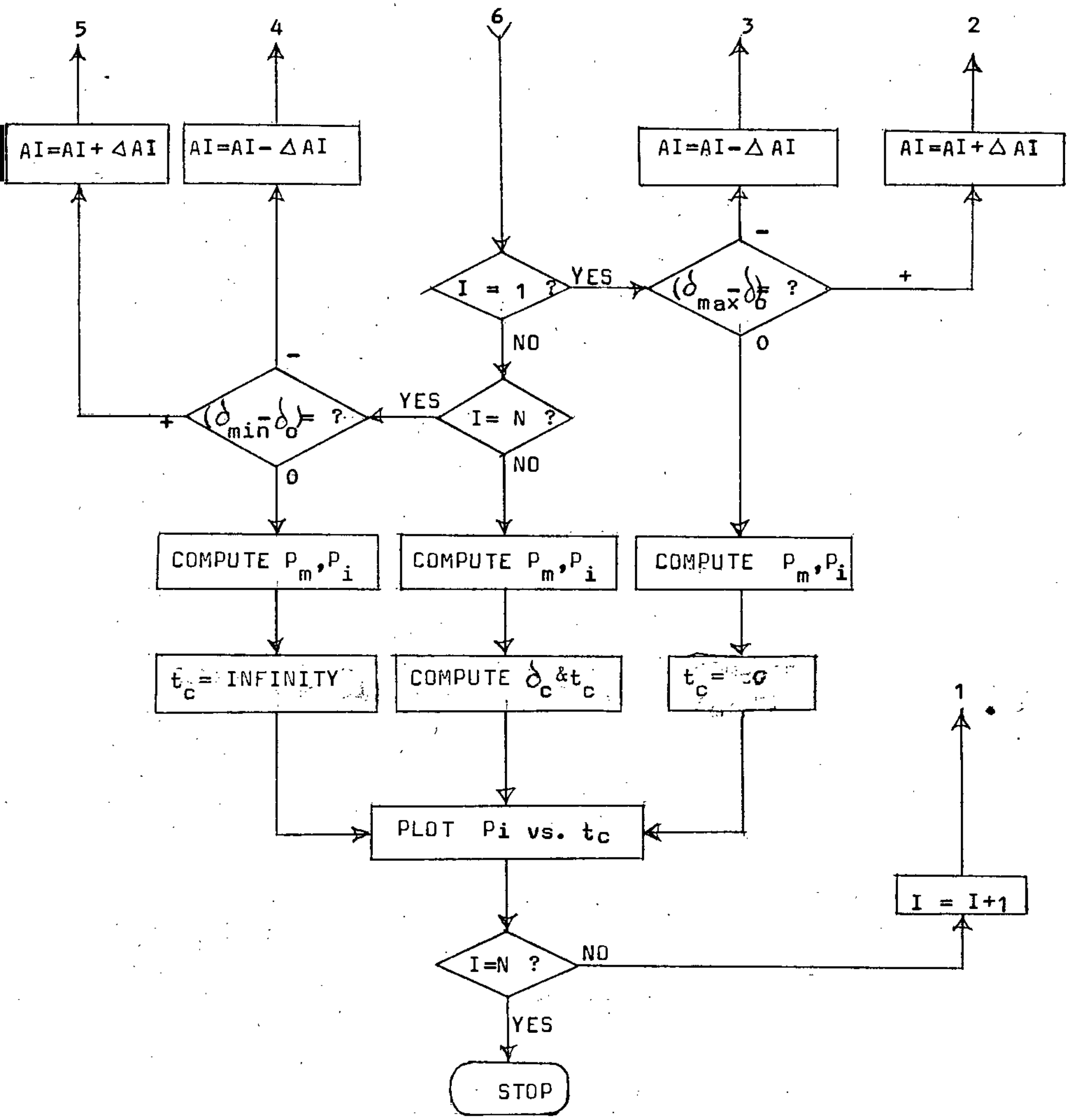
APPENDIX

APPENDIX - A

10.1 FLOW CHART



FLOW CHART(Contd)



