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SENSITIVITY ANALYSIS OF THE MACHINE'S CONTROLLER AND
THE IMPACT OF MACHINE DATA ON OVER-ALL STABILITY STUDIES

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DEDICATION

This dissertation is dedicated to my wife, Laila Khalid Al-Mekanzi, for her patience and understanding during the initial stage of the preparation of this study and who became critically ill during this time as a result of the delivery of our first child. I also dedicate this dissertation to my son, Laith, who I have been away from since right after his birth, a year and 4 months ago.

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ABSTRACT

Presented in this work are some modifications of the synchronous machine by C. C. Young. The development of model III and ½ was suggested. A study of the sensitivity analysis of the machine's controller parameters and their impact on the machine's controller response was an object of this dissertation.

Also, the impact of the machine data variation on the overall system studies is the object of this dissertation. This study could lead to the characterization of those parameters which do not effect the machine's controller model and the machine's model for future studies.

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LIST OF SYMBOLS USED

Excitation System Symbols:

K_f Feedback gain of the exciter

K_A Regulator gain

K_E Exciter constant related to the self-exciter field

K_I Current circuit gain of the exciter type III system

K_P Potenetial circuit gain of the exciter type III system

K_F Fast raise/lower contact setting, exciter type IV

S_E Exciter saturation function

T_A Regulator amplifier time constant

T_E Exciter time constant

T_f Regulator stabilizing circuit time constant

T_{f1}, T_{f2} Regulator stabilizing circuit time constants (rotating rectifier system)

T_R Regulator input filter time constant

T_{RH} Rheostat time constant, exciter type IV system

V_R Regulator output voltage

V_{Rmax} Maximum value of V_R

V_{Rmin} Minimum value of V_R

R_{Ref} Regulator reference voltage setting

V_{RH} Field rheostat setting

V_t Generator terminal voltage

V_{Thev} Voltage obtained by vector sum of potential and current signals, exciter type III system

ΔV_t	Generator terminal voltage error
E_{fd}	Exciter output (applied to the generator field)
I_{fd}	Generator field current

Governor-Turbine System Symbols:

F_{VHP}	Very high pressure turbine power
F_{HP}	High pressure turbine power fraction
F_{IP}	Intermediate pressure turbine power fraction
F_{LP}	Low pressure turbine power fraction
P_M	Mechanical power
P_0	Initial mechanical power
T_{SR}	Speed relay time constant
T_{CH}	Steam chest time constant (control valves to HP (VHP) exhaust)
T_{RH1}	Reheat time constant (HP VHP exhaust to IP HP) exhaust
T_{RH2}	Second reheat time constant (HP exhaust to IP exhaust)
T_{CO}	Crossover time constant (IP exhaust to LP exhaust)
$K_1 - K_7$	General model parameters
W	Speed
ΔW	Speed deviation
S	Differential operator

Synchronous Machine Symbols:

δ	Angle between the q-axis and the synchronous reference (degree)
t	Time (sec)
f	Frequency (hertz)
H	Inertia constant (MW - Seconds/MVA)
K	Damping coefficient

T_m	Mechanical torque (per-unit)
T_e	Electrical torque (per-unit)
X_ℓ	Stator leakage reactance (per-unit)
X''_d	Direct-axis subtransient reaotance
X'_d	Direct-axis transient reactance (per-unit)
X_d	Direct-axis synchronous reactance (per-unit)
X_q	Quadrature-axis synchronous reactance (per-unit)
X'_q	Quadrature-axis transient reactance (per-unit)
X''_q	Quadrature-axis subtransient reactance (per-unit)
X_p	Potier reactance (per-unit)
T''_{do}	Direct-axis subtransient open-circuit time-constant (seconds)
T''_{qo}	Quadratuer-axis subtransient open-circuit time-constant (seconds)
T'_{do}	Direct-axis transient open-circuit time-constant (seconds)
T'_{qo}	Quadrature-axis transient open-circuit time-constant (seconds)
i_q	Quadrature-axis component of stator current (per-unit)
i_d	Direct-axis component of stator current (per-unit)
i_{Kd}	Direct-axis amortisseur current (per-unit)
E_I	Field current (per-unit)
ΔE_I	Correct to field current for saturation (per-unit)
$\check{e}'$	Phasor voltage behind transient (per-unit)
$\check{e}''$	Phasor voltage behind subtransient (per-unit)
e'_q	Field flux-linkages (per-unit)
e'_d	Quadrature-axis iron-circuit flux-linkages (per-unit)
E_{fd}	Field voltage (per-unit)
E_p	Potier voltage (per-unit)
λ_{Kd}	Direct-axis amortisseur flux-linkage (per-unit)

λ_{Kq}	Quadrature-axis amortisseur flux-linkages (per-unit)
λ''_d	Direct-axis component of rotor subtransient flux-linkage (per-unit)
λ''_q	Quadrature-axis component of rotor subtransient flux-linkage (per-unit)
I_t	Machine terminal current (per-unit)
V_t	Machine terminal voltage (per-unit)
λ_j	Flux-linkage of circuit j (per-unit)
L_{ij}	Inductance between rotor circuits i and j (per-unit)
L_{ajm}	Inductance between stator circuit a and rotor circuit j maximum value (per-unit)
ω_o	Base angular velocity
ω_r	Angular velocity of rotor

CHAPTER I

INTRODUCTION AND REMARKS

Present day power systems are large and very complicated. With the current rise in the demand of electrical energy, power systems will continue to grow both in size and complexity. Our dependence on electricity is so great it is essential to have an uninterrupted supply of electrical power within set limits of frequency and voltage levels. This can be achieved by a well-coordinated operation and planned system.

Therefore, one of the most important steps in power system planning is studying the transient and dynamic stability characteristic of the systems. Stability studies involve the simulation of the behavior of generators and their control using a digital computer model program. The computation cost of this process is a function of the complexity of the model being used. The value of bus voltages to be maintained or compensated for load and circuit changes may be of great importance. Also, generator model complexity effects the accuracy of the stability study results which varies with many factors. The dynamic behavior of the real generators varies in a non-linear way with the electrical load on the generator.

The parameters of synchronous machine control equipment in a generation station have a considerable influence on the overall system performance. The parameters of exciter and governor need to be adjusted to satisfy the system from an overall performance standpoint.[50] Therefore a carefully chosen model to represent the generator must be accurate over a range of operating conditions.[49] The loads are assumed to be linear in such stability simulation in order to simplify the solution. It is well known that the method of supply excitation to systems has an adverse effect on stability.[33]

Recently, exciter parameters, such as exciter time constant, T_E, and exciter gain, K_E, were subject to discussion by Francisco P. Demello and C. Concordia. They noted that the parameters were important as well as what was the boundary of their values for the exciter determined by the exciter system stability, hence, machine stability studies.[24]

M. K. El-Sherbing shows in his work that the stability of the system is affected by the excitation system and governor system. Both are found to have adverse effects on the damping of the system. Of the two, the voltage regulator has the more detrimental effect; moreover, the system stability is sensitive to gain regulator.[32] There has been a lot of work done in the stability area, but there has been a need for more studies in the literature on the excitation, governor-turbine, and machine data for purposes of modeling system stability studies. Therefore, it is important to draw conclusions on the behavior of the machine's controller as well as the machine upon variation of their data. The end-result is to study the sensitivity analysis of the machine's controller parameters and to see their impact on the machine's controller response. This could help to characterize those parameters which do not contribute a major change on the exciter and governor-turbine response for future work. The impact of machine data on the research work that was done in connection with this dissertation tests the machine's parameters in the sense that it checks which of these parameters influences the machine's performance. Hence, this could lead to characterize these parameters which do not effect the machine model's representation, in their absence.

Chapter II, which is a review, presents some modifications of synchronous machine modeling by C. C. Young,[2,44] defining new terms of the machine, stating their physical representation and developing new model III and ½. The synchronous machine model has been classified based on the assumption used for each model. For instance, the number of rotor windings being used in machine model II is one, while the number of rotor windings in machine model IV is four. Therefore, machine model I represents the classical machine representation. In a sense the assumption has been adopted in Chapter II. Machine model II is characterized by transient voltage behind the direct axis transient reactance. Machine model III is suitable for a round rotor machine. It's characterized by two rotor windings and transient voltage behind the direct axis transient reactance. It was stated by H. E. Lokay and R. L. Bogler[52] that the priority of machine elements can be classified in the following order: 1) damping of machine, 2) excitation, 3) saturation, 4) system damping and 5) speed governor action. The machine damping is the next most important factor in the stability study over the saturation factor, therefore, the idea to develop the machine model III and ½ is highly recommendable for digital representation to the stability studies. This model will be in between machine model II and machine model IV. The model is characterized by three coils in the rotor winding, voltage behind the direct axis subtransient reactance and no saturation factor being represented. Machine model IV is a more complicated model. It's characterized by four rotor windings, voltage behind the direct axis subtransient reactance and the saturation factor is included.

Chapter III presents a study of data sensitivity analysis on the machine controller system using C.S.M.P. computer package for four types of excitation system (see appendix B) and two models of governor-turbine (see appendix E). Root locus technique and frequency response technique are used to study some coupling points of the excitation system data for the first two types.

Chapter IV presents the impact of the machine's data variation on the overall system studies. Performance of the four machine model's simulation (machine model two, machine model three, machine model four, and machine model five) upon variation of machine five data (figure 4-1) is the goal of this chapter. The system study is a model of a 345 KV transmission system typical of Northeast utilities in figure 4-1.(58) This consists of 10 machines being equipped with an IEEE type I excitation system(8) and a Philadelphia Electric Company (PECO) generalized steam and hydro model.(61) It is the EPRI 39 bus, 46 line, 10 generators.(62)

Chapter V presents a summary and the conclusion of this work and an indication of those problems which remain subject to further research.

CHAPTER II

THEORETICAL ASPECTS OF SYNCHRONOUS MACHINE MODELING

The synchronous machines, both generators and motors, have several ways to describe their physical characteristics. A complete description of the dynamic behavior of the synchronous machine requires consideration of its electrical and mechanical characteristics as well as those of associated control systems. The necessary mathematical statements as well as a vector diagram will describe the machine's model in relation to the stability analysis of a power system.

The synchronous machine to be analyized is assumed to be an ideal machine proposed by Park.[1, 5, 6] The assumptions are:

1) The stator winding is sinusoidally distributed around the air gap as far as the mutual effects between them and the rotor are concerned.

2) Nonlinearities such as the hysteresis and saturation effect of the flux interlinkage are neglected.

3) The stator-winding self and mutual inductances vary sinusoidally as the rotor moves and are of the form phase A.

$L_{aa} = L_{aao} + L_{aa2} \cos 2\theta$ and $L_{ab} = -\left[L_{abo} + L_{aa2} \cos 2\theta\right]$.

The sinusoidal voltage output of the machines demonstrate the validity of assumption 1.

Basically machines have saturation effects and we will illustrate how these effects might be included by changing the representation of the ideal machine.

Recently there has been expressed some doubt on the validity of assumption 3 in the case of salient pole machines but there is no evidence to suggest that it is unsatisfactory for round rotor machines.[27] These self and mutual inductances include fundamental and second harmonic frequency terms which make the solution really hard but which may be removed from the equations by using an axis transformation from R. H. Park.[6,48]

At this time there is a need to define certain quantities of the synchronous machine. Basically synchronous machines are classified into two principle types, round-rotor machines and salient-pole machines. If the air gap is uniform the machine is called a round-rotor machine. For example, the steam-turbine generator is a round-rotor type. Salient pole machines have laminated rotors, to minimize eddy currents, and round-rotor machines have solid steel rotors, in which eddy currents can flow. The eddy current flowing in the solid steel rotor of a round-rotor machine performs the same damping function as the amortisseur currents except that they cannot be used for starting or for any condition where dangerous heating might occur. The basic difference in their representation is that there are now an infinite number of short circuited windings and the paths that the current take are a complex function of the frequency of the currents and saturation effects. The current paths in a round-rotor machine are usually referred to as "iron circuits" and the current is referred to as "iron current". It is assumed that the salient pole machine has the winding structure given in figure 2-1.

The stator has the three phase windings each located 120° apart electrically. The rotor has one field winding and the damper

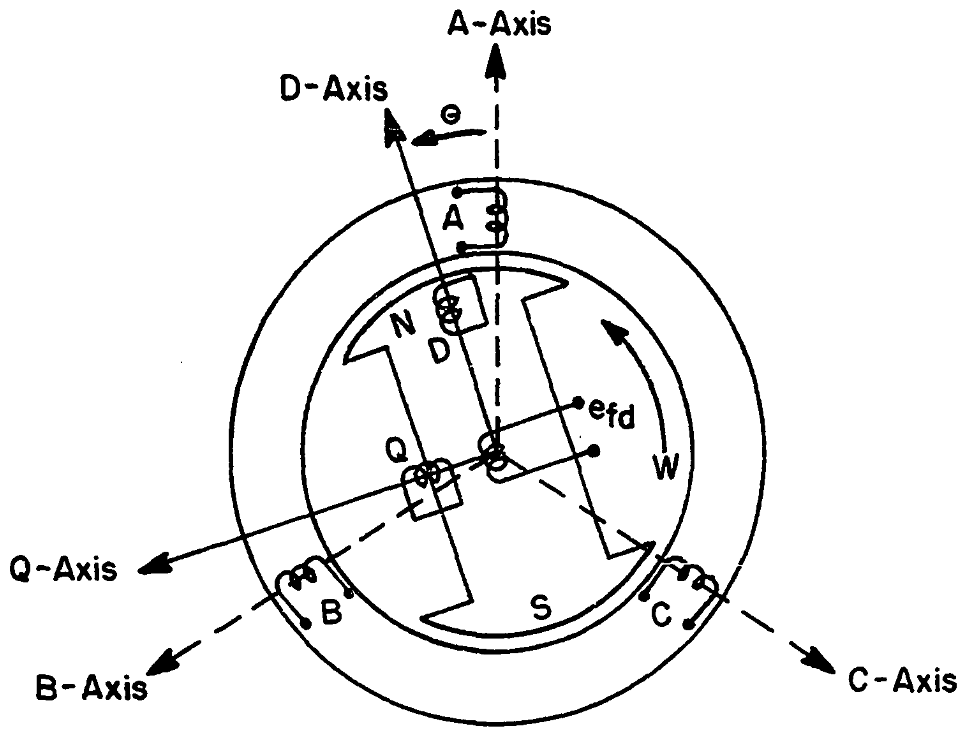


FIGURE 2-1
RELATION OF SYNCHRONOUS MACHINE WINDINGS

windings are represented by two orthorgonally closed circuits. The rotor has two axes that are symmetrical; one axis passes through the center line of the north pole and is defined as the direct axis; the other axis is located 90° from the direct axis and is called the quadrature axis. The angle θ is the angle between the center line of the "a" phase and the direct axis.

The installation of damper windings may take many different physical forms. The generators for one installation were supplied with a new type of damper winding which consists of a double cage arrangement in which the outer row of bars is made of high-resistance material and the inner row of bars is made of a low-resistance material imbedded in the iron.[2] For double frequency associated with the negative sequence the copper bars possess a high reactance and, therefore, force most of the current through the high-resistance bars, but for the low frequency associated with the system oscillations, the current varies inversely with the resistance of the damper bars in which case most of the current flows through the copper winding.

The benefits from high-resistance damper windings will be decreased as the fault duration is decreased by the use of faster breakers and relays. Damper windings also have characteristics which tend to suppress spontaneous hunting and to reduce system voltages and recovery rates arising from short circuit. So in these respects low-resistance copper dampers are somewhat more effective than high-resistance dampers.[43]

Damping windings have been installed in the salient pole machine because of the need requirement to increase starting torque for the automatic operation in the case of the motor. It has been found that the effect of the damper windings on the machine's behavior can usually be represented by two equivalent short circuit windings. These windings will carry current when the machine is subjected to a disturbance which causes the rotor to temporarily depart from synchronous speed.[3]

Electrical torques will be introduced in the case of disturbances which will help the machine to maintain the stability and to damp out any oscillations. If a machine loses synchronism and operates continuously out of step, then these windings will continuously carry slip frequency currents. If the machine is operated under steady state conditions, there is no current flowing in the damper windings.

2-1 Steady State Operation

When an ideal synchronous machine is operating at synchronous speed, under balance conditions and in a steady state condition, the machine's performance can be described by a vector diagram. One form of a vector diagram is shown in figure (2-2).[28,29,30]

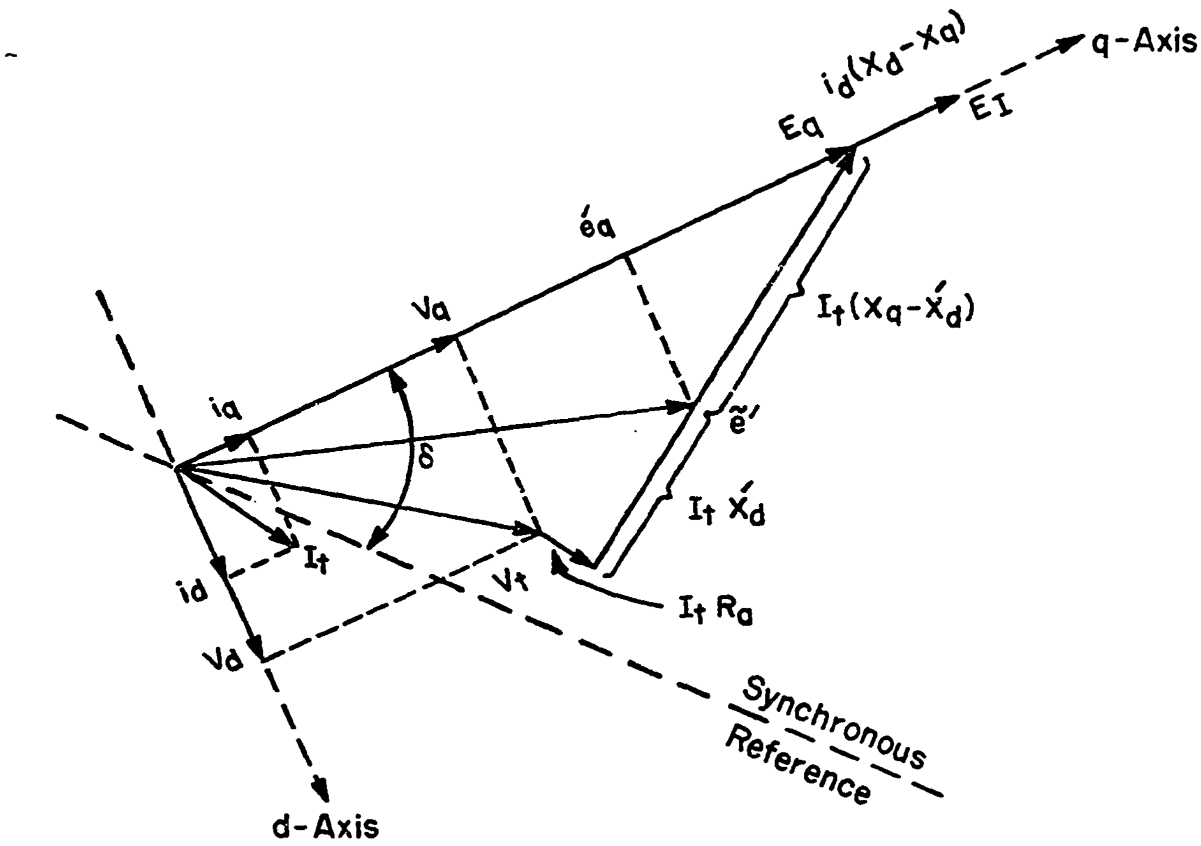


FIGURE 2-2
VECTOR DIAGRAM OF AN IDEAL SYNCHRONOUS MACHINE

The construction of this vector diagram is from the knowledge of terminal conditions V_t, I_t, and from machine reactances. From it one can find out some important quantities such as E_I, the voltage corresponding to the field excitation, the voltage back of the transient reactance, $\tilde{e}'$, and the angle between the rotor quadrature axis and a synchronously rotating axis δ. The reference axis is arbitrarily chosen when solving the system's steady state equation. All of the individual machine's axis and system phasors are measured in reference to reference axis δ. Under steady state conditions all amortisseur current and brake torques are equal to zemo. The vector diagram, figure 2-2 could be adapted for either a salient pole machine or a round rotor machine. The only difference which affects the vector diagram is that the quadrature axis synchronous reactance x_q and direct axis synchronous reactance x_d are almost equal numerically for an ideal round rotor machine. Otherwise, the diagram is the same as that of the salient pole machine.