APPENDIX- B

COMPUTER PROGRAMME

```
      SUBROUTINE SIND (R,SD,SDX,ITER)
      COMMON PIE
      ITER= 0
      ITER= ITER+1
      IF(R.EQ.0.0) GO TO 99
   50 SM= SQRT(R*R-SD*SD)
      DELM1= ATAN(SD/SM)
      DELM= PIE-DELM1
      SSD= SQRT(1.0-SD*SD)
      DEL = ATAN(SD/SSD)
      ANUM1= COS(DEL)
      ANUM2= -COS(DELM)
      ANUM3= ANUM1+ANUM2
      ANUMO= R*ANUM3
      DENO= DELM-DEL
      SDX= ANUMO/DENO
      RESI= SDX-SD
      IF(RESI.LE..0001) GO TO 100
      IF(ITER.GT.50) GO TO 100
      SD= SD+1.2*RESI
      GO TO 50
   99 SDX= SD
  100 RETURN
      END
```

```
      SUBROUTINE CLEAR (I,AI,SG,DEL,R2,R1,DELC)
      DIMENSION SG(25),DELC(25),AI(25)
      COMMON PIE
      Z=SG(I)/R2
      AZ=SQRT(1.0-Z*Z)
      PHIE=ATAN(Z/AZ)
      DELM=PIE-PHIE
      XDEL=DELM-DEL
      A=XDEL*SG(I)
      AB= R1*COS(DEL)
      AC=R2*COS(DELM)
      ADD=A-AB+AC
      DIV=R2-R1
      AX=ADD/DIV
      AD=SQRT(1.0-AX*AX)
      DELC(I)= ATAN(AD/AX)
      IF(DELC(I).GE.0.0) GO TO 330
      DELC(I)=DELC(I)+PIE
  330 RETURN
      END
```

```
      SUBROUTINE CTIME (I,AI,FPM,DEL,DELC,PI,TOWC)
      DIMENSION DELC(25),TOWC(25),PI(25),FPM(25),AI(25),ITER(25)
      COMMON PIE,FREQ
      P= 2.0*PIE*FREQ
      W=P
      TOW=0.0
      DTOW= 0.1
      ITER(I)=0
  110 ITER(I)=ITER(I)+1
      TOW=TOW+DTOW
      B1=(W-P)*DTOW
      CALL POWER(I,PI,FPM,PE,DEL,TA)
      C1= TA*DTOW
      ST=  B1/2.0
      DELT=DEL+ST
      B2=((W+C1/2.0)-P)*DTOW
      CALL POWER (I,PI,FPM,PE,DELT,TA)
      C2= TA*DTOW
      ST=  B2/2.0
      DELT=DEL+ST
      B3=((W+C2/2.0)-P)*DTOW
      CALL POWER (I,PI,FPM,PE,DELT,TA)
      C3= TA*DTOW
      ST=  B3
      DELT=DEL+ST
      B4=((W+C3)-P)*DTOW
      CALL POWER (I,PI,FPM,PE,DELT,TA)
      C4= TA*DTOW
      BT=(B1+2.0*(B2+B3)+B4)/6.0
      CT=(C1+2.0*(C2+C3)+C4)/6.0
      DELTC=DEL+BT
      IF(ITER(I).GT.50) GO TO 155
      IF(DTOW.LE.0.005) GO TO 155
      IF(ABS(DELTC-DELC(I)).LE.0.001) GO TO 155
      IF(DELTC-DELC(I)) 154,155,150
  154 DEL= DELTC
      W= W+CT
      GO TO 110
  150 TOW= TOW-DTOW
      DTOW=0.5*DTOW
      DEL=DELTC-BT
      GO TO 110
  155 DELC(I)=DELTC
      TOWC(I)= TOW
      RETURN
      END
```

```
      SUBROUTINE POWER (I,PI,FPM,PO,TEL,XA)
      DIMENSION PI(25),FPM(25)
      COMMON PIE
      PO= PI(I)/FPM(I)
      XA=PO-SIN(TEL)
      RETURN
      END
```

```
      SUBROUTINE CTIMED (I,AI,SD,DEL,DELC,ROWC)
      DIMENSION SD(25),DELC(25),AI(25),ROWC(25)
      COMMON PIE
      ANEU= 2.*(DELC(I)-DEL)
      ROWC(I)=SQRT(ANEU/SD(I))
      RETURN
      END
```

```
C         ****************************************************************
C         ****************************************************************
C         *******  DETERMINATION OF TRANSIENT STABILITY LIMIT       *******
C         *******  OF INTER-GRID POWER TRANSFER,FOR 230KV SYSTEM   *******
C         *******  AN M.SC. ENGINEERING THESIS.                     *******
C         *******  PROGRAMMER  -  MD. YEAKUB HUSSAIN                *******
C         *******  M.SC. ENGG. STUDENT , ROLL NO. 811303(F).        *******
C         *******  ASSISTANT PROFESSOR OF ELECT. ENGG. DEPTT.       *******
C         *******--RAJSHAHI ENGINEERING COLLEGE, RAJSHAHI.          *******
C         *******  APRIL , 1984                                     *******
C         ****************************************************************
C         AI=CURRENT IN P.U.
C         E1= VOLTAGE OF M/C 1 IN P.U.
C         E2= VOLTAGE OF M/C 2 IN P.U.
C         ER1= REFERANCE VOLTAGE OF BUS-1
C         ER2= REFERANCE VOLTAGE OF BUS-2
          DIMENSION AI(25),E1(25),E2(25),P1(25),PM(25),DELTA(25),SD(25),AS(2
         +5),ALPHA(25),THETA(25),TOWC(25),TC(25),DELC(25),FPM(25),FOWC(25),
         +ARRAY(110),L(25)
          DATA DASH/'-'/,DOT/'.'/,CROSS/'X'/,BLANK/' '/
          COMMON PIE,FREQ
          READ(1,11) N,MF,FREQ,LEVEL
          NN=N-1
      801 READ(1,103,END=999) IREF
          READ(1,10,END=999) (AI(I),I=1,N)
          READ(1,12,END=999) Y1,Y2,YM,H1,H2
      101 GO TO(1,2,3,4),IREF
        4 READ(1,102,END=999) ER1,ER2
          GO TO 7
        3 READ(1,102,END=999) ER1,ER2
          GO TO 7
        2 READ(1,102,END=999) ER1,ER2
          GO TO 7
        1 READ(1,102,END=999) ER1,ER2
        7 GO TO (100,200),MF
      100 SUMY1M= Y1+YM/2.+YM
          Y1M=(Y1*YM/2.)/SUMY1M
          YM0=(YM*YM/2.)/SUMY1M
          Y2M0= YM+YM0
          SUMY12= Y1M+Y2M0+Y2
          YF=(Y1M*Y2)/SUMY12
          GO TO 9
      200 YF= 0.0
        9 XAF=(1./Y1)+(2./YM)+(1./Y2)
          YAF= 1./XAF
          WRITE(3,115)
          WRITE(3,13)
          WRITE(3,14) (AI(I),I=1,N)
          WRITE(3,15)
          WRITE(3,16) ER1,ER2
          WRITE(3,17)
          WRITE(3,18) Y1,Y2,YM,YF,YAF,H1,H2
          PIE= 3.14159
          F=180.0/PIE
          H=H1*H2/(H1+H2)
          XT=(1./Y1)+(1./Y2)+(1./YM)
          R1=XT*YF
          R2=XT*YAF
          SD1= 0.0
          CALL SIND (R1,SD1,SUMIN,ITER)
          WRITE(3,80)R1,SUMIN,ITER
          CALL SIND (R2,SD1,SUMAX,ITER)
          WRITE(3,81)R2,SUMAX,ITER
          WRITE(3,82) H
          ER1S= ER1**2
          ER2S= ER2**2
          DO 20 I=1,N
          ITER=0
          DAI= 0.05
       50 ITER=ITER+1
          IF(ITER.GT.99) GO TO 59
       63 AM=(AI(I)/YM)
          AL=(AI(I)/Y1)
          AR=(AI(I)/Y2)
          AMS= AM**2
          ALS= AL**2
          ARS= AR**2
          E= 0.5*(ER2S+AMS-ER1S)/(AM*ER2)
```

```
      C= 0.5*(ER1S+AMS-ER2S)/(AM*ER1)
      IF(B.GT.1.0) GO TO 50
      IF(B.LT.-1.0) GO TO 50
      BB= SQRT(1-B*B)
      CC= SQRT(1-C*C)
      ALPHA(I)= ATAN(BB/B)
      THETA(I)= ATAN(CC/C)
      IF(ALPHA(I)) 46,47,47
   46 ALPHA(I)= ALPHA(I)+PIE
   47 E5= COS(PIE-ALPHA(I))
      IF(THETA(I)) 25,26,26
   25 THETA(I)= THETA(I)+PIE
   26 C5= COS(PIE-THETA(I))
      E1S= ER1S+ALS-2*ER1*AL*C5
      E1(I)=SQRT(E1S)
      E2S=ER2S+ARS-2*ER2*AR*E5
      E2(I)=SQRT(E2S)
      AS(I)=(XT*AI(I))**2
C     D= COS(DEL)
      D= 0.5*(E1S+E2S-AS(I))/(E1(I)*E2(I))
      DD= SQRT(1-D*D)
      DEL= ATAN(DD/D)
      SO(I)=SIN(DEL)
      IF(I-1) 55,55,58
   58 IF(I-N) 59,70,70
   55 IF(ABS(SO(I)-SOMAX).LE.0.0001)GO TO 59
      GO TO 61
   61 IF(SO(I)-SOMAX) 56,59,57
   56 AI(I)=AI(I)+DAI
      GO TO 60
   57 IF(ITER.EQ.1) GO TO 64
      AI(I)=AI(I)-DAI
      DAI=DAI*0.5
      AI(I)=AI(I)+DAI
      GO TO 60
   64 DAI=0.05
      AI(I)=AI(I)-DAI
      GO TO 63
   70 IF(SOMIN.EQ.0.0) GO TO 65
      IF(ABS(SO(I)-SOMIN).LE.0.0001)GO TO 59
      GO TO 62
   62 IF(SO(I)-SOMIN) 56,59,57
   59 DELTA(I)=DEL*F
      IF(I.EQ.1) GO TO 169
      IF(I.EQ.N) GO TO 169
      IF(SO(I).GT.SOMAX) GO TO 900
      IF(SO(I).LT.SOMIN) GO TO 901
  169 PM(I)=E1(I)*E2(I)/XT
      FPM(I)=E1(I)*E2(I)*YF
      FI(I)=PM(I)*SO(I)
      GO TO 164
   65 SO(I)= 0.0
      DEL=0.0
      GO TO 59
  164 IF(I-1) 160,160,165
  165 IF(I-N) 170,175,175
  170 CALL CLEAR (I,AI,SO,DEL,R2,R1,DELC)
      FACT=SQRT(PIE*FREQ/H)
      IF(R1.EQ.0.0) GO TO 500
      CALL CTIME (I,AI,FPM,DEL,DELC,PI,TOWC)
      FPMR=SQRT(FPM(I))
      TC(I)=TOWC(I)/(FACT*FPMR)
      GO TO 20
  500 CALL CTIMEO (I,AI,SO,DEL,DELC,ROWC)
      PMR=SQRT(PM(I))
      TC(I)=ROWC(I)/(FACT*PMR)
      GO TO 20
  160 TOWC(I)=0.0
      FOWC(I)= 0.0
      TC(I)= 0.0
      DELC(I)=DEL
      GO TO 20
  175 TOWC(I)= INFINT
      FOWC(I)= INFINT
      TC(I)= INFINT
   20 CONTINUE
      WRITE(3,201)
      WRITE(3,21)
```

```
          WRITE(3,22)(AI(I),E1(I),E2(I),DELTA(I),SC(I),PI(I),PM(I),I=1,N)
          IF(R1.EQ.0.0) GO TO 123
          WRITE(3,23)
          WRITE(3,24) (AI(I),DELC(I),TOWC(I),TC(I),PI(I),I=1,NN)
          GO TO 124
      123 WRITE(3,225)
          WRITE(3,24) (AI(I),DELC(I),ROWC(I),TC(I),PI(I),I=1,NN)
      124 I=N
          WRITE(3,29) (AI(I),PI(I))
    C        PLOTTING OF GRAPH
          DO 120 K=1,120
          ARRAY(K)=DASH
      120 CONTINUE
          SCALE= 18.0
          WRITE(3,121)
          WRITE(3,704) LEVEL
          WRITE(3,705) ER1,ER2
          IF(R1.EQ.0.0) GO TO 700
          WRITE(3,701)
          GO TO 703
      700 WRITE(3,702)
      703 IF(LEVEL.EQ.132) GO TO 131
          WRITE(3,122)
      710 WRITE(3,223) ARRAY
          GO TO 711
      131 WRITE(3,132)
          SCALE= 50.0
          GO TO 710
      711 DO 125 K=1,120
          ARRAY(K)=BLANK
      125 CONTINUE
          ARRAY(1)=DOT
          J=0
          DO 130 I=1,N
          IF(I.EQ.N)  TC(I)=1.5
          L(I)=INT(TC(I)*50.0+0.5)
          M=INT(PI(I)*SCALE +0.5)
      126 IF(J-L(I)) 128,127,130
      127 IF(M.GE.0.AND.M.LE.120) ARRAY(M)=CROSS
          WRITE(3,133)PI(I),TC(I),ARRAY
          IF(M.GE.0.AND.M.LE.120)ARRAY(M)=BLANK
          J=J+1
          GO TO 130
      128 IF(M.GE.0.AND.M.LE.120)ARRAY(M)=BLANK
          WRITE(3,75) ARRAY
          J=J+1
          GO TO 126
      130 CONTINUE
          GO TO 600
      900 WRITE(3,902) AI(I)
          GO TO 600
      901 WRITE(3,903) AI(I)
      600 IREF= IREF-1
          IF(IREF.EQ.0) GO TO 404
          GO TO 101
      404 MF= MF-1
          IF(MF.EQ.0) GO TO 999
          GO TO 801
       10 FORMAT(14F5.3)
       11 FORMAT(2I3,F5.2,I4)
       12 FORMAT(5F10.6)
       13 FORMAT(/44H                                        CURRENT IN P.U./)
       14 FORMAT(10X,14F6.3/)
       15 FORMAT(/46H                                        REFERANCE VOLTAGE/)
       16 FORMAT(2(32X,F10.5//))
       17 FORMAT(88H                                    Y1           Y2           YN          Y
         +          YAF          H1                  H2/)
       18 FORMAT(/20X,7F10.6//)
       21 FORMAT(/15X,'AI',9X,'E1',10X,'E2',8X,'DELTA',5X,'SIN(DELTA)',6X,
         + 'PI',8X,'PM'//)
       22 FORMAT(10X,F10.5,2X,F10.6,2X,F10.6,2X,F10.6,1X,F10.6,1X,F10.6,1X,
         + F10.5/)
       23 FORMAT(/////15X,'AI',4X,'CLEARING ANGLE',4X,'TCWC',5X,'CLEARING TI
         +ME',4X,'POWER INPUT'/)
       24 FORMAT(10X,F10.5,1X,F10.5,3X,F10.5,5X,F10.5,5X,F10.5/)
       29 FORMAT(10X,F10.5,4X,'SUSTND',7X,'INFINT',9X,'INFINT',6X,F10.5//)
       75 FORMAT(T20,120A1)
       80 FORMAT(1H1,////
```