The effect of saturation has been shown to be important in an analysis of the steady state performance of synchronous machines. It is necessary during a transient oscillation to include the effects of generator saturation. Most transient stability analyses are made on the basis of constant field flux linkages during the first swing of the machine. The effect of saturation is very important when representing the excitation system because it directly influences the initial operating conditions of the excitation system.[1] Saturation effects are very complex. There are several methods to represent the saturation effect in the calculation of other values.

Most methods used for the analysis of a machine'e performance use a single index of saturation together with an open-circuit saturation curve of the machine so as to estimate the saturation effect on the field current. One index usually adapted is the Potier voltage which will represent the voltage back of a reactance called the Potier reactance X_p.[2] The Potier voltage E_p is shown on figure 2-3.

The magnitude of this voltage is used to estimate the difference between the actual field current and the field current predicted when saturation is neglected. This difference, e_s, is, therefore, added to the field current determined by neglecting saturation. So as to predict the actual field current figure 2-3 has been illustrated.

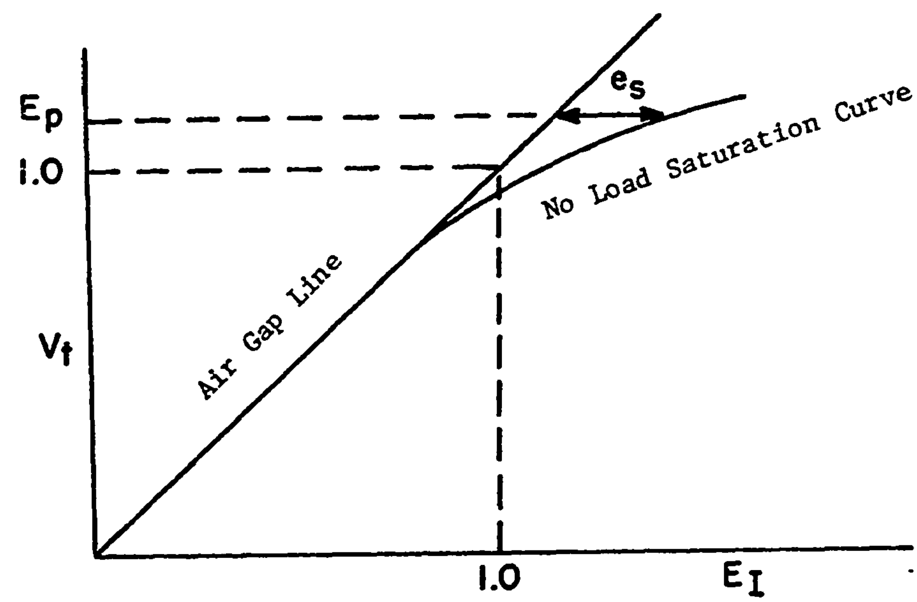


FIGURE 2-3
OPEN CIRCUIT SATURATION CURVE*

*e_s equals per unit saturation mmf corresponding to the voltage back of Potier reactance X_p.

Figure 2-4 illustrates the machine vector diagram showing e_s voltage. So far almost all of the methods in common have been using predicted field currents which are very close to measured values. This implies that no unique method has been adapted to represent the main field saturation for the purpose of stability analysis.

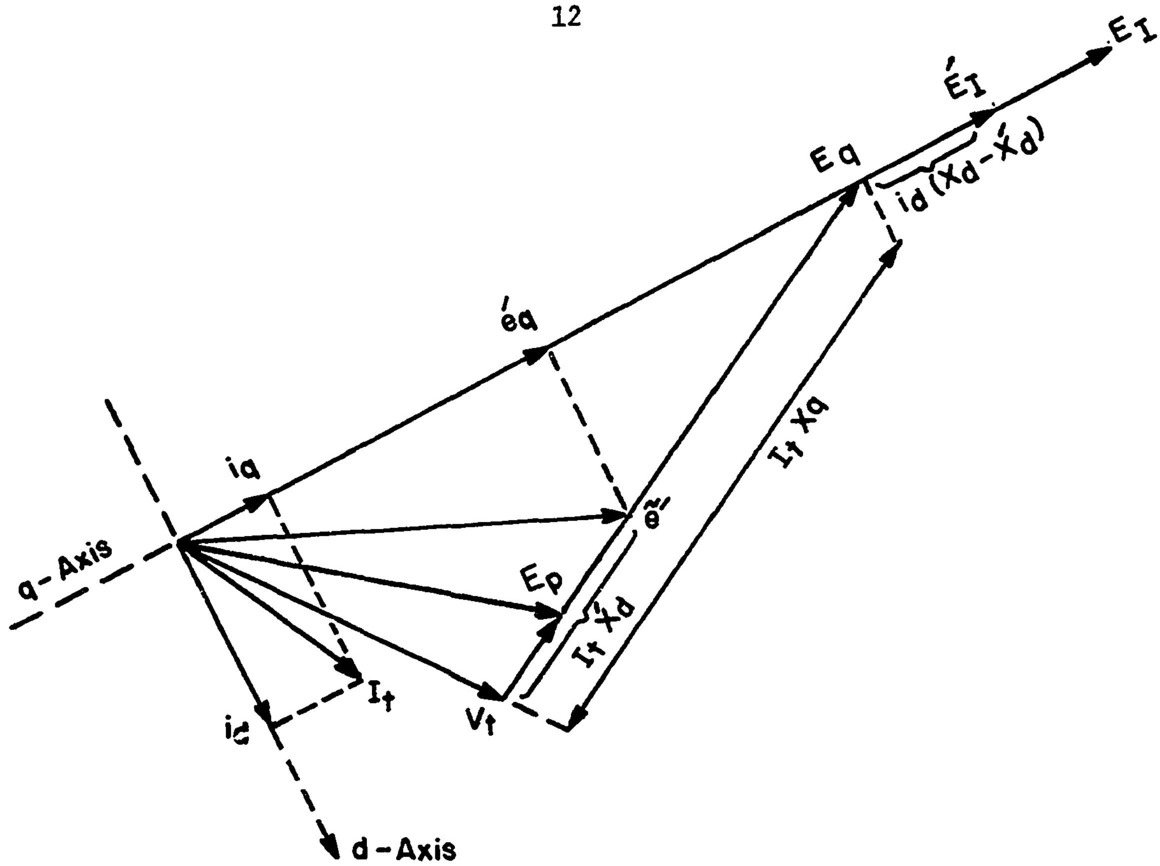


FIGURE 2-4
SALIENT POLE VECTOR DIAGRAM
INCLUDING EFFECT OF SATURATION

2-2 MACHINE REPRESENTATION FOR STABILITY ANALYSIS[2]

A synchronous machine characteristic in relation to the stability study has a practical assumption regarding machine model interface with the exciter and the network. In describing the machine's model, with taking care of the saturation effect, it will be required to also represent the transmission line and transformer in detail. On the other hand, implying that it increases the complexity of the computation to the point that only a relatively simple system could be represented on even a large scale digital computer, it leads to higher computing costs without gaining many benefits. The simplification of the particular type of study being made needs to be recognized and as many appropriate simplifying assumptions as possible need to be made. Therefore, the assumptions that are made for a stability analysis may not be used as well in the other kinds of studies, hence, one has to be careful in using a stability program for other branches of study.

There are some assumptions that can be made that are acceptable for power system stability analysis regardless of the detail of representation of the control systems, the load or the machines.[3] These are:

1. Only fundamental frequency current and voltage, in this case d.c. and second harmonic components of the phase current and phase voltage, are represented in the stator and the connected system. Therefore, the d.c. offset current and the rest of harmonic currents and voltages are neglected.[1]
2. The effect of machine speed variations is neglected.
3. Symmetrical components will be used in the representation of an unbalanced condition.

The first assumption assumes that all of the machine and system voltages and currents can be represented by a vector diagram. Generally, this first assumption gives substantially correct results for stability analysis with one important exception. This is that during a fault which occurs near the machine terminals, a significant amount of d.c. offset current may be produced in the machine stator and, therefore, a significant electrical torque may be produced by this current.[3] This "d.c. offset torque" decays rapidly. Its magnitude is large and will have an important effect upon the actual machine angle and eventually the velocity will change during the fault. The generator when its torque is neglected gives conservative results (a system more likely unstable than it may actually be), system designers often feel a desire to have some representation of the effect of the d.c. offset torque during a fault. This can be accomplished by making a separate and special calculation of this torque, in other words, we could correct the electrical torque during the fault period.

The third assumption represents the system by a symmetrical component model. This assumption reduces the calculation time of the model substantially.

These machine equations are relatively complex and taking in a large system these equations need further simplifying assumptions. The studies indicate[2] for specific situations, other simplifying assumptions might be necessary with little effect on the result. Obviously, if the situation changes, the assumptions might have to change too.

To have an idea of what some of these assumptions might be and their effect upon the representation, five classes of models have been chosen. Four of the five models presented include most of the models currently being used for stability analysis.

2-3 Model I

In addition to the previous assumptions we could have the following assumptions:

1. The voltage behind the direct axis transient reactance is constant in magnitude but, of course, not in phase.
2. All generators in the same power plant have to be represented as one machine.
3. The amortissuer winding effects are neglected.

4. Stability is determined by the first swing of the machine including those with the longer period.

5. Damping torques are neglected.

6. Armature resistance is neglected.

The resulting model is the so-called classical machine representation for transient stability analysis. The vector diagram in figure 2-5 and the equations (2-1) and (2-2) will represent the "classical model".

$$\frac{d\delta}{dt} = \omega \tag{2-1}$$

$$\frac{d\omega}{dt} = \frac{180f}{H} (T_m - T_e + K\omega) \tag{2-2}$$

where T_m is the mechanical torque (per unit); T_e is the electrical torque (per unit); δ is the angle between the q axis and the synchronous reference (degree); and H is the inertia constant (MW - seconds/MVA). K is the damping factor.

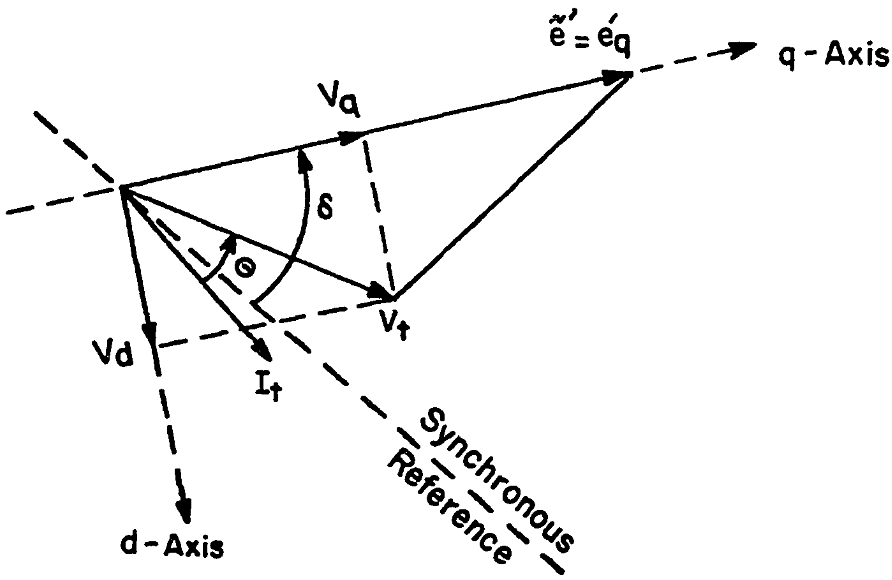


FIGURE 2-5
VECTOR DIAGRAM OF MODEL I

Assumption one represents a great simplification of the synchronous generator in which transient saliency and saturation are neglected. Therefore, the rational of this assumption depends largely upon a good regulator and exciter that can maintain constant voltage behind a transient reactance and secondly, the assumption depends on the severity as well as the duration of the fault.. For severe, long duration faults (greater than 6 cycles), a constant voltage behind transient reactance is often optimistic and the classical model may not give a proper indication of stability.[2] Therefore, this representation is not good for dynamic stability studies where the damping is an important consideration. The amortissure currents contribute positive damping effect and thus, the damper winding effects the interaction of the field and stator. Also, the assumption of constant field flux linkages would not be added to the value of the representative model for it to represent the damper winding effect. Therefore, the amortissure effects need to be represented as well as the fixed field transient by an equivalent damping coefficient in the torque equation which is represented by $K\omega$ in order to give reasonable results. Saliency can be shown to have little effect on the power limit.[54,55]

Saturation in the synchronous machine has only a minor effect on transient stability because the currents induced in the rotor circuits by changes in the stator currents tend to maintain constant flux linkages in the rotor circuits.[55]

The period of swing of the machine is short and the motion of the machine was calculated only to the crest of the first swing (one second or less). In so short a time, the effect of speed governors is negligible.

With the assumption of the machine's combination, it is quite true that if two or more similar machines are connected to the same node, they may be represented by an equivalent machine whose resistance and reactance parameters are obtained by treating them as if the corresponding resistances or reactances of the individual machines were connected in parallel. The equivalent inertia constant is the sum of the inertia constants of individual machines.[4]

The conclusion is the classical model is suitable for some transient studies. However, it may be necessary to use a more complicated model which would result in more reliable stability studies.

The advantages of model I are:

1) There is a simple approach toward transient stability.

2) It requires less computer time.

3) Data requirements are minimum (see table 2-1).

4) This model is adequate for studying first swing transient stability.

The disadvantages of model I are:

1) The voltage behind the transient reactance is constant implying that there is abundant exciter action, therefore, we may lose the affect of exciter on the machine and that may cause questionable results.

2. It is very difficult to judge whether the results obtained are conservative or not.

2-4 Model II

In addition to the previous assumptions we could make some additional assumptions.

1) All generators in the same power plant are represented as one machine.

2) The amortissure effects are neglected.

3) Damping torques are neglected.

4) Armature resistance is neglected.

The vector diagram for this model is shown in figure 2-6 and the dynamic equations are shown in equations (2-3), (2-4) and (2-5).

$$\frac{de'_q}{dt} = \frac{1}{T'_{do}} (E_{fd} - E_I) \tag{2-3}$$

E_{fd} is the exciter output.

$$\frac{d\delta}{dt} = \omega \tag{2-4}$$

$$\frac{d\omega}{dt} = \frac{180f}{H} (T_m - T_e + K\omega) \tag{2-5}$$

In the vector diagram the correction for field saturation e_s is a function of the saturation index, where the saturation index is Potier voltage which has been exposed. The function used might be the open-circuit saturation curve, which was described earlier under the steady state vector diagram. The method used for representing saturation during stability analysis must be consistant with the steady state model.

At any instant of time the angel δ, rotor angle, and the magnitude of the field flux linkages e'_q are known from the solution of the dynamic equation (2-3). Therefore, it is necessary to find a value of E_q which will simultaneously satisfy the known conditions for every machine and the system conditions. Once E_q is known the field current can be found from the vector diagram relations. The field voltage and field current, calculated from the excitation system equation (2-3), can be used to predict the change in e'_q.

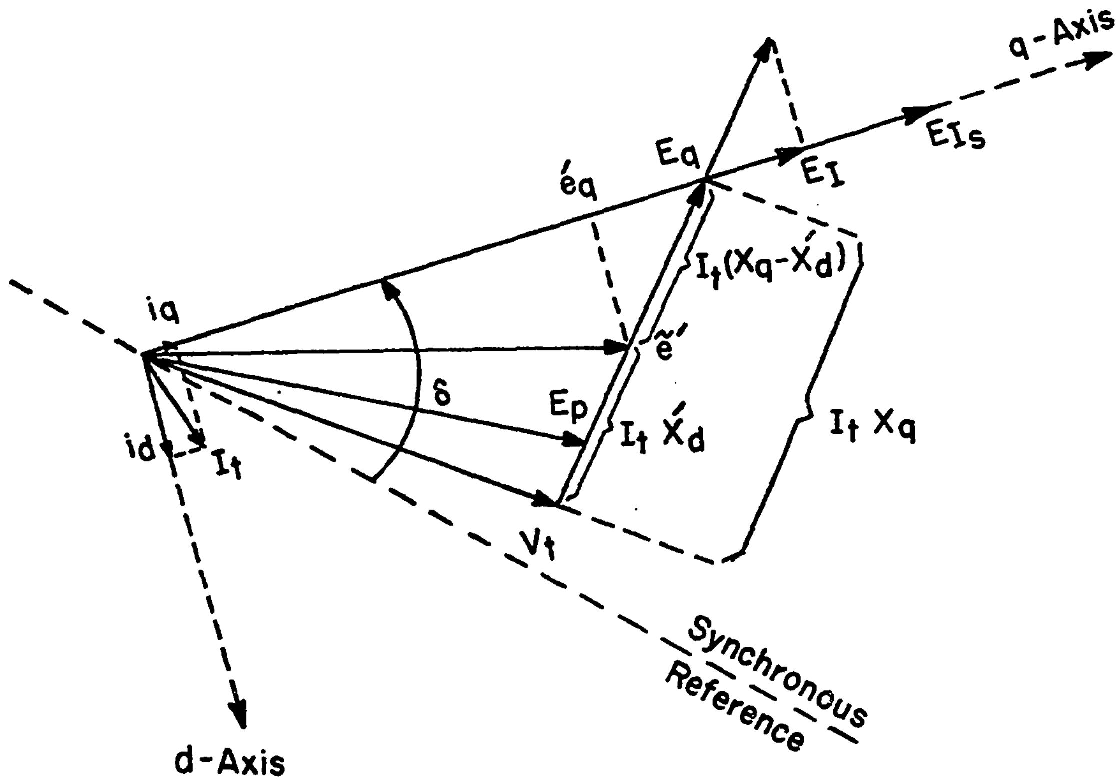


FIGURE 2-6
VECTOR DIAGRAM FOR MODEL II

The assumption of ignoring the amortissure currents implies that the amortissure damping is being ignored too as well as neglecting the shield effect of the amortissures between the field and stator during transient. The damping contributed from the armature is primarily of significance upon the inter-unit damping of closely coupled machines. The contribution to the inter-system damping is not as large. Therefore, the effect of amortisseur damping can be approximated by adding an equal element damping coefficient to the motion equation (2-5) in order to have a better solution. The shielding effects of the amortisseurs are relatively unimportant for rotation exciters, but it may be relatively unimportant for rotating exciters, but it may be relatively important for some static exciter systems.[26] To be more secure and avoid the doubt of the shielding effect, a more complicated model needs to be represented.

The advantages of this model are:

1) It exposes the representation of field transients, in other words, saturation effects are included which are a more accurate representation.

2) It is the simplest model to use for dynamic stability studies.[2,44]

3) It requires a fair amount of machine data (see table 2-1).

The disadvantages of model II are:

1) It requires more machine data than the previous model.

2) It requires more computing time than model I.

2-5 Model III[2]

This model is concerned particularly with round rotor machines (with solid iron rotors). The damping of the round rotor machine is provided by iron circuits while the salient machine eliminates these iron circuits.

The additional assumptions that are required are:

1) The armature resistance is neglected.

2) All generators in the same power plant are represented as one machine.

3) Transient saliency is neglected.

4) The quadrature axis iron circuit is represented by a single circuit whose constants are established for a rotor current frequency of one hertz.

This model will be represented by vector diagram figure 2-7 and dynamic and algebraic equations (2-6), (2-7), (2-8), (2-9), (2-10), (2-11) and (2-12).

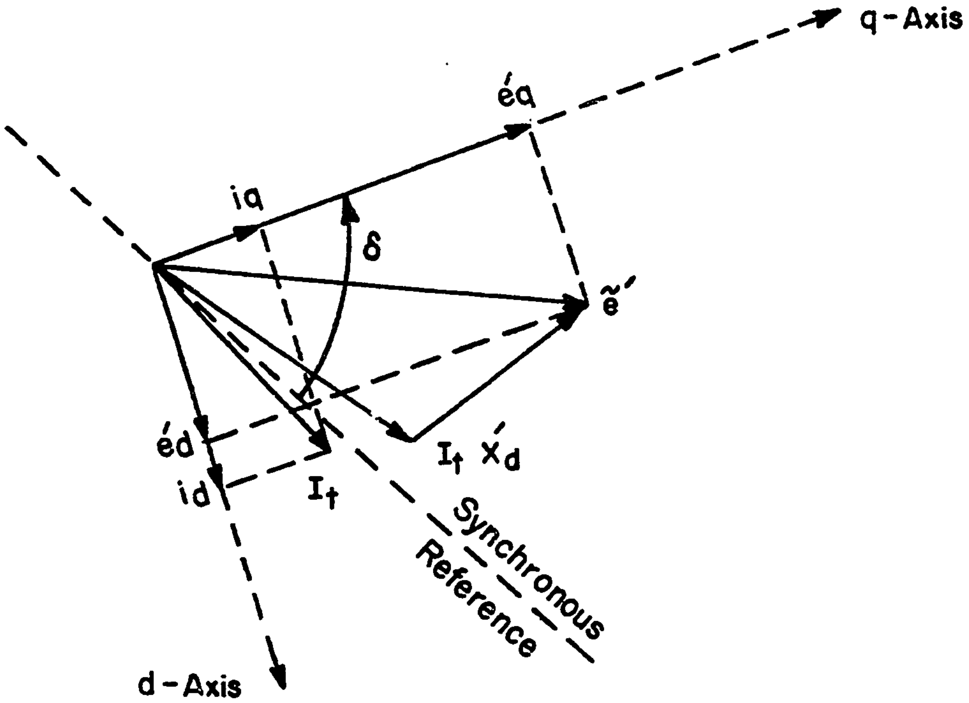


FIGURE 2-7
VECTOR DIAGRAM FOR MODEL III

$$\tilde{e}' = (e_q' + Je_d')\, e^{j\omega t} \tag{2-6}$$

$$\frac{de_q'}{dt} = \frac{1}{T_{do}'} (E_{fd} - E_I) \tag{2-7}$$

$$\frac{de_d'}{d_t} = \frac{1}{T'_o} (-E_d) \tag{2-8}$$

$$E_d = E_d' - (x_q - x_q')\, I_q \tag{2-9}$$

$$E_q = E'_q + (x_d - x'_d)\, I_d + e_s \tag{2-10}$$

$$\frac{d\delta}{dt} = \omega \tag{2-11}$$

$$\frac{d\omega}{dt} = \frac{180f}{H}\,(T_m - T_e + K\omega) \tag{2-12}$$

Note equation (2-6) can be written in general form if we don't accept ignoring the saliency transient.

$$\tilde{e}' = \{e'_q + J\left[e'_d - (x'_q - x'_d)\; i_q\right]\}\, e^{j\omega t}$$ (44)

Therefore, at any instant of time all of the quantities are known.

Strictly speaking, x'_q and x'_d have quite different values, but trouble comes about if they are not equal because i_q needs to be found as well as $\tilde{e}'$. The procedure might be to assume a value of $\tilde{e}'$ and solve the system equations.(2) The question is how far are we right when assuming the value for $\tilde{e}'$. Therefore, it is practical to only assume that $x'_q = x'_d$.

Model III can be represented as model I if we assume that internal voltage behind the transient reactance is constant.

As it has be shown, model II was derived with neglecting all damping winding or iron circuit effects. Therefore, amortisseur damping was not represented directly in the equations. But model III represents directly the major part of this form of damping by representing the quadrature axis iron circuit whose constants are appropriate for the usual order of magnitude of inter-unit oscillations. At no load all of the amortisseur's damping is produced by the quadrature axis iron circuit whose constants are appropriate for the usual order of magnitude of inter-unit oscillations. At no load all of the amortisseur's damping is produced by the quadrature axis iron circuit. At full load, for the usual range of reactances, the quadrature axis iron circuit continues to provide a major amount of this form of damping. X'_q and X'_d can be adjusted so as to represent more of the total damping effect of the iron circuit and for other frequencies. This requires information which is not available.

The advantages of model III are:

1) Representation of the quadrature axis iron circuit may provide a direct representation of damping, hence, a better result.

2) This model is used only for a round rotor machine where the field effects are represented and where a direct representation of inter-unit damping is desired.

3) It is simple and accurate enough to use for all kinds of stability studies.

The disadvantages of model III are:

1) Model III requires more computing time than does model II.

2) It requires more machine data (see table 2-1).

2-6 Model III & ½

This model represents the damper winding of the machine in both the direct and quadrature axis.

The additional assumptions that are needed are:

1) The armature resistance is neglected.

2) All generators in the same power plant are represented as one machine.

3) Saturation is not represented.

This model is illustrated in vector diagram figure 2-8 and dynamic equations as well as algebraic equations (2-13), (2-14), (2-15), (2-16), (2-17), (2-18), (2-19) and (2-20). For derivation of these equations see appendix A.

$$e''_q = -(x_d - x''_d)\, i_d + e_{q1} + e_{q2}\ ^{**} \tag{2-13}$$

$$e'_q = -(x_d - x''_d)\, i_d + e_{q1} + \left(\frac{x_d - x'_d}{x_d - x''_d}\right) e_{q2} \tag{2-14}$$

$$e''_d = (x_q - x''_q)\, i_q + e_d \tag{2-15}$$

$$\frac{de'_q}{dt} = \frac{1}{T'_{do}} (E_{fd} - e_{q1}) \tag{2-16}$$

$$\frac{de''_q}{dt} = -\frac{eq_2}{T''_{do}} \left(\frac{x'_d - x''_q}{x_d - x''_d}\right) \tag{2-17}$$

$$\frac{de''_d}{dt} = -\frac{ed}{T''_{qo}} \tag{2-18}$$

$$\frac{d\delta}{dt} = \omega \tag{2-19}$$

$$\frac{d\omega}{dt} = \frac{180f}{H} (T_m - T_e + K\omega) \tag{2-20}$$

**e_{q1}, e_{q2} and e_d have been defined in Appendix A.

The relative importance of representing damping winding over representing the saturation, amortissure winding has been represented; one winding in each of the direct and quadrature axis. The next model, model IV, will consider the saturation effects in addition to this model.

The advantages of model III & ½ are:

1) Representation of damping winding in direct and quadrature axis will provide a direct representation of damping, hence, a better result.

2) It is modern, simple and sufficient enough for using in stability studies of the machine's representation.

The disadvantage of model III & ½ is it requires more machine data (see table 2-1).

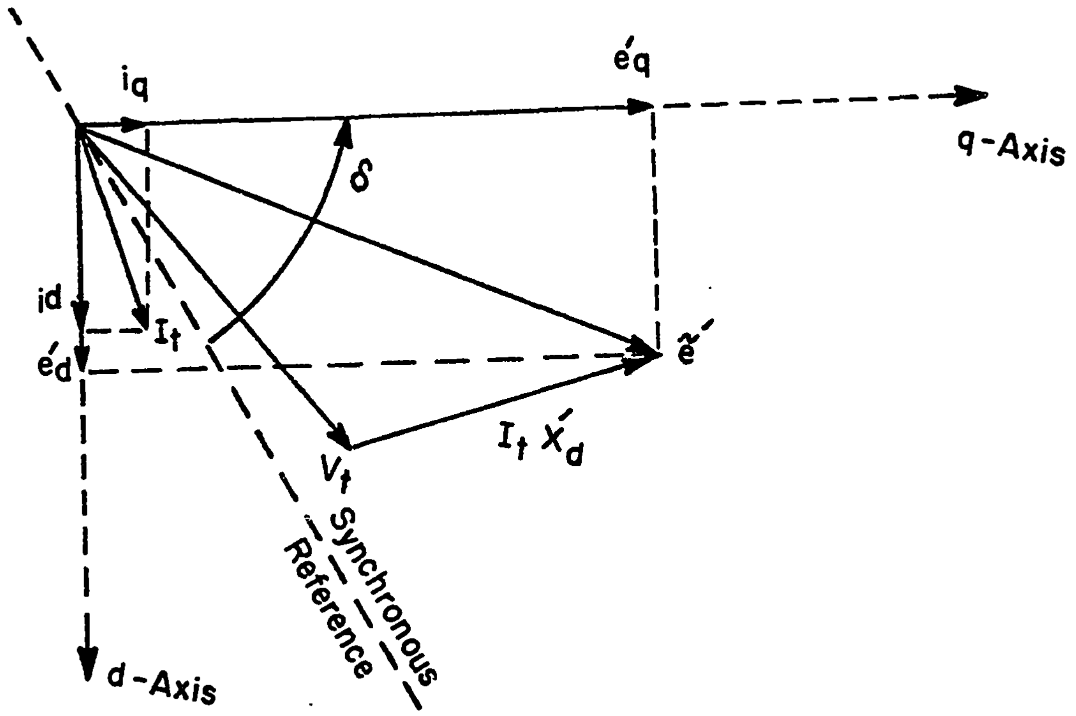


FIGURE 2-8
VECTOR DIAGRAM FOR MODEL III & ½

2-7 Model IV

Model IV is the most complicated model so far. To define this model, in addition to the three assumptions stated previously, the following assumptions are made.

1) Machine subtransient saliency is neglected, that is $x''_q = x''_d$.

2) The braking torque is neglected.

3) All generators in the same power plant are represented as one machine.

Assumption one is valid for a round-rotor machine, but for salient pole generator x_q'', it is some what larger than x_d'', but the effect of assuming that $x_q'' = x_d''$ is negligible for stability analysis.

The vector diagram is represented in Figure 2-9. Dynamic equations as well as algebraic equations are represented as equations (2-21), (2-22), (2-23), (2-24), (2-25), (2-26), (2-27), (2-28), (2-29) and (2-30).

$$\lambda_q'' = e_d'' \tag{2-21}$$

$$\lambda_d'' = \lambda_{kd} + \left(\frac{x_d'' - x_\ell}{x_d' - x_\ell}\right)(e_q' - \lambda_{kd}) \tag{2-22}$$

$$\frac{de_q'}{dt} = \frac{1}{T_{do}'} \; (E_{fd} - E_I) \tag{2-23}$$

$$\frac{d\lambda_{kd}}{dt} = - \left[\frac{(x_d'' - x_\ell)^2}{(x_d' - x_d'')T_{do}''}\right] \; (i_{kd}) \tag{2-24}$$

$$\frac{d''_{ed}}{dt} = \frac{1}{T_{qo}''} \; (-E_d) \tag{2-25}$$

$$E_I = e_q' + (x_d - x_d')(i_d - i_{kd}) + e_s \tag{2-26}$$

$$i_{kd} = \frac{(x_d' - x_d'')}{(x_d' - x_\ell)^2} \left[\lambda_{kd} - e_q' + (x_d' - x_\ell)i_d\right] \tag{2-27}$$

$$E_d = e_d'' + (x_q - x_d'')i_q \tag{2-28}$$

$$\frac{d\delta}{dt} = \omega \tag{2-29}$$

$$\frac{d\omega}{dt} = \frac{180f}{H} \; (T_m - T_e) \tag{2-30}$$

It has been shown that this model represents subtransient amortisseur in both direct and quadrature axis. Amortisseurs are repre-

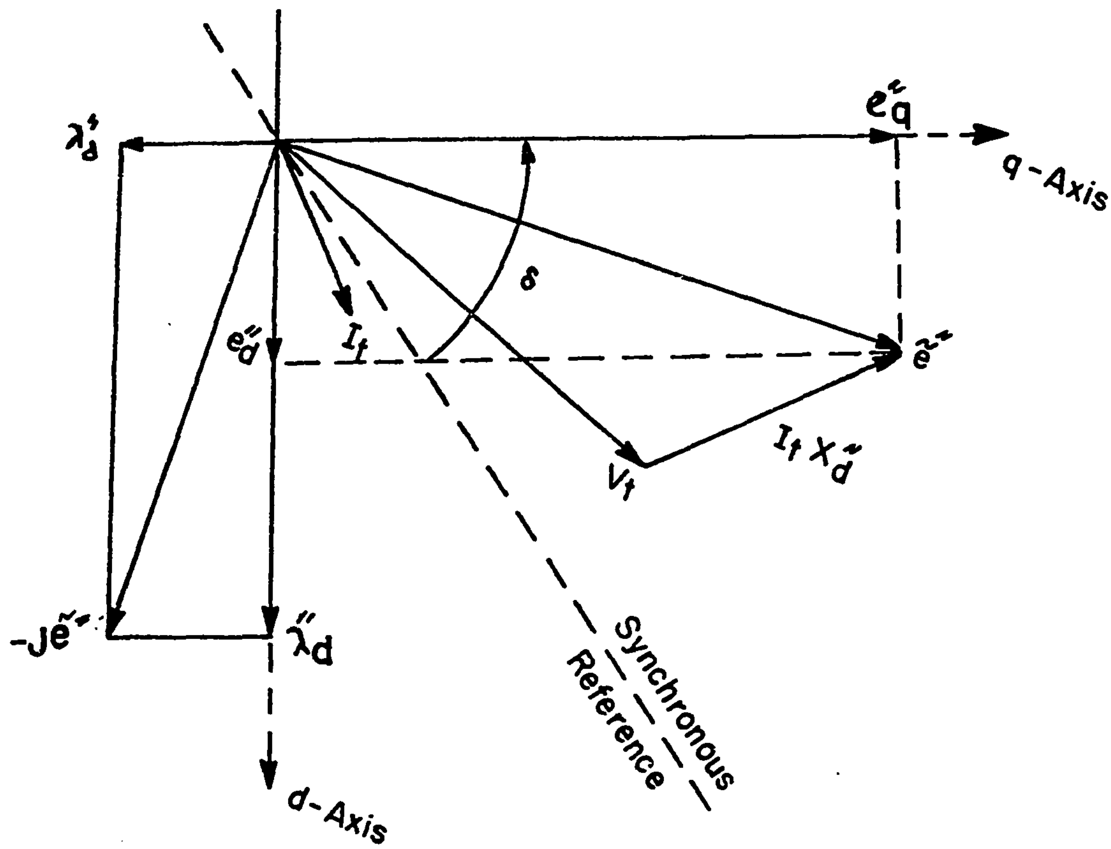


FIGURE 2-9
VECTOR DIAGRAM FOR MODEL IV

sented in both axes and subtransient saliency is neglected. Of course, the equations will change, but the vector diagram will not. Also, the technique for solving the system equations will not change. This model requires ten items of data in addition to the data needed to represent saturation.

At any instant of time, the angle δ, the direct axis components of subtransient flux λ_d'', and the quadrature axis component of subtransient flux λ_q'' are known. Therefore, $\tilde{e}''$ is known. Thus, the representation becomes that of a constant voltage behind a constant subtransient reactance at any point in time.[2]

Therefore, this representation is as simple as that of model I as far as the solution of the system equations is concerned. Once the system conditions are determined, it is a simple process to compute the rotor and stator currents as well as the variations of the rotor flux linkages.[2] For round rotor machines, it is necessary to represent two quadrature axis iron circuits so as to be sure of a complete representation of the damping effect.

The advantage of this model is it represents the field effect and amortisseur effect implying a more accurate solution than others.

The disadvantages are 1) since it so complicated, computing cost compared to the other models is high; 2) a large amount of data is needed which probably discourages many power system engineers from adapting this model (see table 2-1).

CONSTANTS	MODEL I	MODEL II	MODEL III	MODEL III & ½	MODEL IV
X_d	-	-	x	x	x
X'_d	x	x	x	x	x
X''_d	-	-	-	x	x
X_q	-	-	x	x	x
X'_q	-	-	-	x	x
X''_q	-	-	-	x	x
T'_{do}	-	-	x	x	x
T''_{do}	-	-	-	x	x
T'_{qo}	-	-	x	-	x
T''_{qo}	-	-	-	x	x
H	x	x	x	x	x
K	x	x	x	x	-
R	-	-	-	-	-
X_ℓ	-	-	-	-	x

TABLE 2-1

MACHINE PARAMETERS USED FOR EACH MODEL

CHAPTER III

SENSITIVITY ANALYSIS OF MACHINE CONTROLLER

3-1 Introduction to the Excitation System

The field windings of synchronous machines are provided with direct current from d-c devices called exciters. The excitation system is the source of field current for the excitation of the principal electric machine, including the means for its control. An excitation system, therefore, includes all of the equipment required to supply field current to excite an a-c generator.[23]

Loss of excitation of an a-c generator generally means that the generator will act as an induction generator for only a limited amount of time. Therefore, a reliable source of excitation is essential. The common way of providing exciter is for each a-c generator to have its own exciter. Another way, which is impractical, is to have an exciter bus fed by a number of exciters operating in parallel and which will supply power to the fields of all a-c generators in the station.[3]

Several types of excitation systems provide automatic voltage regulation for a-c generation. The physical configuration is discussed as well as the four models of computer representing the excitation system. It is well known that the excitation system does effect the stability of the machine.[24] The lack of excitation data for purposes of modeling system stability studies has a severe impact on the stability studies being conducted.

Hence, data sensitivity of the excitation system in the sense of the effect of each parameter to the response of the exciter will be considered. In other words, the study on the behavior of the exciter models, considered to be a mathematical representation of almost all kinds of excitation systems (see appendix B), are classified by the IEEE committee as four models.[8] Each of the four models have a non-linear term represented by the exciter saturation factor as well as a hard limiter. Therefore, the simulation technique has to be adapted to deal with this kind of system. Root locus and frequency response technique have been used for certain sample points because their responses are reserved only for linear systems. The aid of the digital computer, C.S.M.P. package,[12] enables us to simulate the mathematical representation of the excitation system. C.S.M.P. has three main sections regarding the executing of the problem. The initial section provides the initial conditions of all the variables; the dynamic section is where the integration subroutine is applied to solve the governor's equation; the terminal section is involved with the control statement, plotting, printing, etc. The output listing of programs for all exciter models, shown in appendix C, was used for the simulation.[47] This program provided us with the results of the effect of each parameter variation to the exciter response.

To see how that can be done, let's take one parameter of the exciter and that will be regulator amplifier time constant, T_A. The simulation program enables us to vary the value of T_A by fourty-one values. That is accomplished by incrementing T_A by $T_A + \Delta T_A$. So we have to have fourty-one exciter responses, in other words fourty-one computer runs.

The new variable named by system time constant "T_C" needs to be defined simply to furnish fourty-one exciter responses in one single curve rather than having fourty-one individual computer runs for varying only one parameter. That can be done by defining $TT_C = (1 - e^{-1})$ multiplied by the steady state value of the system. TT_C is an acceptable operating point at the exciter response. Therefore, we use the TT_C as a comparative quantity with exciter output, as seen in figures (3-2) and (3-3). So whenever the exciter response is equal or greater than the TT_C quantity it causes the computer to record the value which is the system time constant. Each exciter response can be characterized by system time constant T_C and that enables us to see the system time constant variation in one single curve versus the time axis which really represents fourty-one exciter responses due to varying one single parameter. A typical exciter response is shown in figure (3-1) with a incremented change of ΔA. So each incremental of ΔA corresponds to a new exciter response. The same thing can be carried over to the rest of the other exciter parameters. Exciter models behavior regarding given data is shown in table (3-1).