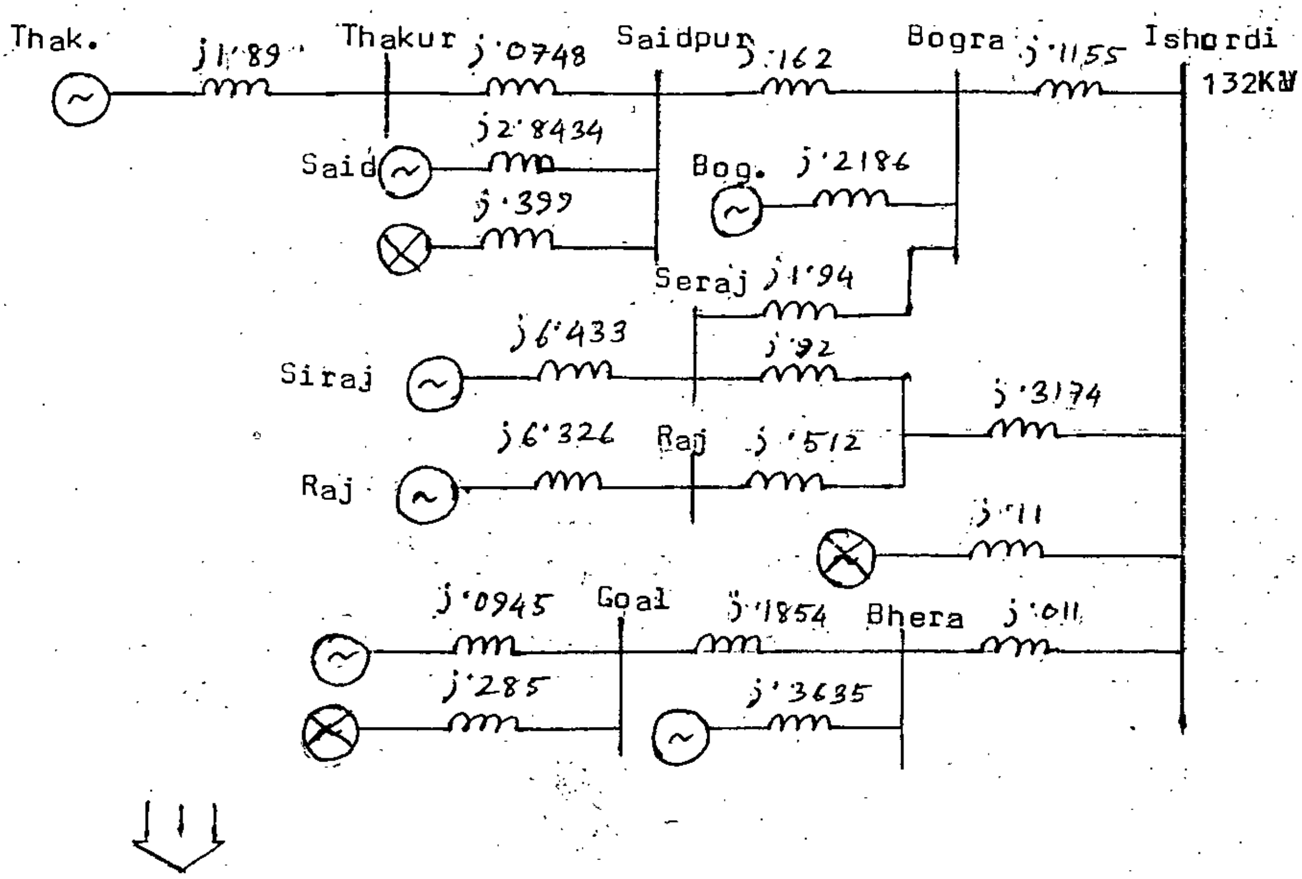
```
     +             30X,'R1=',F10.6,5X,'SUMIN=',F10.6,'ITER=',I4/)
  81 FORMAT(/30X,'R2=',F10.6,5X,'SUMAX=',F10.6,'ITER=',I4//)
  82 FORMAT(//30X,'H=',F10.6////////////)
 102 FORMAT(2F5.3)
 103 FORMAT(I3)
 115 FORMAT(1H1)
 121 FORMAT(1H1,/////)
 122 FORMAT(T59,'POWER INPUT IN P.U. ----------'/T19,'0.0',T28,'0.5',
    + T37,'1.0',T46,'1.5',T55,'2.0',T64,'2.5',T73,'3.0',T82,'3.5', T91
    + '4.0',T100,'4.5',T109,' 5.0',T118,'5.5',T127,'6.0')
 132 FORMAT(T50,'POWER INPUT IN P.U.----------'/T19,'0.0',T44,'0.5',T69
    + '1.0',T94,'1.5',T119,'2.0',T129,'2.2')
 135 FORMAT(F10.5,F10.5,T20,120A1)
 201 FORMAT(1H1)
 223 FORMAT(T5,'PI',T15,'IC',T20,120A1)
 225 FORMAT(15X,'AI',4X,'CLEARING ANGLE',4X,'ROWC',5X,'CLEARING TIME',
    + 4X,'POWER INPUT'/)
 701 FORMAT(T40,'FAULT AT MIDDLE POINT ON ONE LINE'/)
 702 FORMAT(T40,'FAULT NEAR BUS 1 ON ONE LINE'/)
 704 FORMAT(T50,'GRAPH NO.'//T50,I4,' KV SYSTEM')
 705 FORMAT(T40,'REF. VOLTS. IN P.U.',2X,F5.3,1X,'&',1X,F5.3/)
 902 FORMAT(30X,'THE VALUE',F5.3,'IS GREATER THAN MAX. LIMIT VALUE')
 903 FORMAT(30X,'THE VALUE',F5.3,'IS SMALLER THAN MIN. LIMIT VALUE')
 999 STOP
     END
```