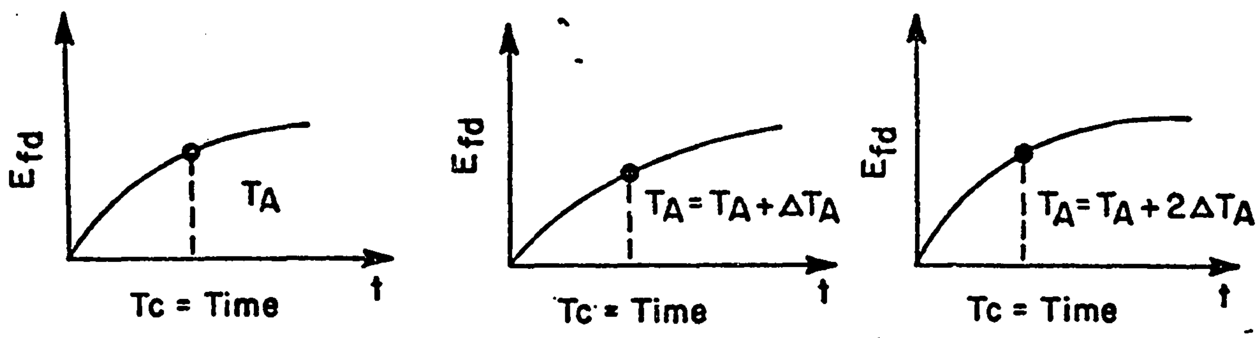


FIGURE 3-1
TYPICAL EXCITER RESPONSE

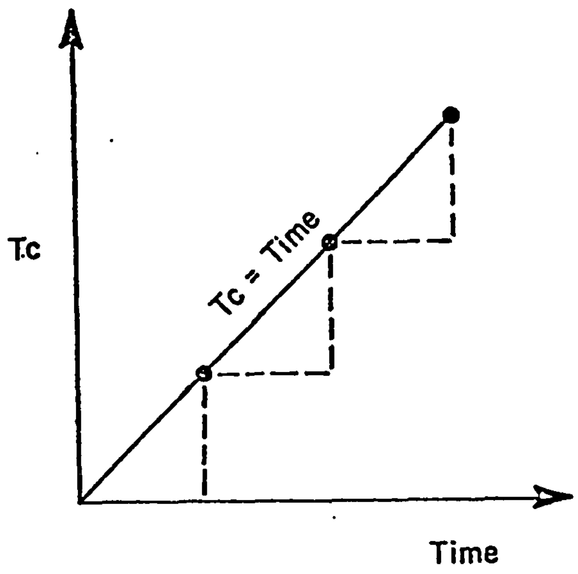


FIGURE 3-2
ONE-TO-ONE RELATION OF T_C AND TIME

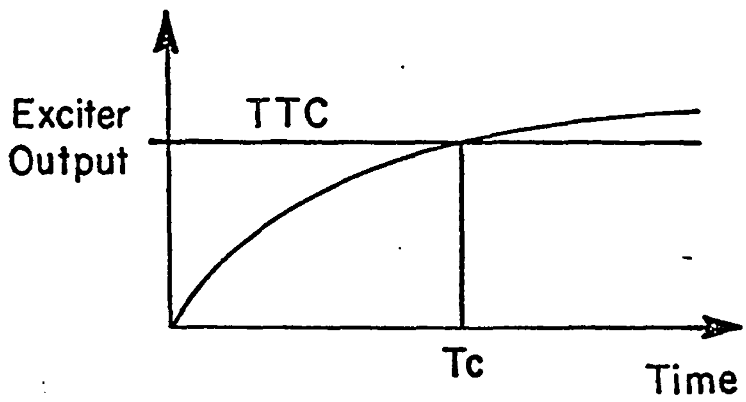


FIGURE 3-3
RELATION OF SYSTEM TIME CONSTANT AND EXCITER OUTPUT

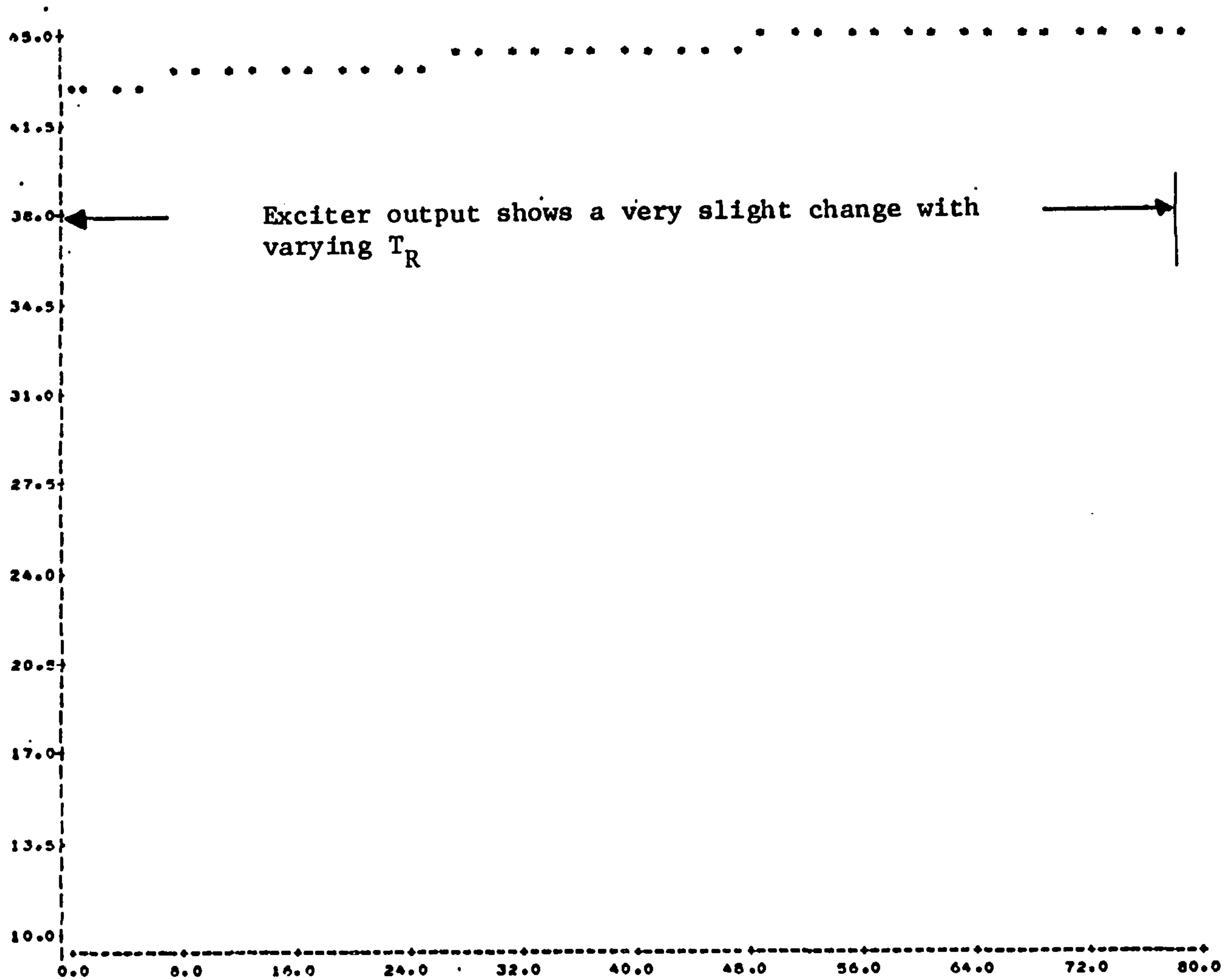
3-2 Exciter Type I

Figure (3-4) illustrates the behavior of exciter model, type I, upon changing the regulator input filter time constant, T_R. Physically T_R is the combined time constant of the regulator input filter of the

EXCITER PARAMETER	EXCITER TYPE 1			EXCITER TYPE 2			EXCITER TYPE 3			EXCITER TYPE 4		
	**	Max	Min	**	Max	Min	**	Max	Min	**	Max	Min
T_R	0.00	.08	0.000	0.00	.08	0.000	0.00	.08	0.00	-	-	-
K_A	40.00	150.00	1.000	40.00	100.00	1.000	40.00	150.00	1.00	-	-	-
T_A	.02	0.40	.000	.02	1.00	0.000	.02	0.00	.50	-	-	-
V_R	-	6.50	-6.500	-	6.50	-6.500	-	6.50	-6.50	-	10.5	-10.50
K_f	0.03	.30	.003	.03	.03	-	.03	.30	.01	-	-	-
K_E	1.00	5.00	.010	1.00	3.50	.100	1.00	15.00	.01	.10	2.0	-.01
T_E	.73	5.00	.010	.73	3.50	.100	.73	5.00	.01	.01	5.0	.01
S_{Emax}	.74	-	-	.74	-	-	.74	-	-	.85	-	-
T_{f_1}	1.00	5.00	.010	-	-	-	1.00	5.00	.01	-	-	-
T_{f_2}	-	-	-	1.00	5.00	.010	-	-	-	-	-	-

**original exciter data

TABLE 3-1
EXCITER DATA



Y SCALE FACTOR USED IS 1.0E-02 X SCALE FACTOR USED IS 1.0E-03

* IS SYSTEM TIME CONSTANT

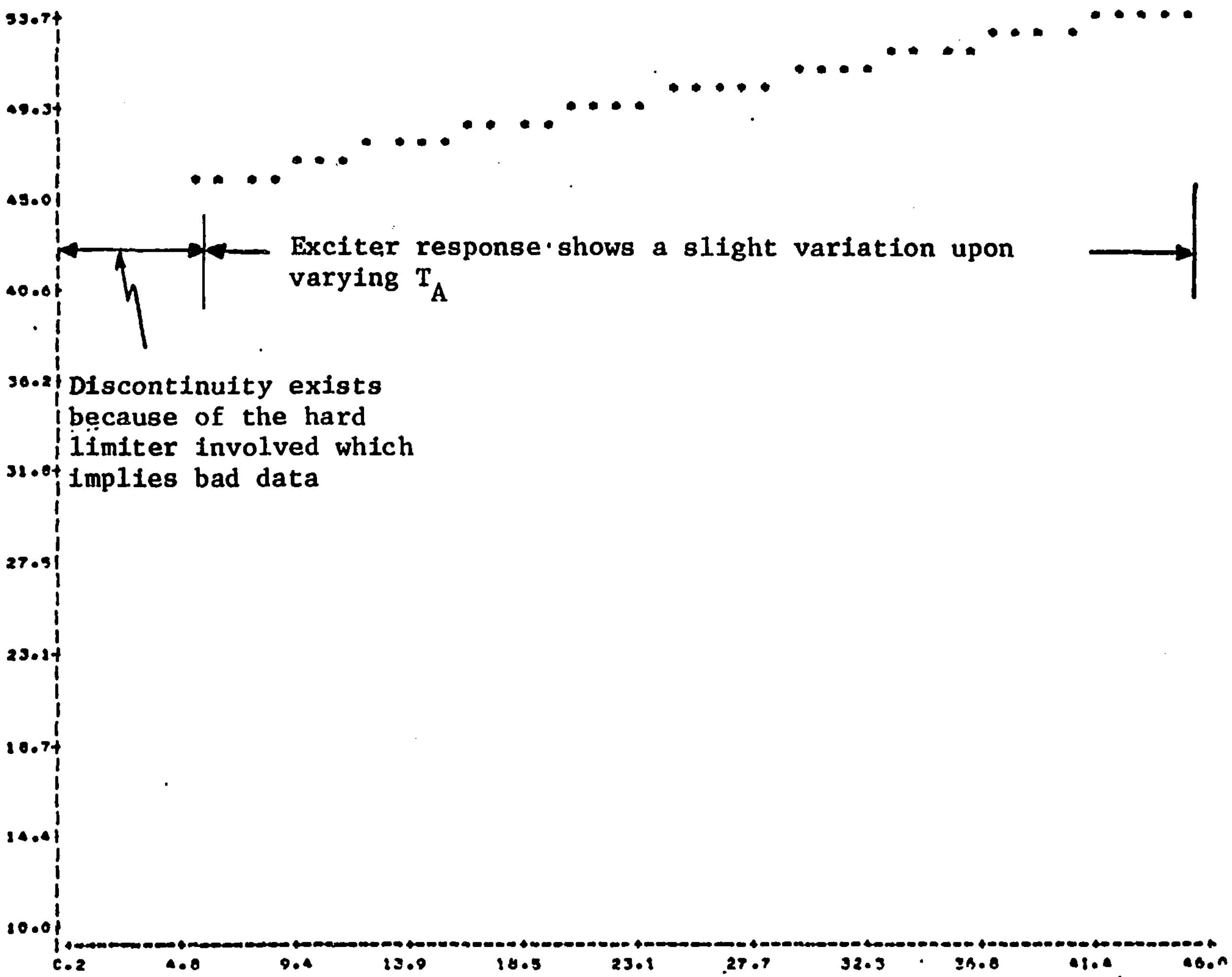
SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08

FIGURE 3-4

exciter. By inspecting the figure regulator input filter time constant T_R doesn't contribute a significant effect on the system time constant of the exciter system. In other words, the output of the exciter does not effect it by changing T_R. The reason is, as we know the nature design of the time constant T_R, that it has a very small value. Therefore, its pole location, in a S-plan configuration, is an infinity relative to the other parameters of the exciter. Thus, it does not contribute a significant change on the exciter output.

Figure (3-5) shows the behavior of exciter model, type I, upon changing the regulator amplifier time constant, T_A. Physically T_A is the combined time constant of the exciter amplifier system. Looking to the figure, system time constant of the exciter shows a slight change upon changing the regulator amplifier time constant, T_A. The reason, as we know the nature design of regulator amplifier time constant, T_A, is that it has a small value compared to other parameters of the exciter. In other words, its pole location in the S-plan is far with respect to the others. The result is that there is little effect on the exciter output.

Figure (3-6) shows the behavior of exciter model, type I, upon changing the feedback time constant, T_F. Physically T_F is the combined damping time constant of the exciter. Again looking to the figure, feedback time constant, T_F, does not contribute a significant value to the system time constant of the exciter model. In other words, the output of the exciter is not effected by changing T_F. Damping feedback transfer function can be plotted in frequency response. The Bode diagram will show the pole effect cancelled by the existing zero. If we have zero

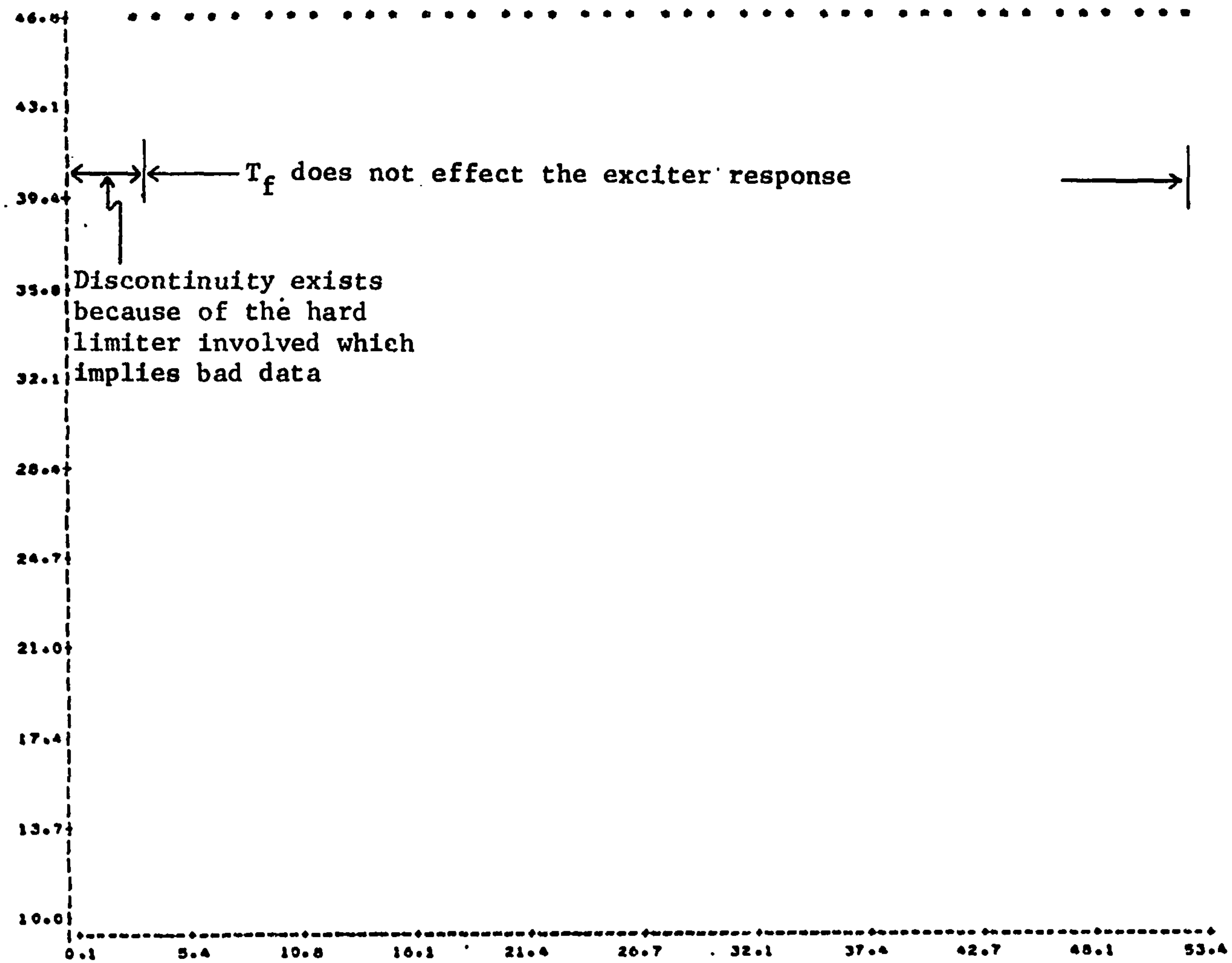


Y SCALE FACTOR USED IS 1.0E-02 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM 0.0 TO .40

FIGURE 3-5



Y SCALE FACTOR USED IS 1.0E-02 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO 5.0

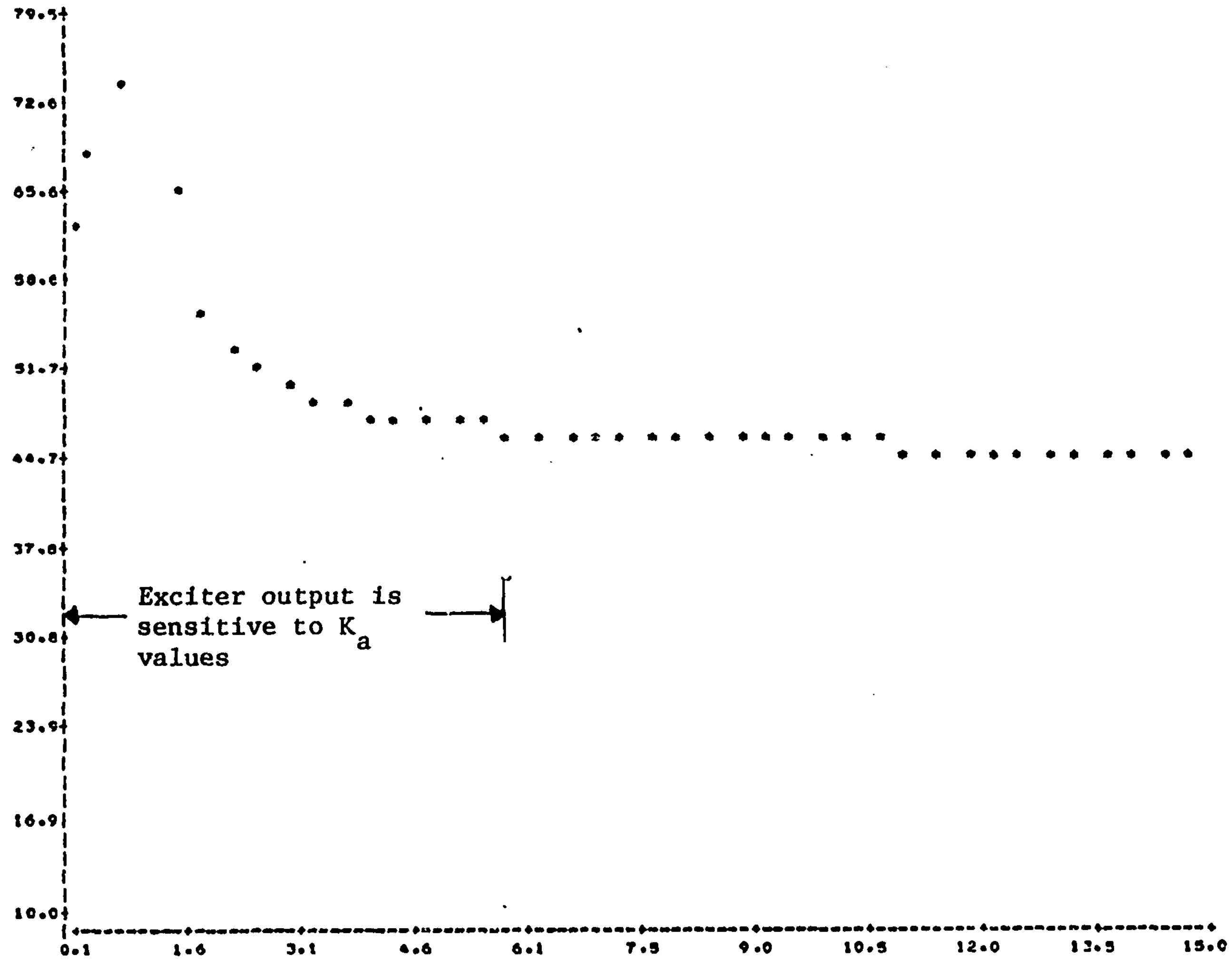
FIGURE 3-6

located at the origin of the axis, they will cancel the effect of each other. This is why the feedback time constant, T_F, does not contribute any change to the exciter output.

Figure (3-7) shows the behavior of the exciter model, type I, upon changing the regulator gain, K_A. Physically K_A is the combined gain parameter of the exciter amplifier system. By inspecting the figure regulator gain K_A shows that the lower value of K_A does effect the output of the exciter, while the higher value of K_A does not contribute any change to the exciter output. The reason is that the existing hard limiter probably takes action which is recommended to limit the value of K_A.

Figure (3-8) shows the behavior of the exciter model, type I, upon changing the exciter time constant, T_E. Physically T_E is the combined time constant of the exciter system itself. Looking to the figure, exciter time constant, T_E, shows the linear relationship with respect to the exciter output. This is the most dominant parameter. It is classified by a greater value than T_R and T_A. The reason for this is that it plays a very strong role on the characteristic of the equation of the exciter system under the assumption that nonlinearity is not defined.

Figure (3-9) shows the behavior of the exciter model, type I, upon changing the damping gain parameter, K_F. Physically K_F is the equivalent damping gain parameter of the exciter. Looking to the figure, the feedback gain parameter, K_F, shows exponentially the changing relative to the system time constant of the exciter. In spite of knowing that the feedback parameter plays a strong role on the exciter model's stability as well as the nature value of K_F is so high relative to other values, I



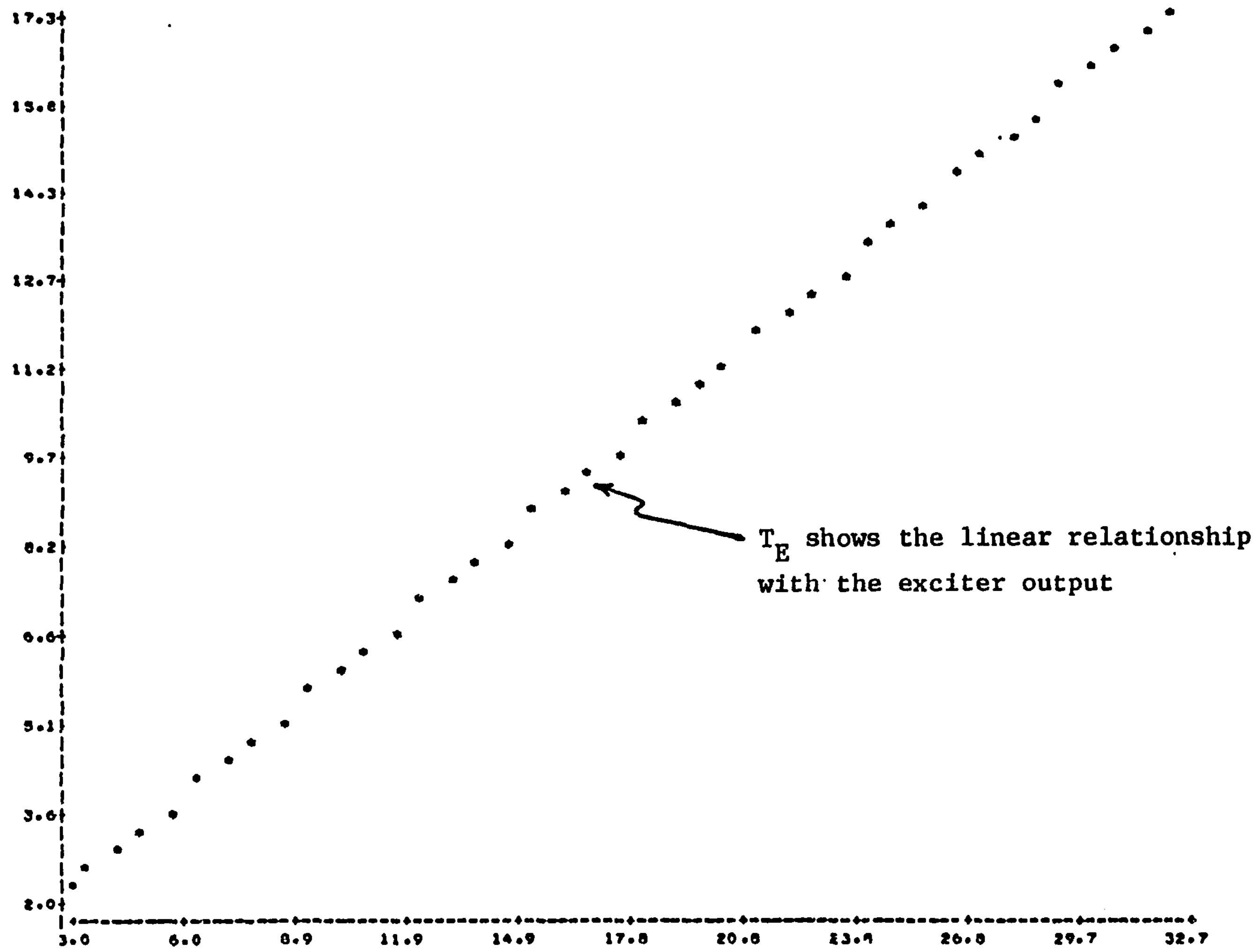
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E 01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE I EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.00 TO 150.0

FIGURE 3-7



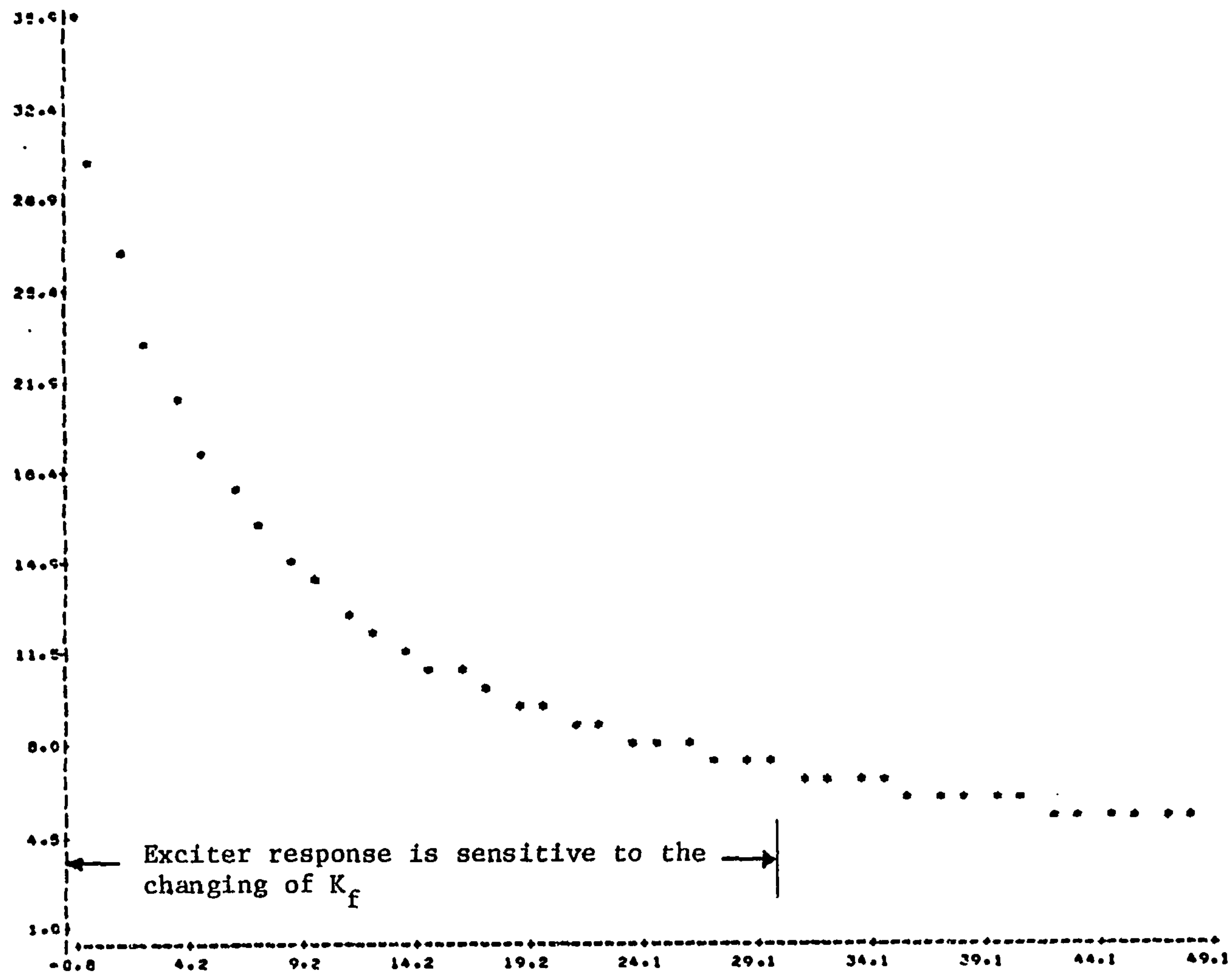
Y SCALE FACTOR USED IS 1.0E-01

X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO 5.00

FIGURE 3-8



Y SCALE FACTOR USED IS 1.0E-01

X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KF IS VARIED FROM .003 TO .3

FIGURE 3-9

could say it is very hard to predict the reason of K_F's change exponentially bearing in mind that the hard limiter exists, thus, nonlinearity is defined.

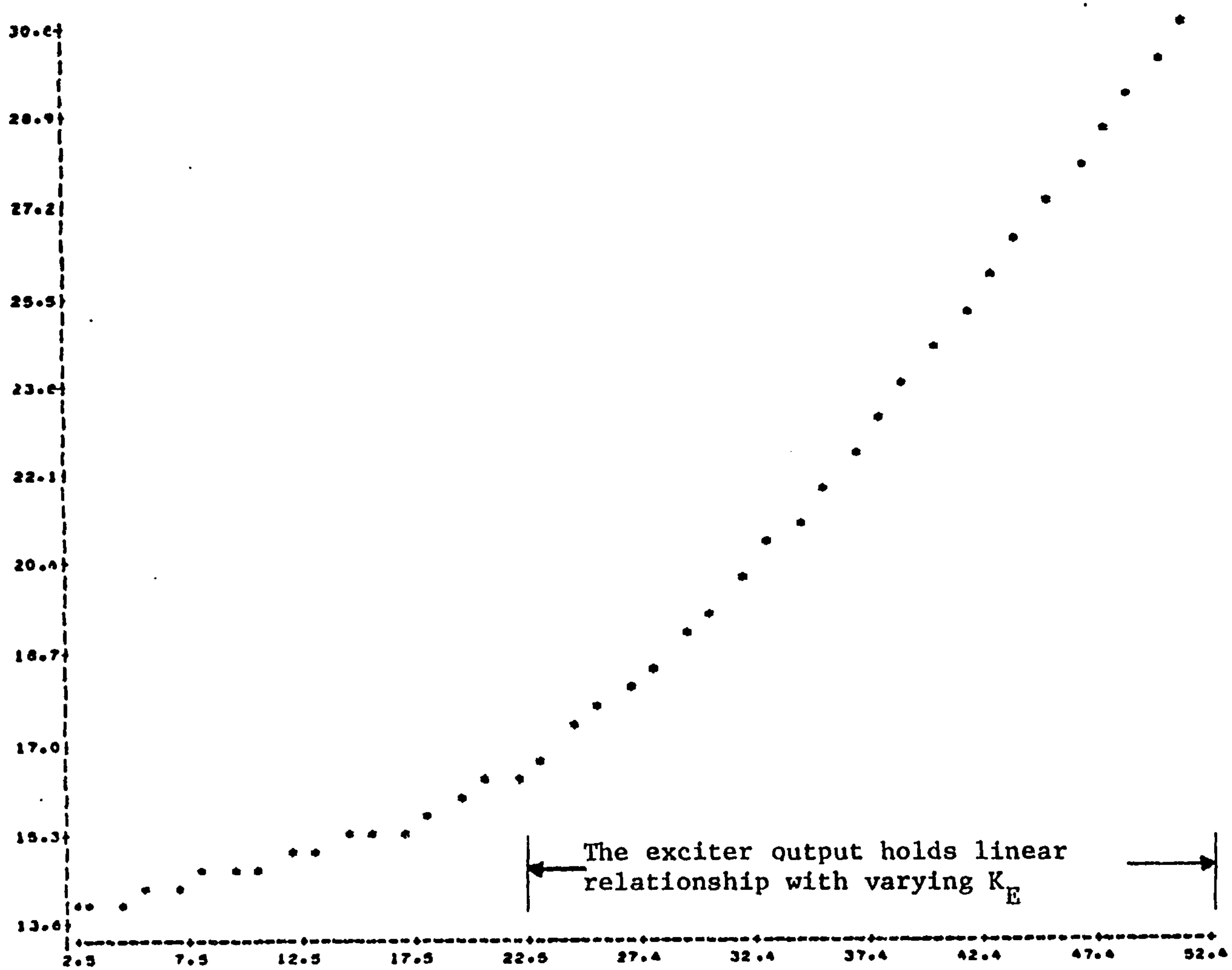
Figure (3-10) shows the behavior of the exciter model, type I, upon changing the exciter gain parameter, K_E. Physically K_E is the equivalent gain parameter of the exciter system itself. Looking to the figure, the gain parameter, K_E, shows an almost linear relationship with the exciter response. It is the most dominant parameter of the exciter system model. Simply, it shows the variation with the exciter output. Secondly, it represents the term A_n of a characteristic equation which makes it an important parameter.

3-3 Exciter Type II

The behavior of the exciter model, type II, upon changing the regulator input filter time constant, T_R, is shown in figure (3-11). Looking to the figure, T_R does not contribute a significant effect on the system time constant of the exciter system. Therefore, the output of the exciter would not be effected either. The reason its value is so small is that you can hardly see its effect on the system's behavior.

Figure (3-12) shows the behavior of the exciter model, type II, upon changing the feedback time constant, T_F. Looking to the figure the feedback time constant, T_F, does not contribute a significant value on the system time constant of the exciter. Therefore, the output has not been effected by changing T_F. This is because of the small value of T_F as well as the adverse effect of the existing zero.

Figure (3-13) shows the behavior of the exciter model, type II, upon changing the regulator gain, K_A. Looking to the figure regulator

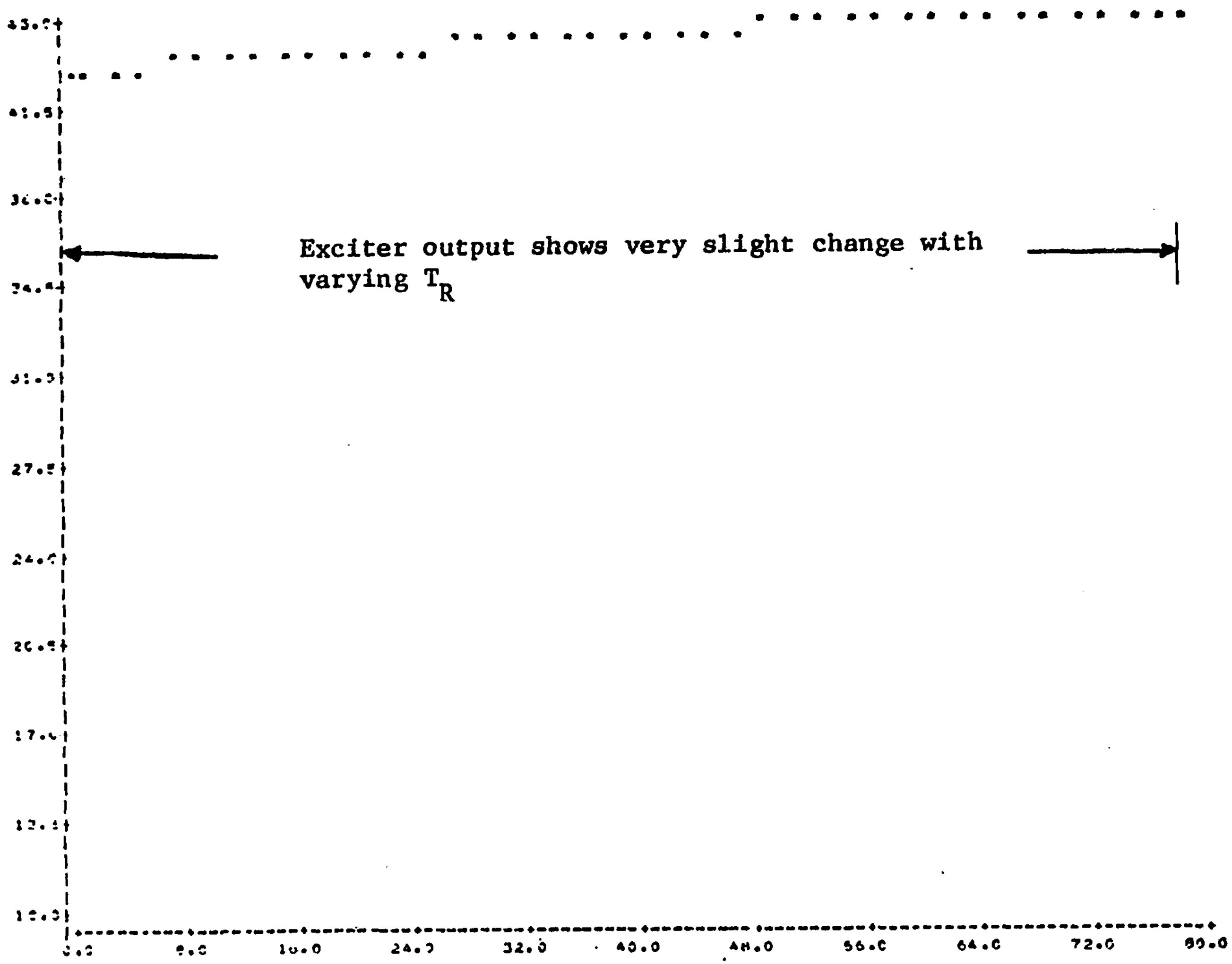


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KE IS VARIED FROM .01 TO 15.0