10.3 APPENDIX - C

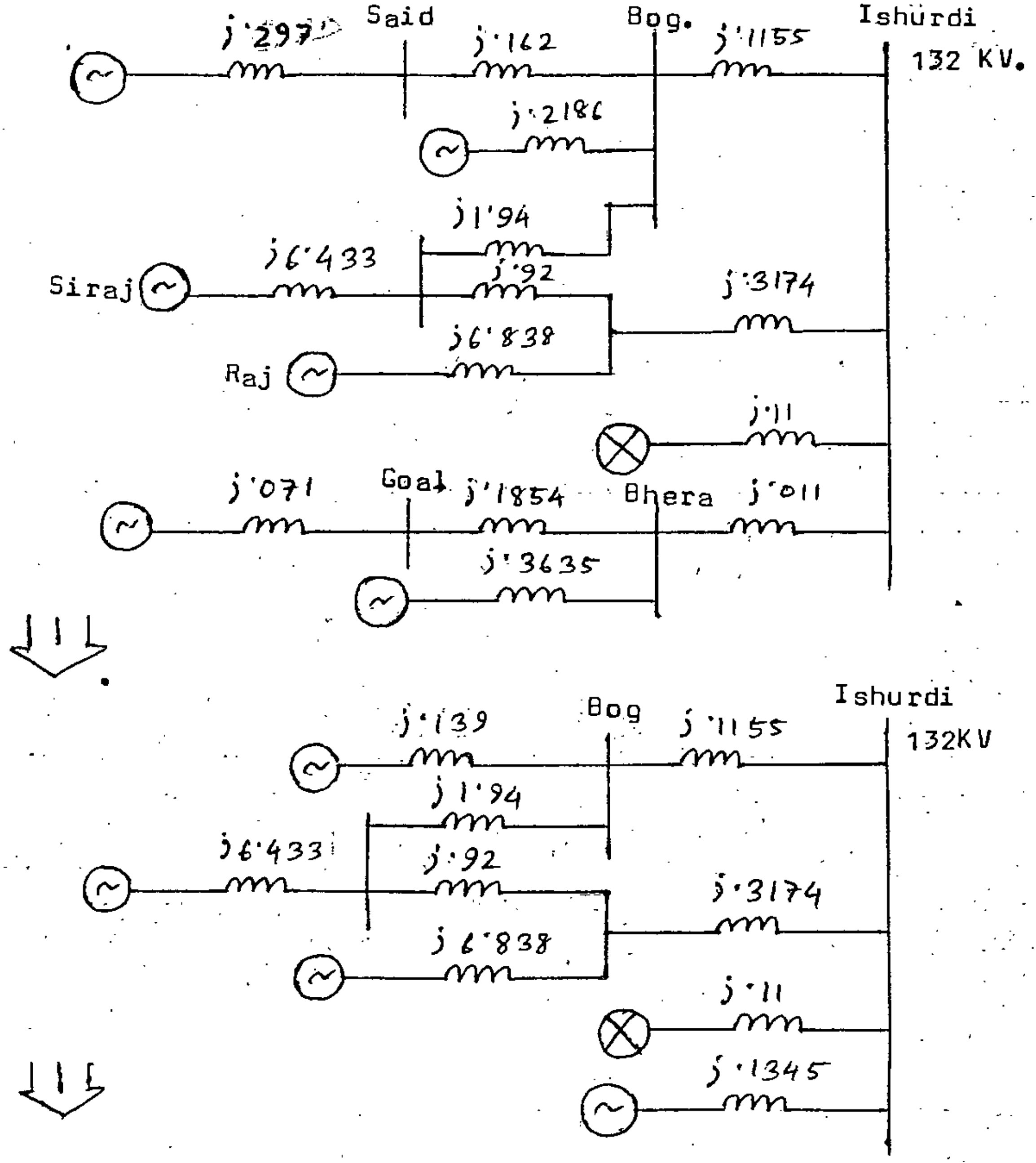
The network reduction of BPDB Power System for formation of equivalent generator is detailed hereunder.

WESTERN GRID

Interconnector energized with 230 KV.