FIGURE 3-10



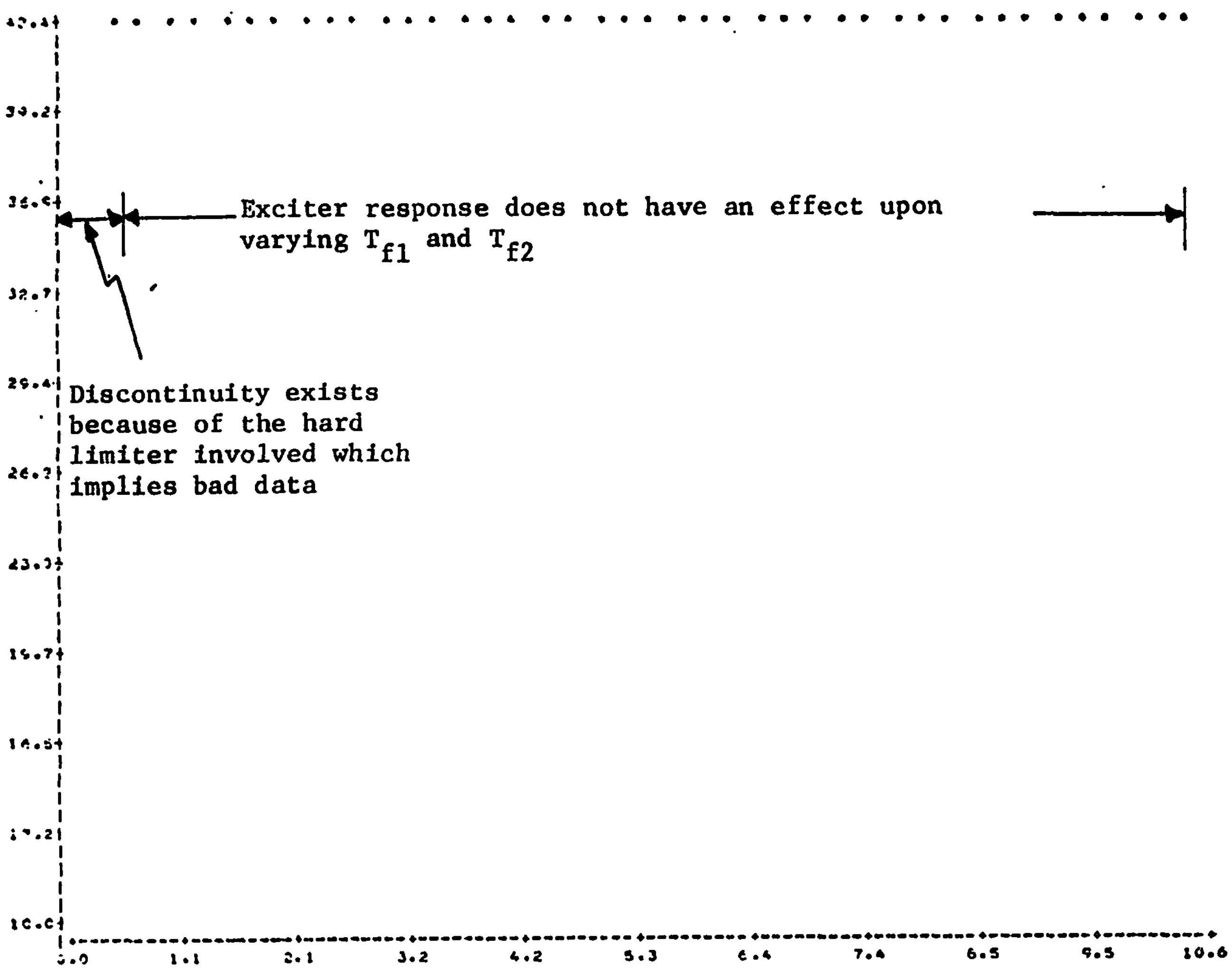
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E-03

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08

FIGURE 3-11



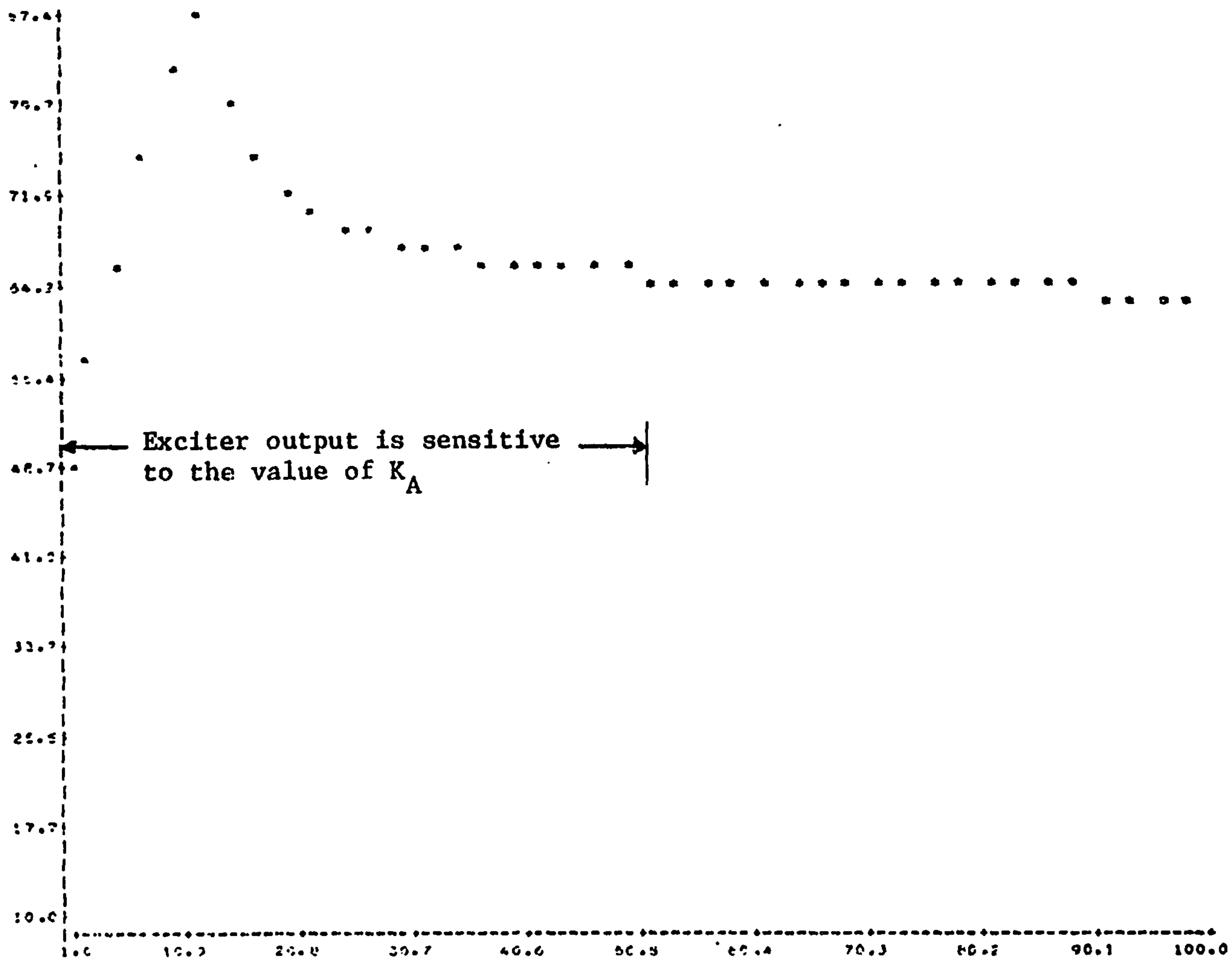
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO 10.

FIGURE 3-12



Y SCALE FACTOR USED IS 1.0E-02 X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.00 TO 100.

FIGURE 3-13

gain parameter, K_A, shows that the lower value of K_A does effect the output of the exciter, this is the same as type I, while the higher value of K_A does not contribute any significant change to the exciter output. This is because of the hard limiter's involvement.

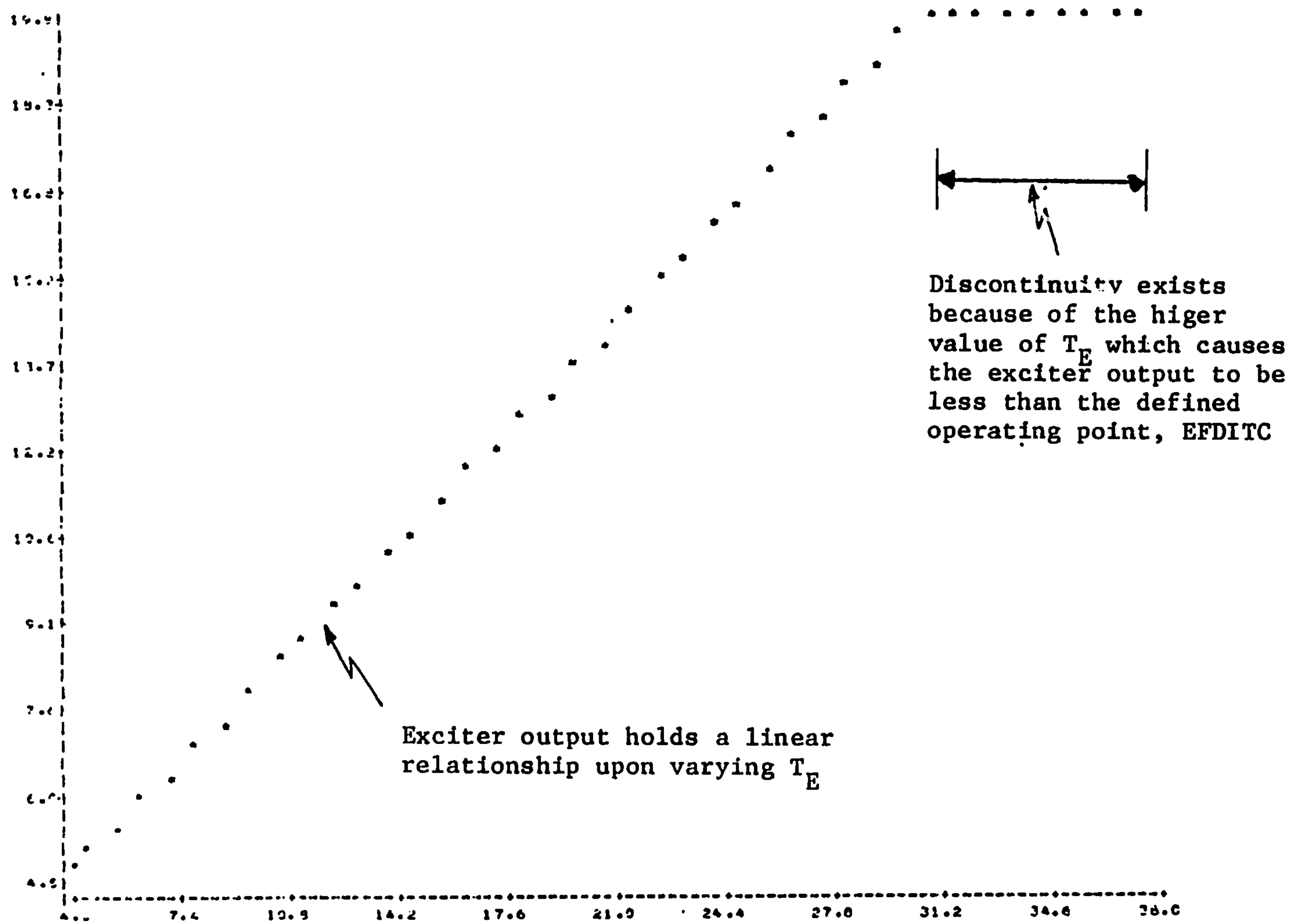
The behavior of the exciter model, type II, upon changing the exciter time constant, T_E, is shown in figure (3-14). Again, the exciter time constant, T_E, shows the linear relationship with respect to the exciter output, which is the same as type I. It is the most dominant parameter which one would expect. Discontinuity exists at the end of the curve which shows that the exciter output at a higher value of T_E is less than the defined operating point, EfDITC.

Figure (3-15) shows the behavior of the exciter model, type II, upon changing the exciter gain parameter, K_E. Looking to the figure, the parameter, K_E, shows an approximate exponential relationship with the output. Again, it is also the most dominant parameter of the exciter and it has an adverse effect on the exciter response.

Figure (3-16) shows the behavior of the exciter model, type II, upon changing the regulator amplifier time constant, T_A. Looking to the figure the system time constant of the exciter shows a slight change upon changing T_A, obviously T_A is a larger value than T_R. Therefore, it has to effect the exciter output as its value is increased.

3-4 Exciter Type III

Figure (3-17) shows the behavior of the exciter model, type III, upon changing the filter regulator time constant, T_R. Looking to the figure, the filter regulator time constant, T_R, does not contribute any significant effect on the system time constant. It states early its

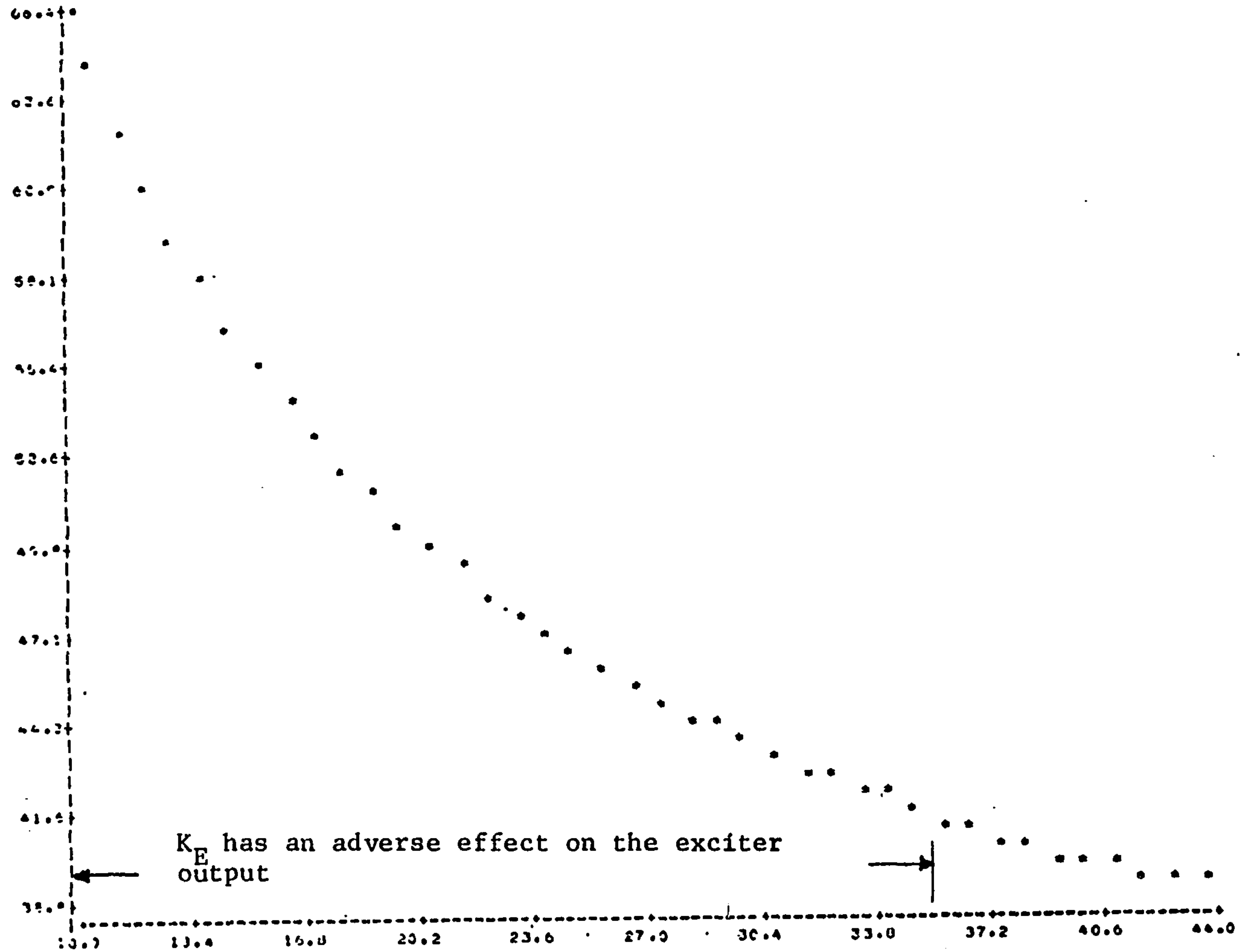


Y SCALE FACTOR USED IS 1.0E-01　　　X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .1 TO 3.50

FIGURE 3-14



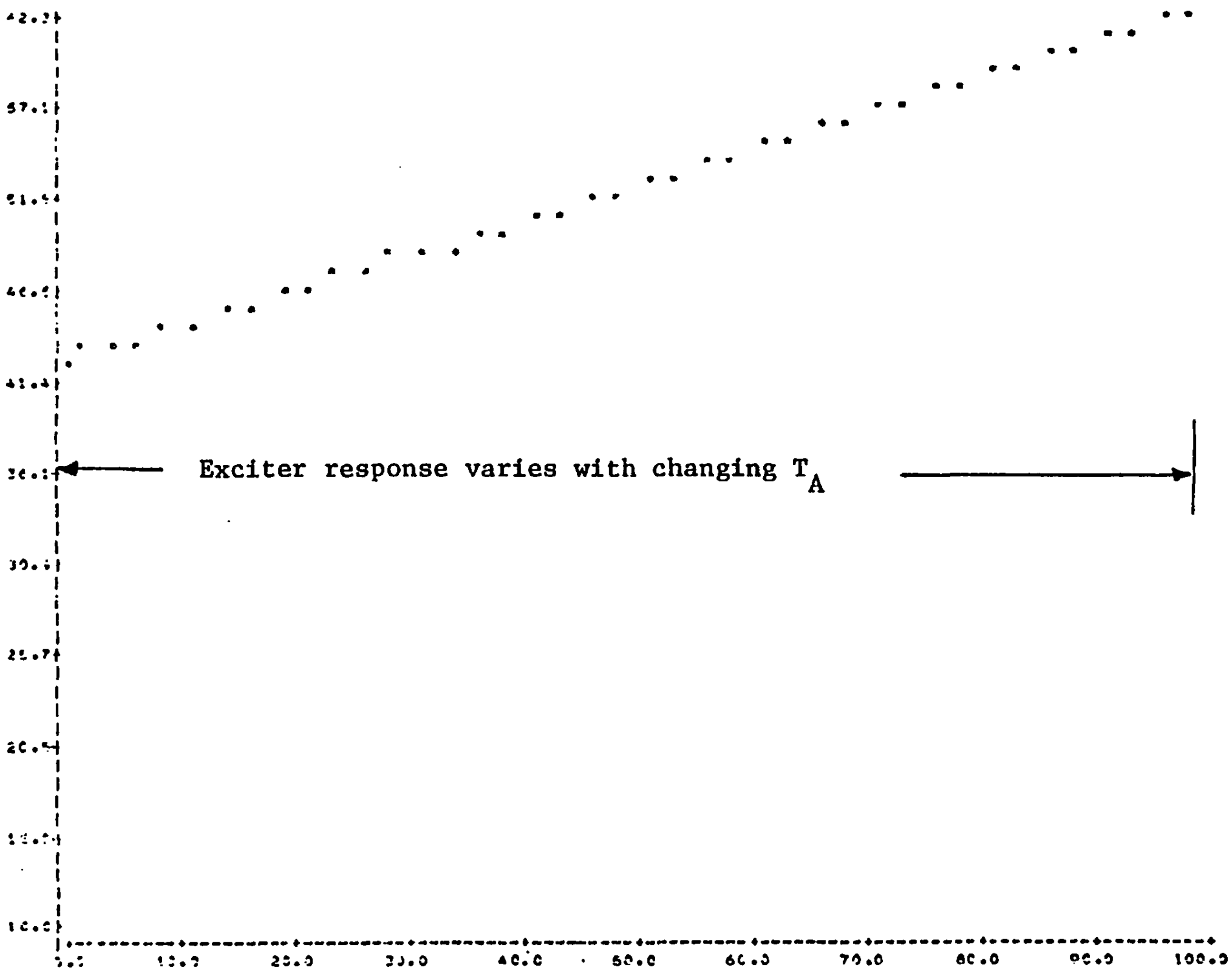
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KE IS VARIED FROM .1 TO 3.5

FIGURE 3-15



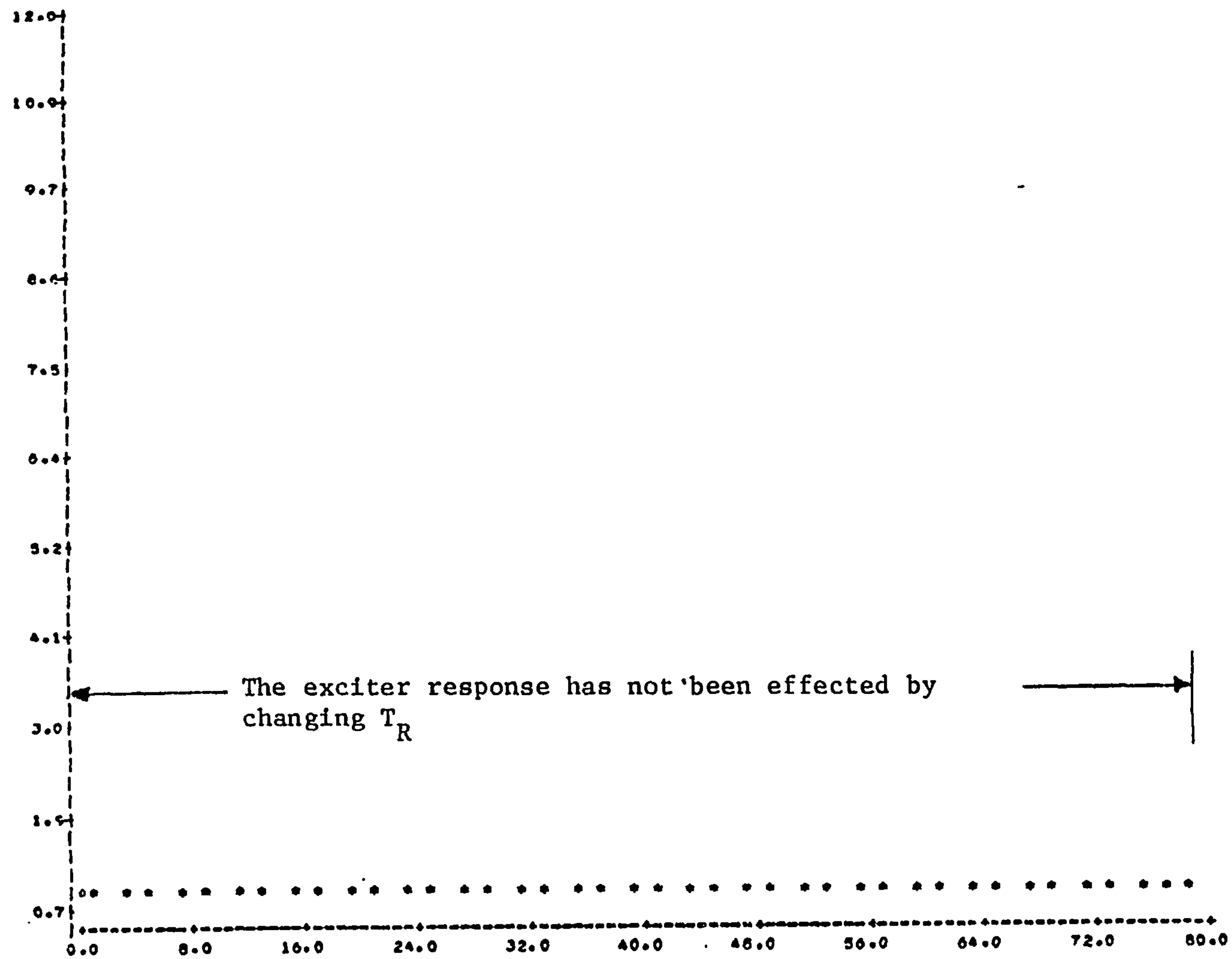
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM 0.0 TO 1.

FIGURE 3-16



Y SCALE FACTOR USED IS 1.0E 00

X SCALE FACTOR USED IS 1.0E-03

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08

FIGURE 3-17

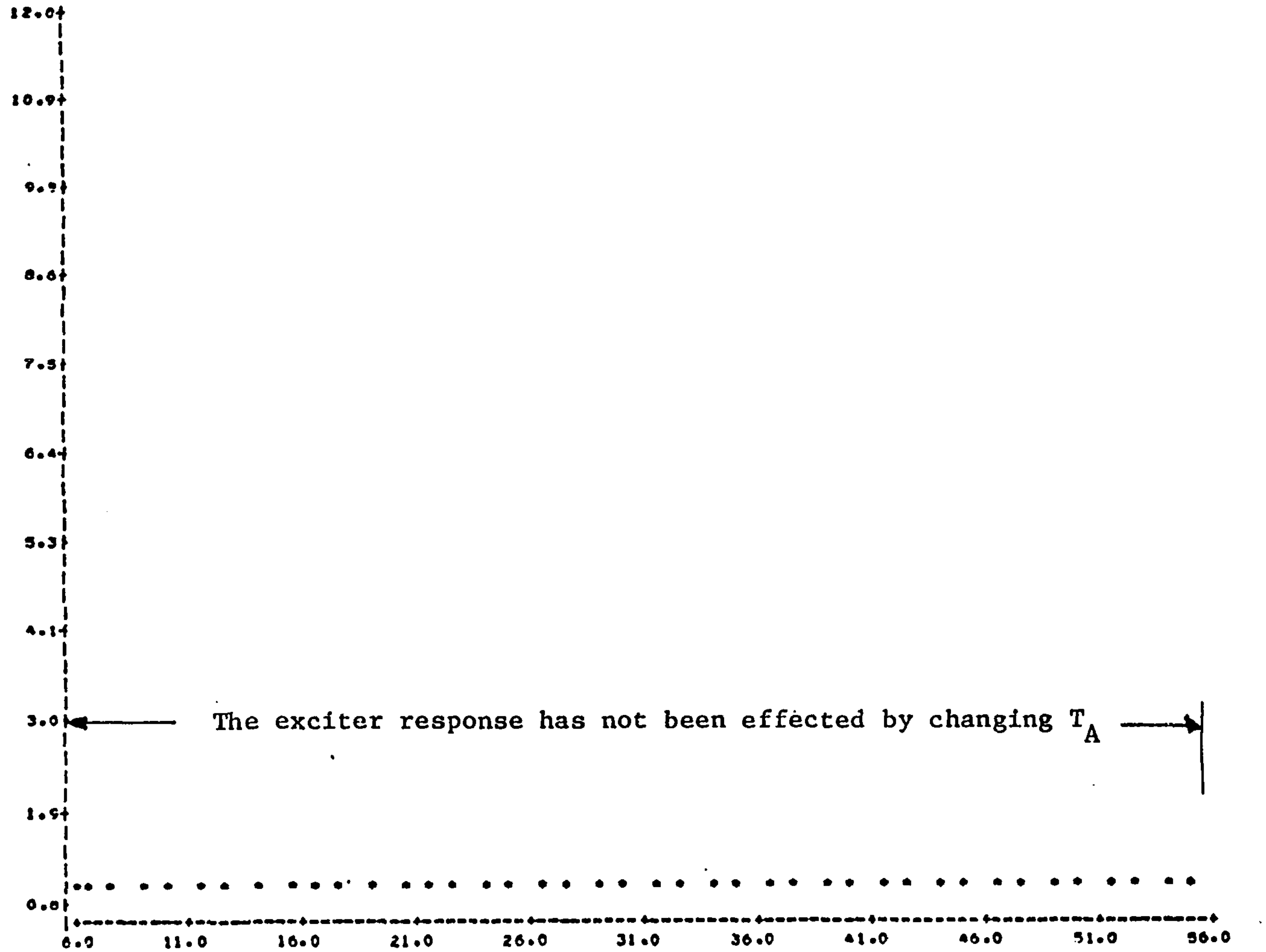
nature design of a small value, abundant on its effect of the exciter system's behavior.

Figure (3-18) shows the behavior of the exciter model, type III, upon changing the regulator amplifier time constant, T_A. Looking to the figure, the regulator amplifier time constant does not effect the exciter response in this model, while it does show a slight effect on the previous two models. Appendix B shows the differences between type II and type III which is why we have a different result. Figure (3-19) shows the behavior of the exciter model, type III, upon changing the feedback time constant, T_F. This figure shows that the system time constant does not change under changing the feedback time constant, T_F. Thus, all three models show that the system time constant does not change under changing feedback time constant, T_F, for the same reason stated previously.

The behavior of the exciter model, type III, upon changing the regulator gain parameter, K_A, is shown in figure (3-20). Upon changing the value of K_A the system time constant does show a change at the first portion of the curve while it became steady at the rest of it. So, the exciter output is sensitive to the smaller value of K_A. K_A shows the same behavior with all three models.

Figure (3-21) shows the behavior of the exciter model, type III, upon changing the feedback gain parameter, K_F. The system time constant decreases exponentially with the increase of the gain parameter, K_F. this is because of the nature values of the data set assigned to the exciter system of this model.

Figure (3-22) shows the behavior of the exciter model, type III, upon changing the exciter time constant, T_E. The exciter time constant

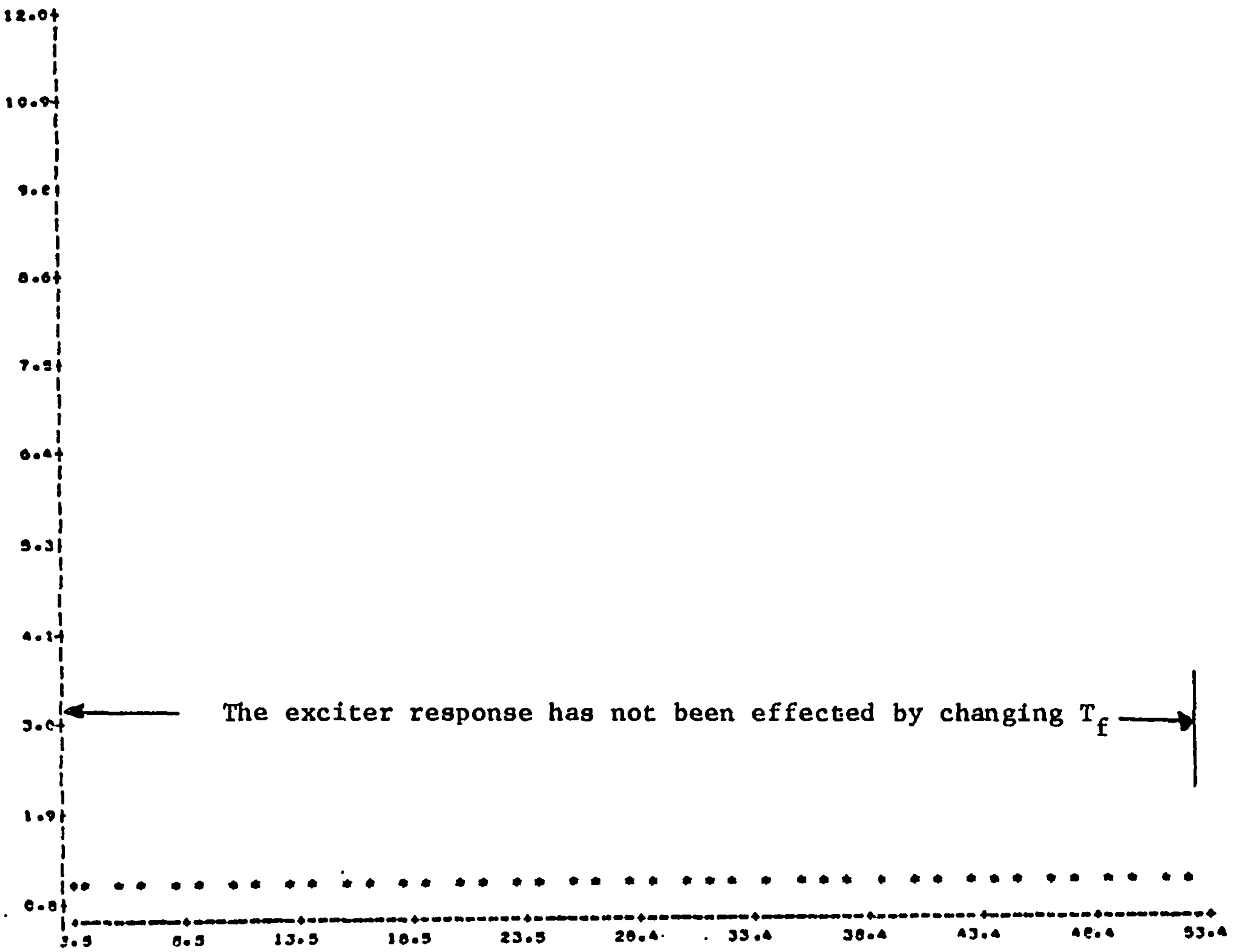


Y SCALE FACTOR USED IS 1.0E 00 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM .0 TO .5

FIGURE 3-18

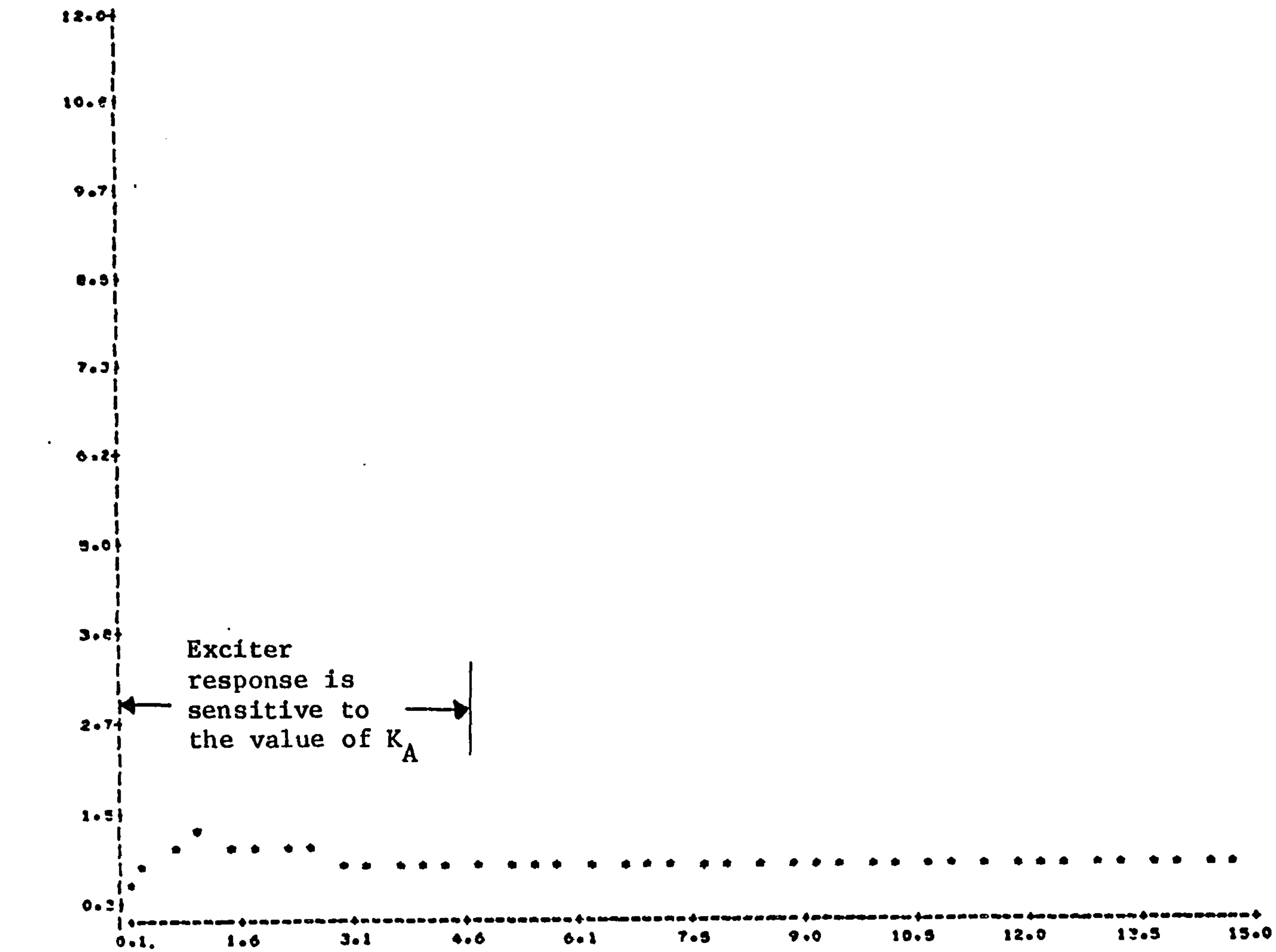


Y SCALE FACTOR USED IS 1.0E 00 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO 5.0

FIGURE 3-19

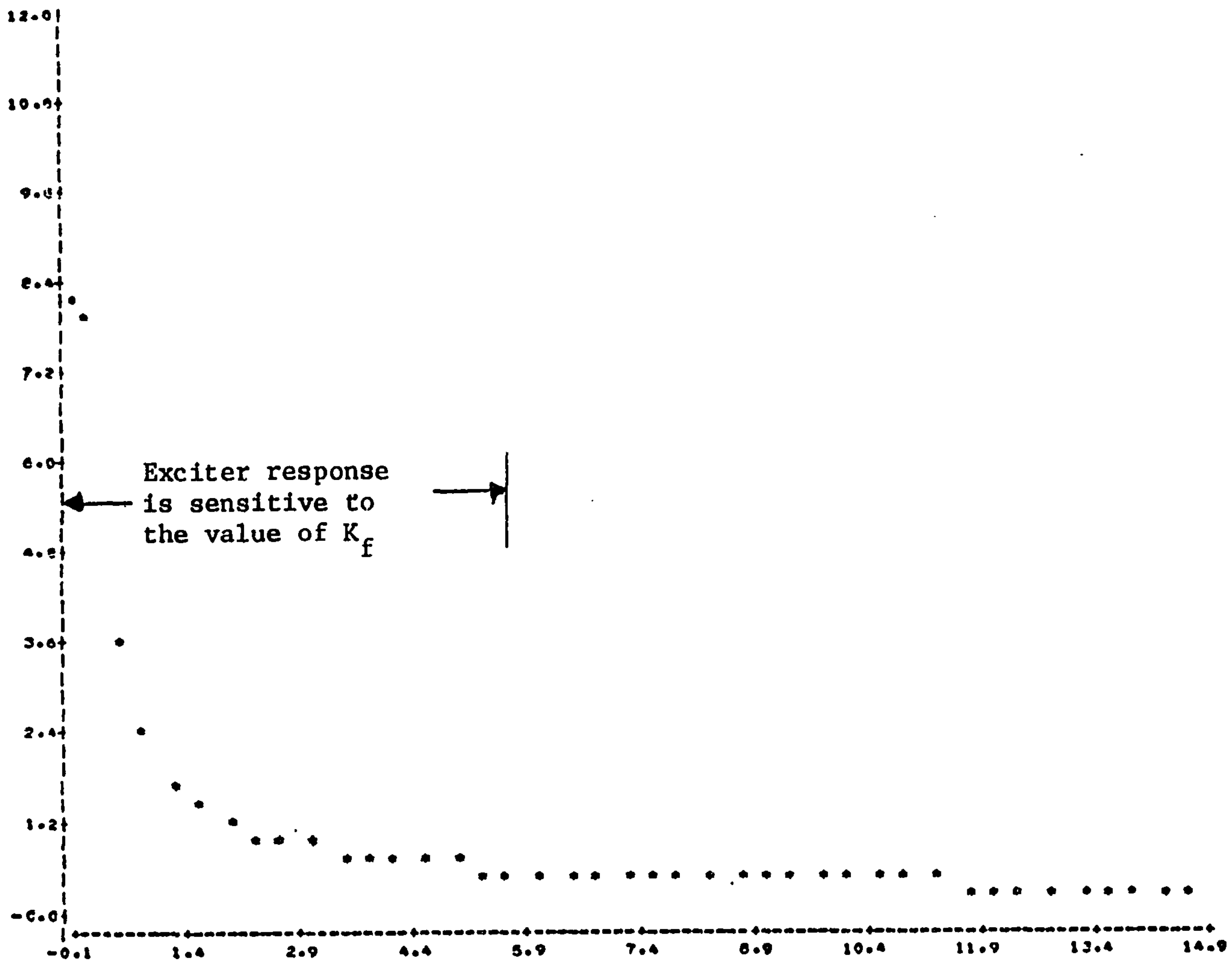


Y SCALE FACTOR USED IS 1.0E 00 X SCALE FACTOR USED IS 1.0E 01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.0 TO 150.