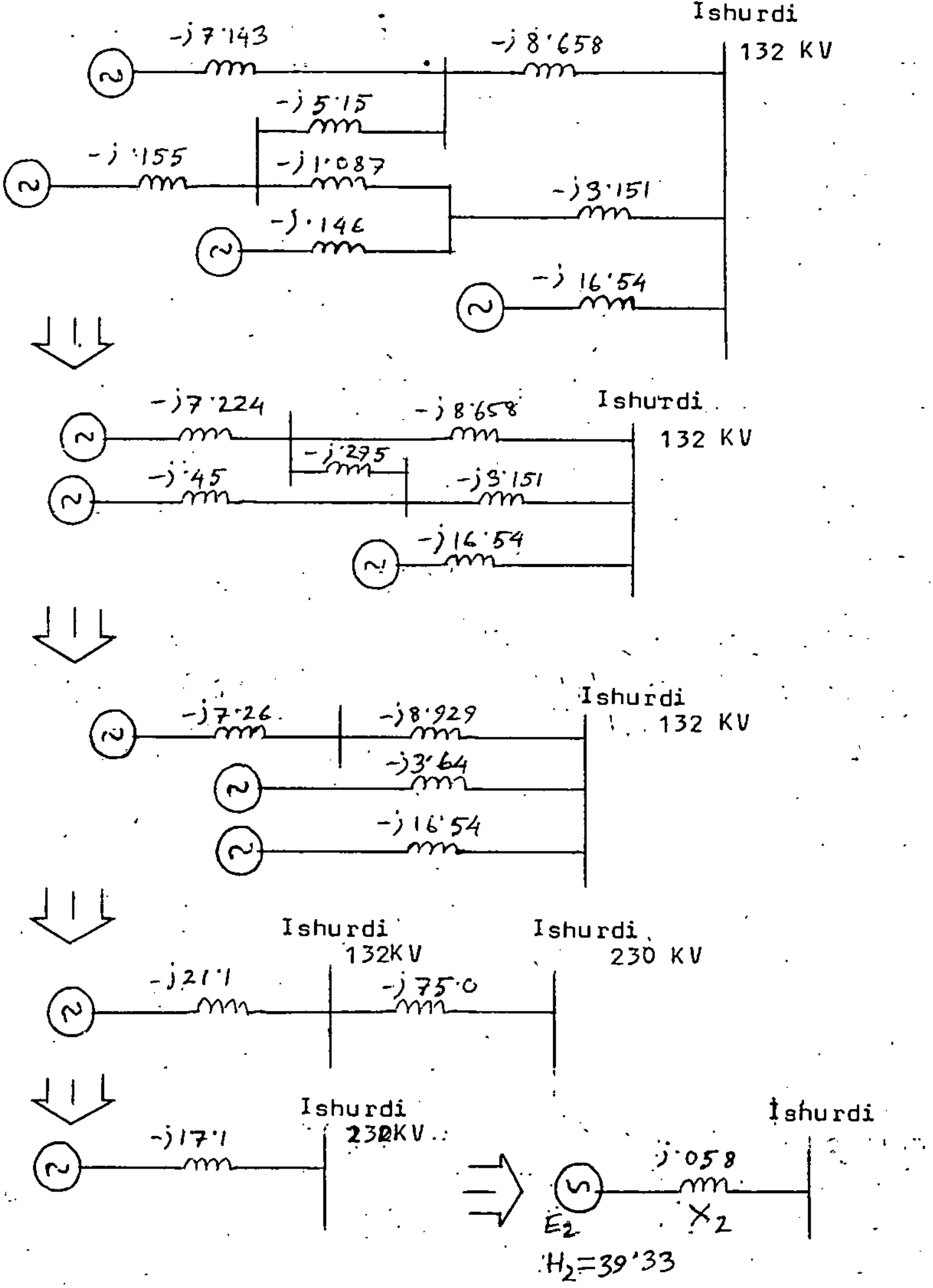


Western Grid (continued)

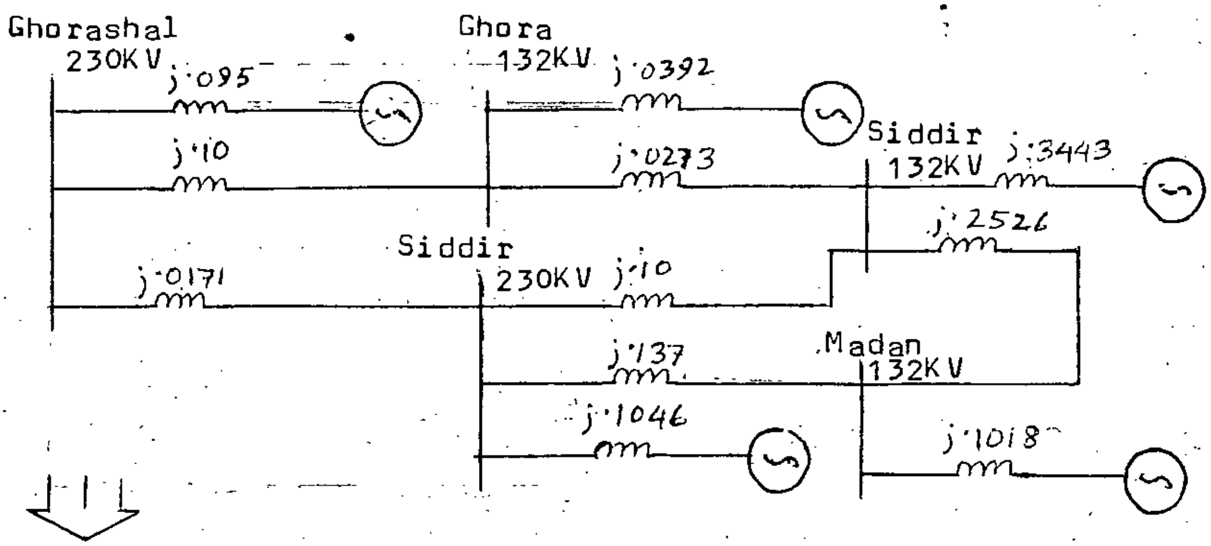


Western Grid (Continued)

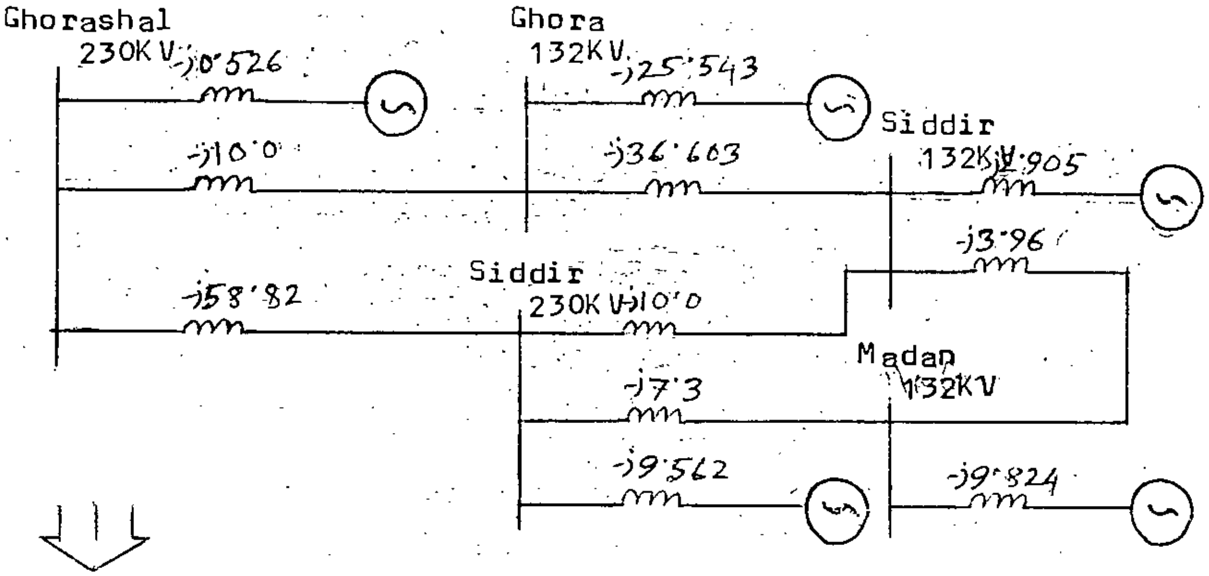
In admittance Form



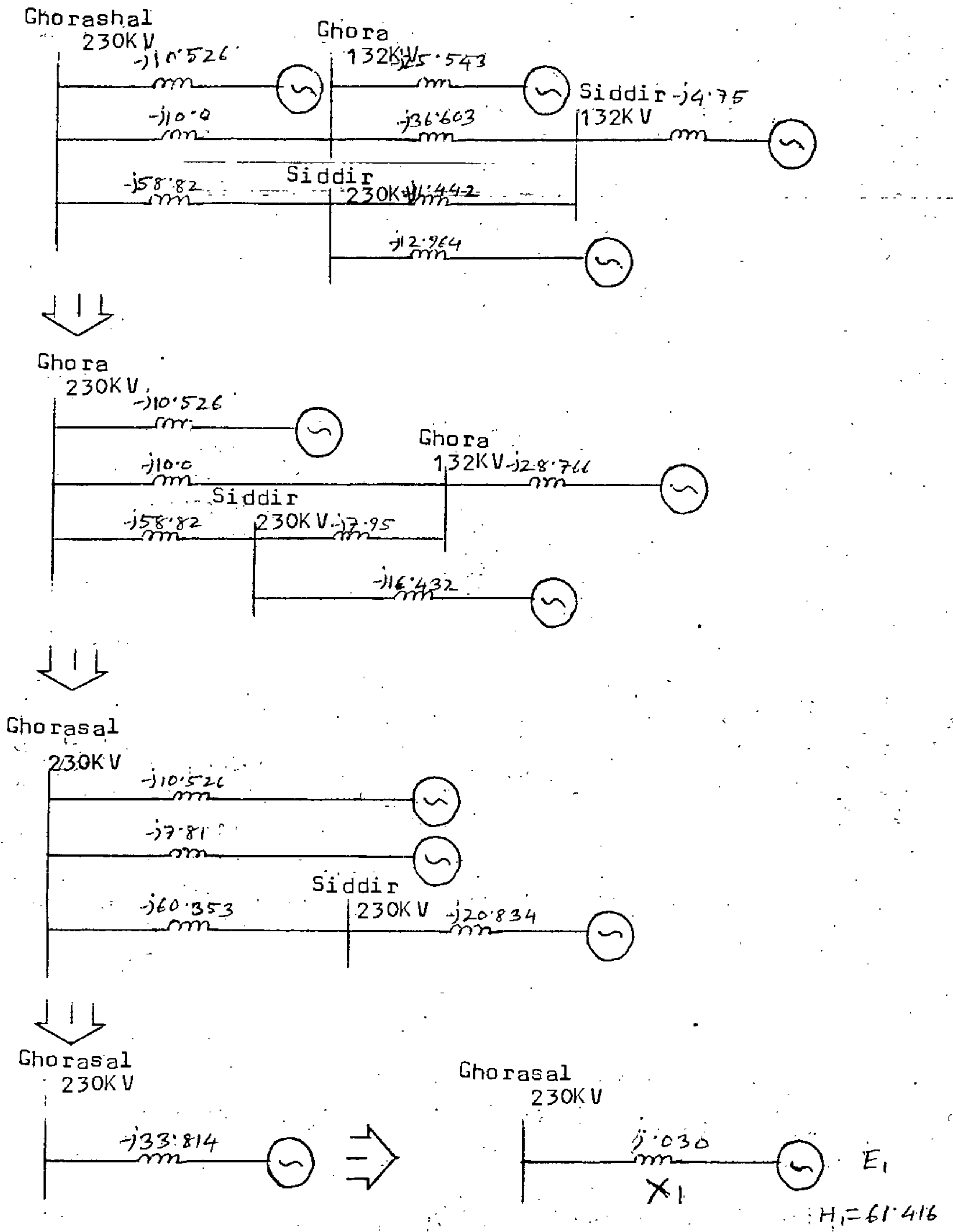
Eastern grid (contd)



In admittance form

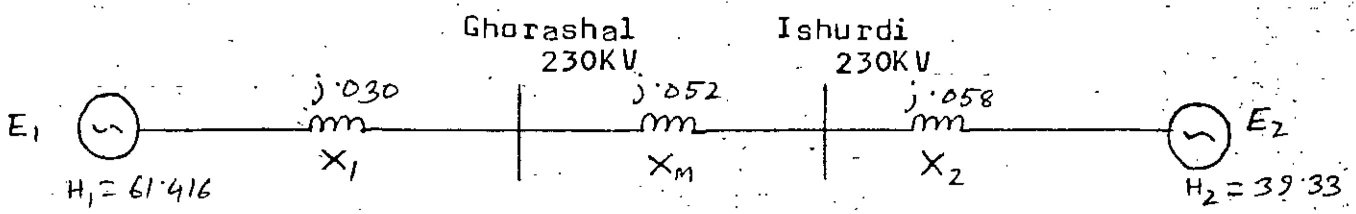


Eastern Grid (continued)



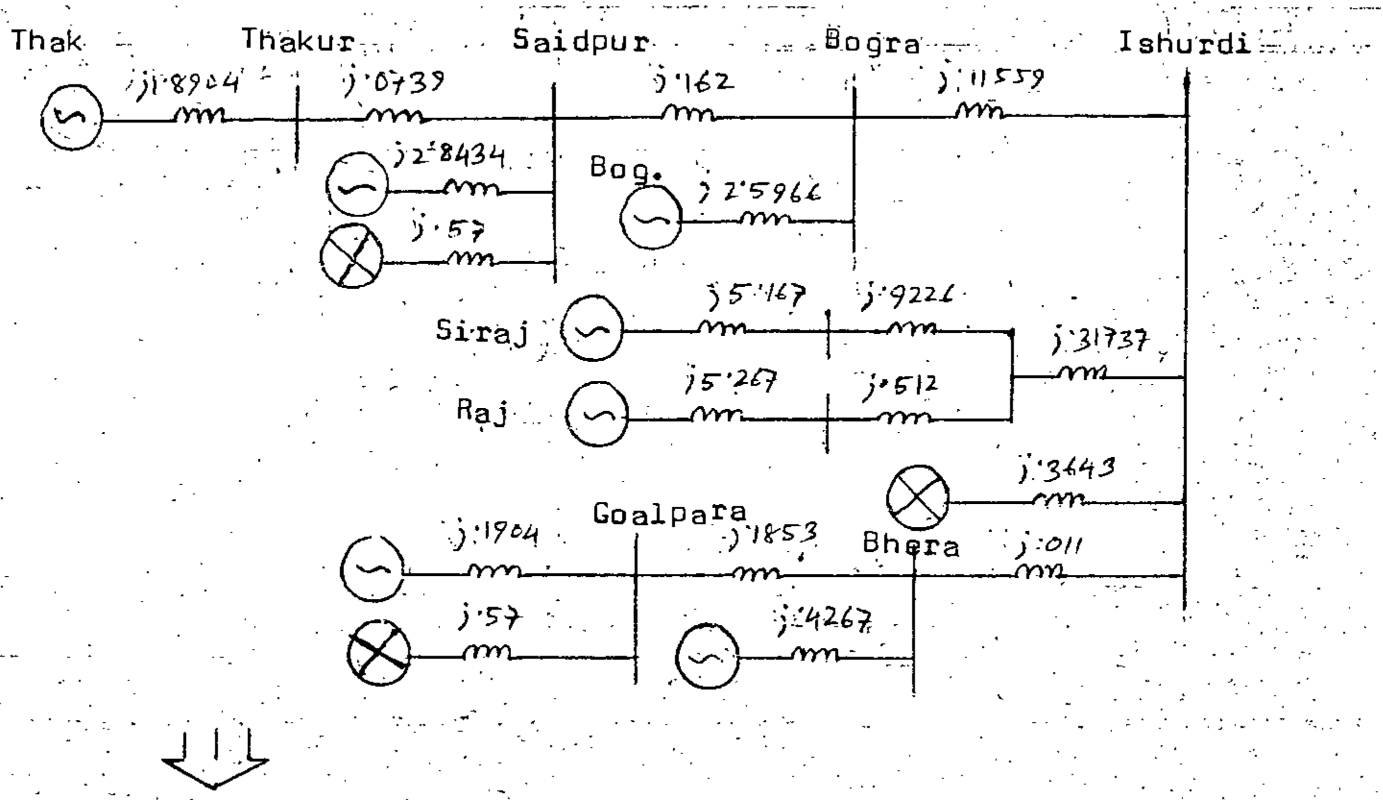
EQUIVALENT TWO MACHINE SYSTEM OF BPDB NETWORK

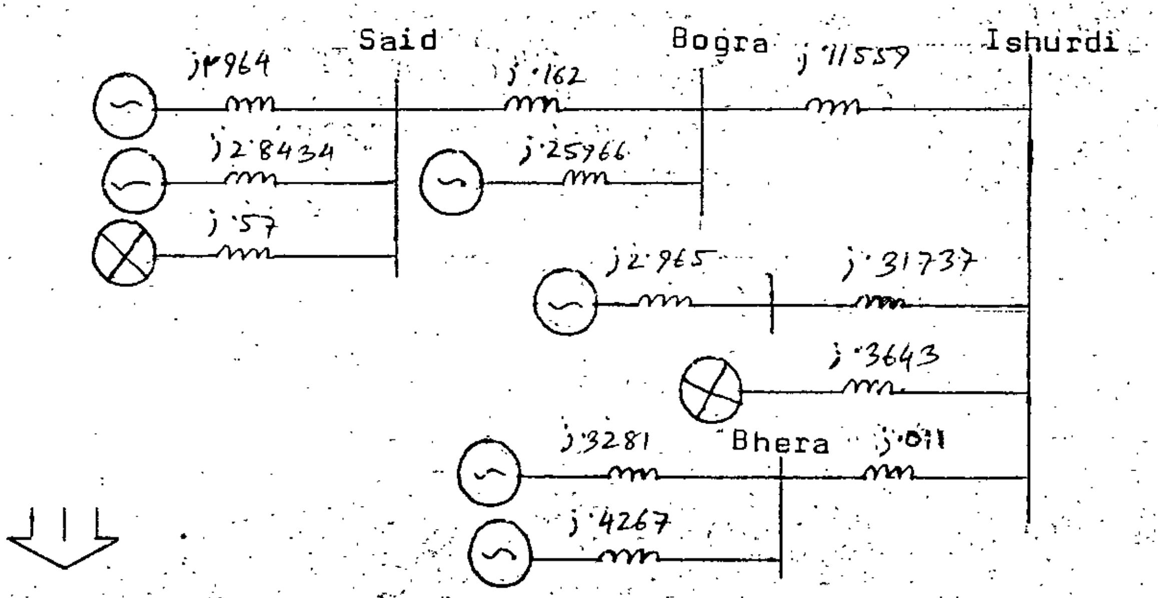
Interconnector energized with 230KV



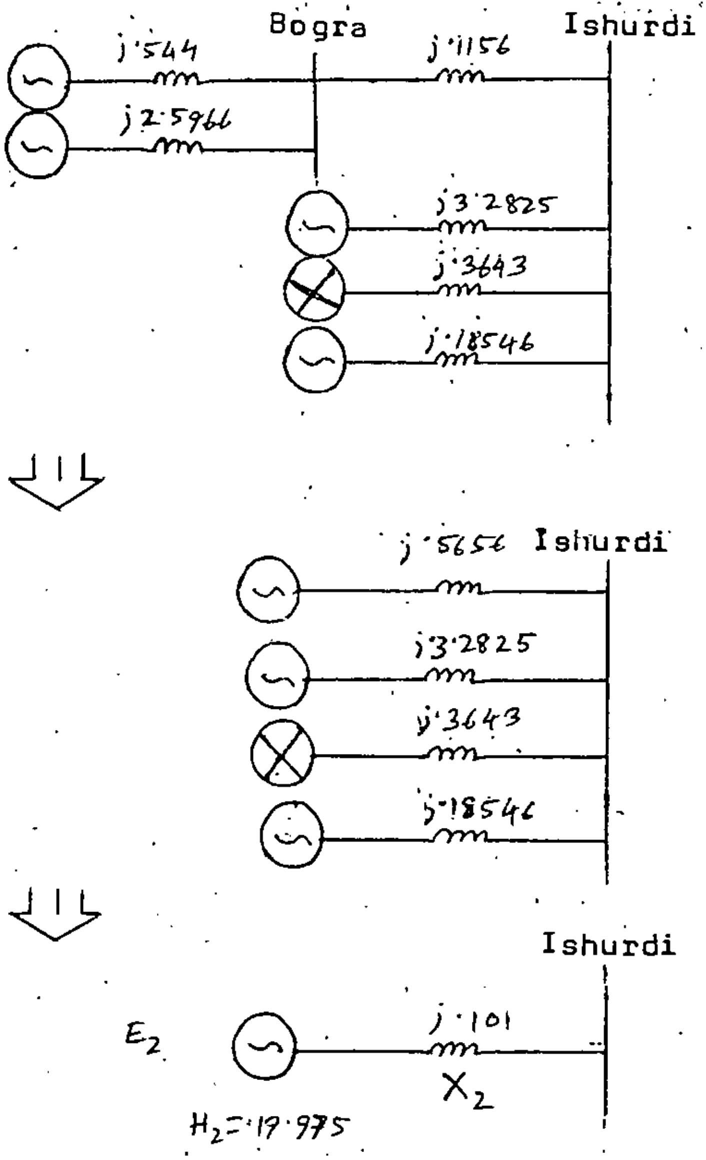
WESTERN GRID

Interconnector energized with 132 KV.



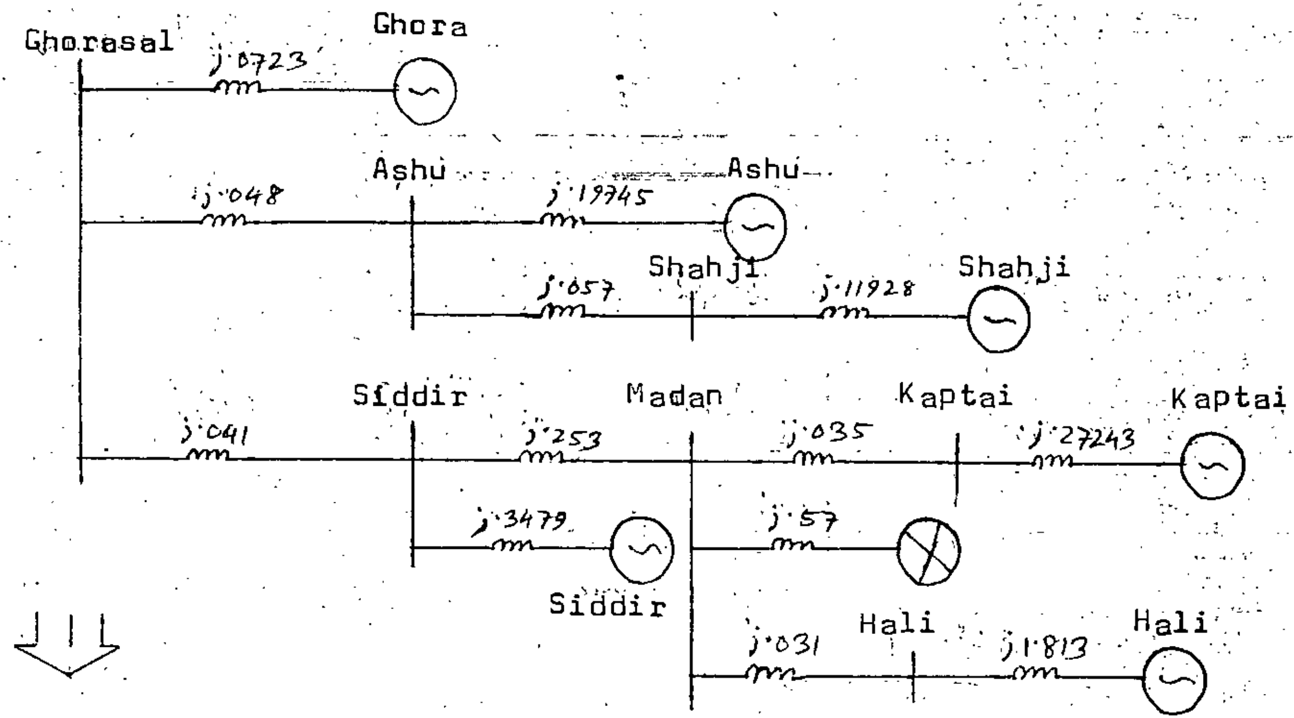


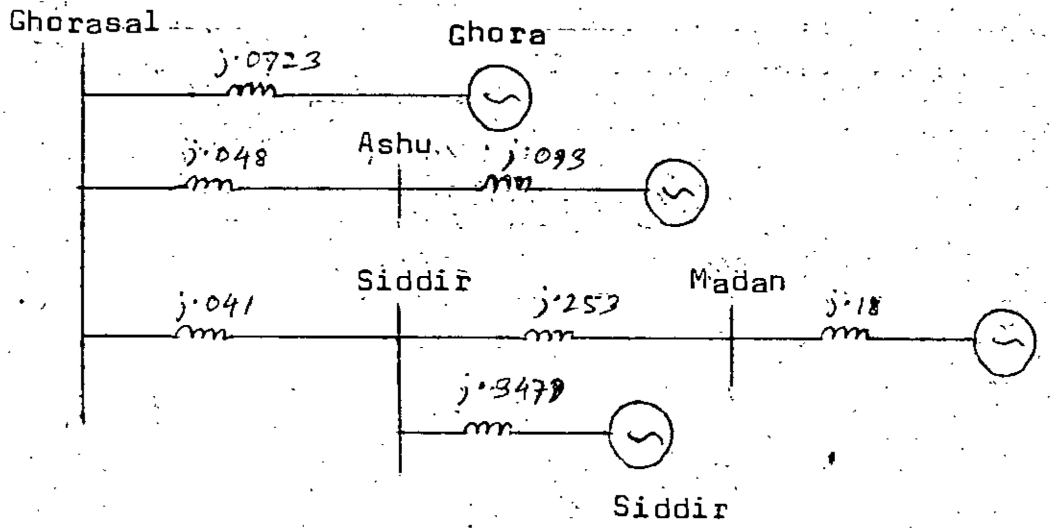
Western Grid (continued)



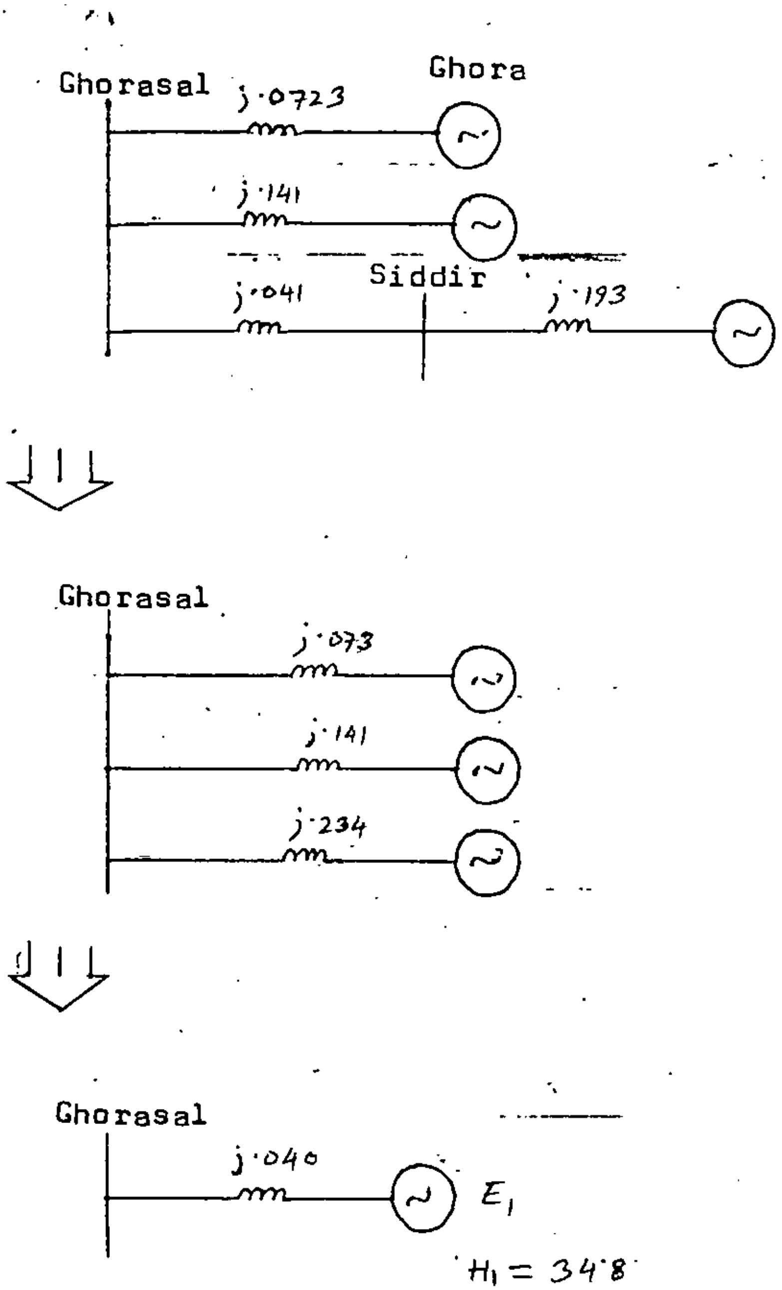
EASTERN GRID.

Interconnector-energized with 132 KV.





Eastern Grid (continued)



EQUIVALENT TWO-MACHINE SYSTEM OF BPDB NETWORK

Interconnector energized with 132KV.