FIGURE 3-20

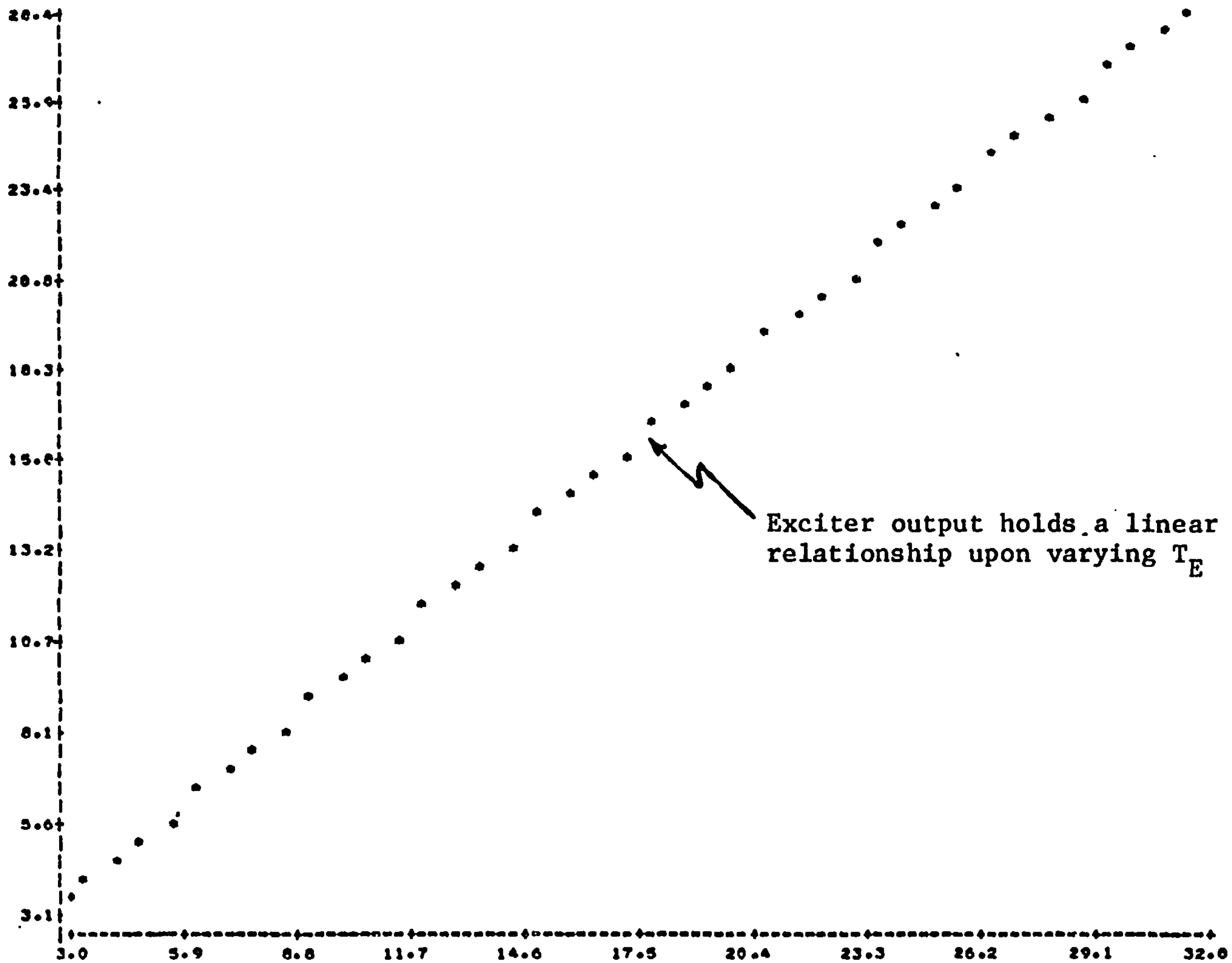


Y SCALE FACTOR USED IS 1.0E 00 X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KF IS VARIED FROM .01 TO .3

FIGURE 3-21



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO 5.0

FIGURE 3-22

is the one most dominated by the exciter response, as seen in the figure that a linear relationship does exist between them. Also, the fact of its value makes it play a strong role on the characteristic equation.

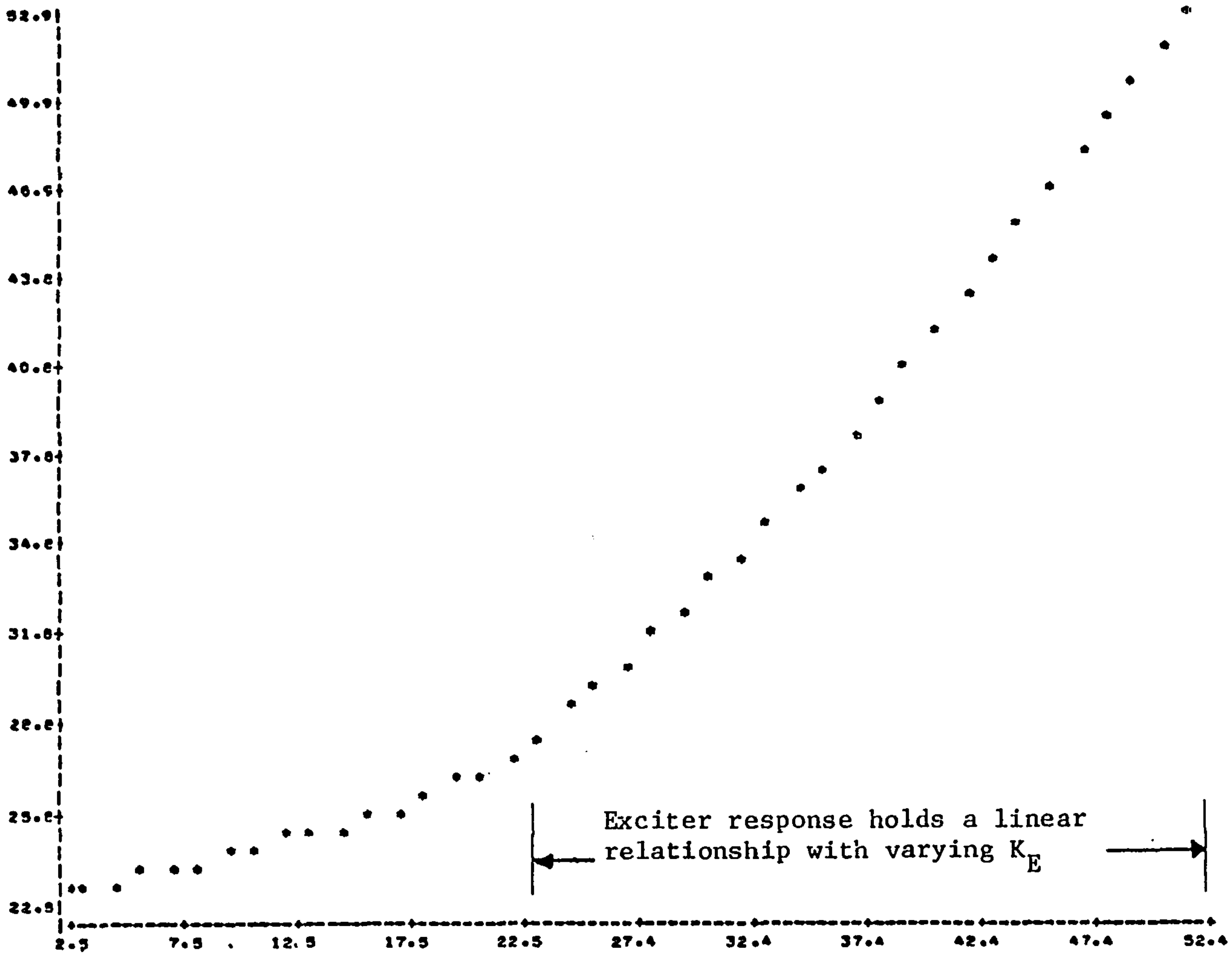
Figure (3-23) shows the behavior of the exciter model, type III, upon changing the exciter gain parameter, K_E. Again the exciter gain parameter is the one most dominated by the exciter response. It almost has a linear relationship with the exciter response. It plays a very strong role in the characteristic equation of the exciter system under the assumption that nonlinearity does not exist.

3-5 Exciter Type IV

Figure (3-24) shows the behavior of the exciter model, type IV, upon changing the exciter time constant, T_E. Again T_E has a linear relationship with the exciter response. This is reflected in its importance on the characteristic equation of the exciter system. K_E shows a linear relationship of this model too. The conclusion is that T_E and K_E are the most important parameters of the excitation system for all model types.

3-6 Linear Technique

The root locus technique and frequency response technique have been implemented to help in the understanding of the behavior of the exciter data. We are dealing with a nonlinear system but it is worth while to determine, for some sampling point of data, how the roots of the characteristic equation of a given system migrate about the S-plane as the parameters are varied. It is useful to see the behavior of the exciter model by adapting both root locus technique and frequency response technique.

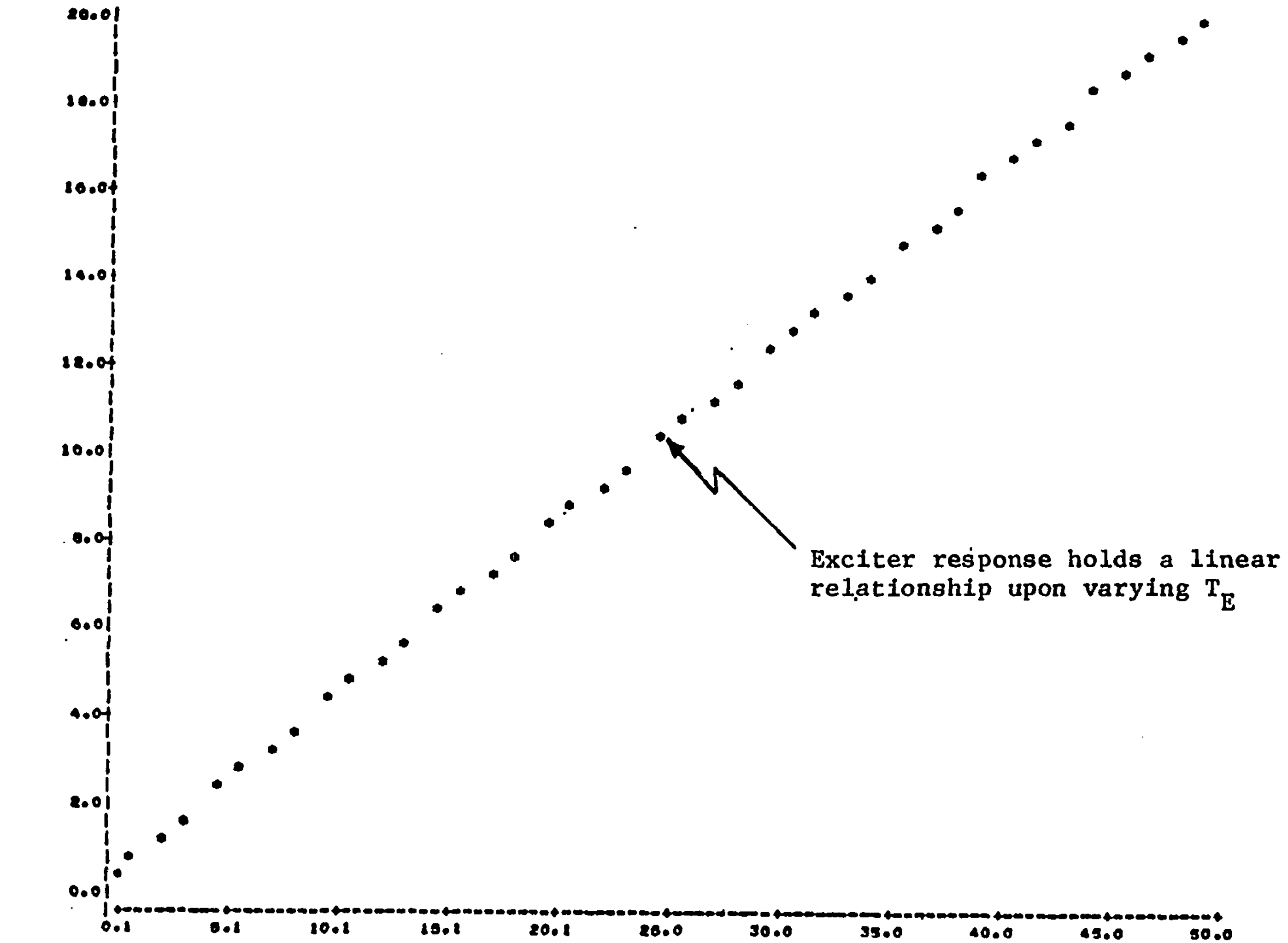


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KE IS VARIED FROM -0.1 TO 15.0

FIGURE 3-23



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 4 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO 5.0

FIGURE 3-24

The root locus method provides the engineer with a measure of the sensitivity of the roots of the characteristic equation to a variation in the parameter being considered.[13,14] Hence, it leads us to see the system performance of a relative stability of the excitation system.

Computer facilities provided us with the solution of the above technique.[15] Another approach to test the relative stability of a system is the frequency response method. The advantage of it is the availability of sinusoidal test signals for a different range of frequencies and amplitudes of any given transfer function. Computer facilities provided us with the solution of this technique.[15] The close and open loop transfer function of the excitation system are (for the first and second type) in equations (3-1), (3-2), (3-3), and (3-4).

The close loop transfer function of the exciter type I is shown in equation (3-1).

$$\frac{E_{fd}}{\Delta vt} = \frac{K_A\,(1 + S\,T_f)}{S^3 T_E\,T_A\,T_F + S^2\left[(K_E + S_E)\,T_A\,T_F + T_E(T_F + T_A)\right] + S\left[(T_F + T_A)\,(K_E + S_E) + T_E + K_A\,K_F\right] + (K_E + S_E)} \qquad (3\text{-}1)$$

The open loop transfer function of the exciter type I is shown in equation (3-2).

$$GH = \frac{K_A\,K_f\,S}{(1 + S\,T_A)\,(K_E + S\,T_E + S_E)\,(1 + S\,T_f)} \qquad (3\text{-}2)$$

The close loop transfer function of the exciter type II is shown in equation (3-3).

$$\frac{E_{fd}}{\Delta vt} = \frac{K_A (1 + T_f S)^2}{T_E T_f^2 T_A S^4 + S^3 \left[T_f^2 T_A (K_E + S_E) + T_E T_f^2 + 2T_f T_E T_A\right] + S^2 \left[T_f^2 (K_E + S_E) + 2T_f T_A (K_E + S_E) + 2T_f T_E + T_A T_E + K_f T_E K_A\right] + S \left[2 T_f (K_E + S_E) + T_A (K_E + T_E) + T_E + K_f K_E K_A + S_E K_A K_f\right] + (K_E + S_E)} \tag{3-3}$$

The open loop transfer function of the exciter type II is shown in equation (3-4).

$$GH = \frac{S K_A K_f}{(1 + T_f S)^2 (1 + S T_A)} \tag{3-4}$$

Figure (3-25) shows the root locus of exciter type I behavior of a given value of the exciter parameter. There are three poles and one Zero located at S-plane with the Zero located at the value S = 0.0. Therefore, the segment of the root locus exists on the real axis between S = 0.0 and S = -1.0 in which is the first loci. The second segment of the root locus exists on the real axis between S = -2.34 until break-point, at S = -26.0, at real axis and then it goes to positive infinity which is the second loci. The third segment of the root locus exists on real axis between S = -50.0 until the breakpoint, at S = -26.0, at real axis and goes to negative infinity which is the third loci. The arrow shows the direction of loci in the curve. Fourteen different sets of data have been conducted. These data have been already used on C.S.M.P. simulation, on exciter model type I. It has been found that as the exciter parameter increases incrementally, it has resulted in a breakpoint in-

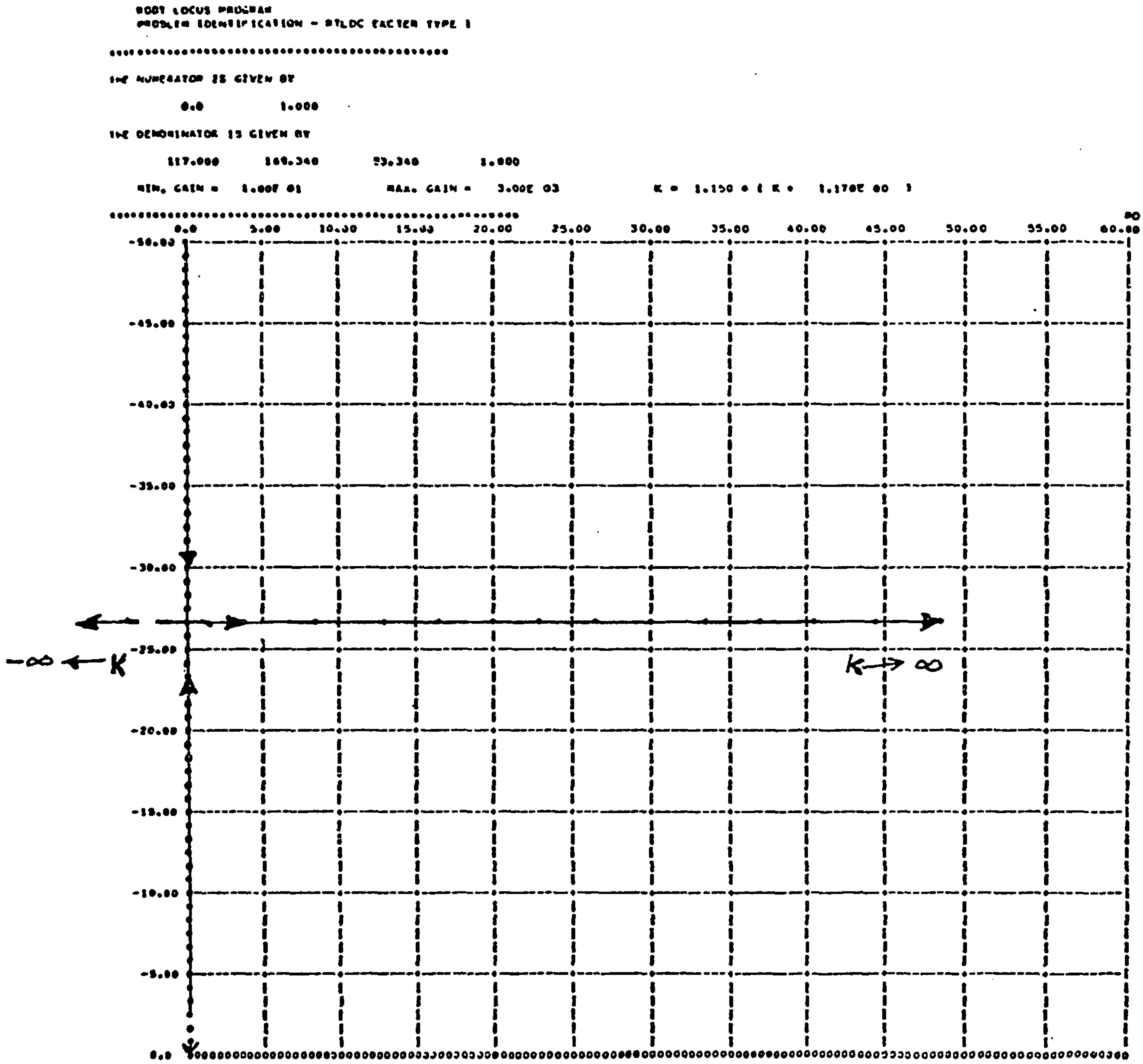


FIGURE 3-25
ROOT LOCUS OF EXCITER TYPE I

crease too. The loci breakpoint is varying from S = -26 to S = -10 at the real axis. This shows that as the exciter parameter values increase, they become more dominant. Exciter model type I is stable in the sense of root locus analysis in which all loci at the left side of the S-plane satisfies the stability condition. The slower response has dominated the characteristic equation of the model, while the faster response has had a less effect on the characteristic equation of the exciter model.

Figure (3-26) and (3-27) show the Bode Diagram of the exciter model type I behavior of a given data set of exciter parameters. The gain and phase margin are easily evaluated from the Bode diagram. The critical point for stability is $\mu = -1$, $\gamma = 0$ in which the $GH(j\omega)$ plane, which is equivalent to a logarithmic magnitude of 0db and phase angle of 180° in the Bode diagram. Figure (3-26) and (3-27) represent the results of an assigned data set; this data set has been used in C.S.M.P. simulation of exciter model type I. It shows the phase margin is 70° while the gain margin is high. Based upon this result, the exciter model is stable. In addition, there has been fourteen data sets conducted. Also, these data sets have been used in C.S.M.P. simulation of exciter model type I. Their results were phase variance as well as amplitude of the Bode diagram. This causes the critical points to vary too. The phase margin, of fourteen data sets, is tolerated between 40° to 70° and that satisfies the stability condition. It is extremely hard to correlate the results obtained by C.S.M.P. simulation of a nonlinear system with results obtained by linear techniques although it did give a slight indication of model behavior.

FREQUENCY RESPONSE
PROBLEM IDENTIFICATION - FRESP EXCITER TYPE I

ABSCISSA - RADIAN FREQ. IN POWERS OF TEN

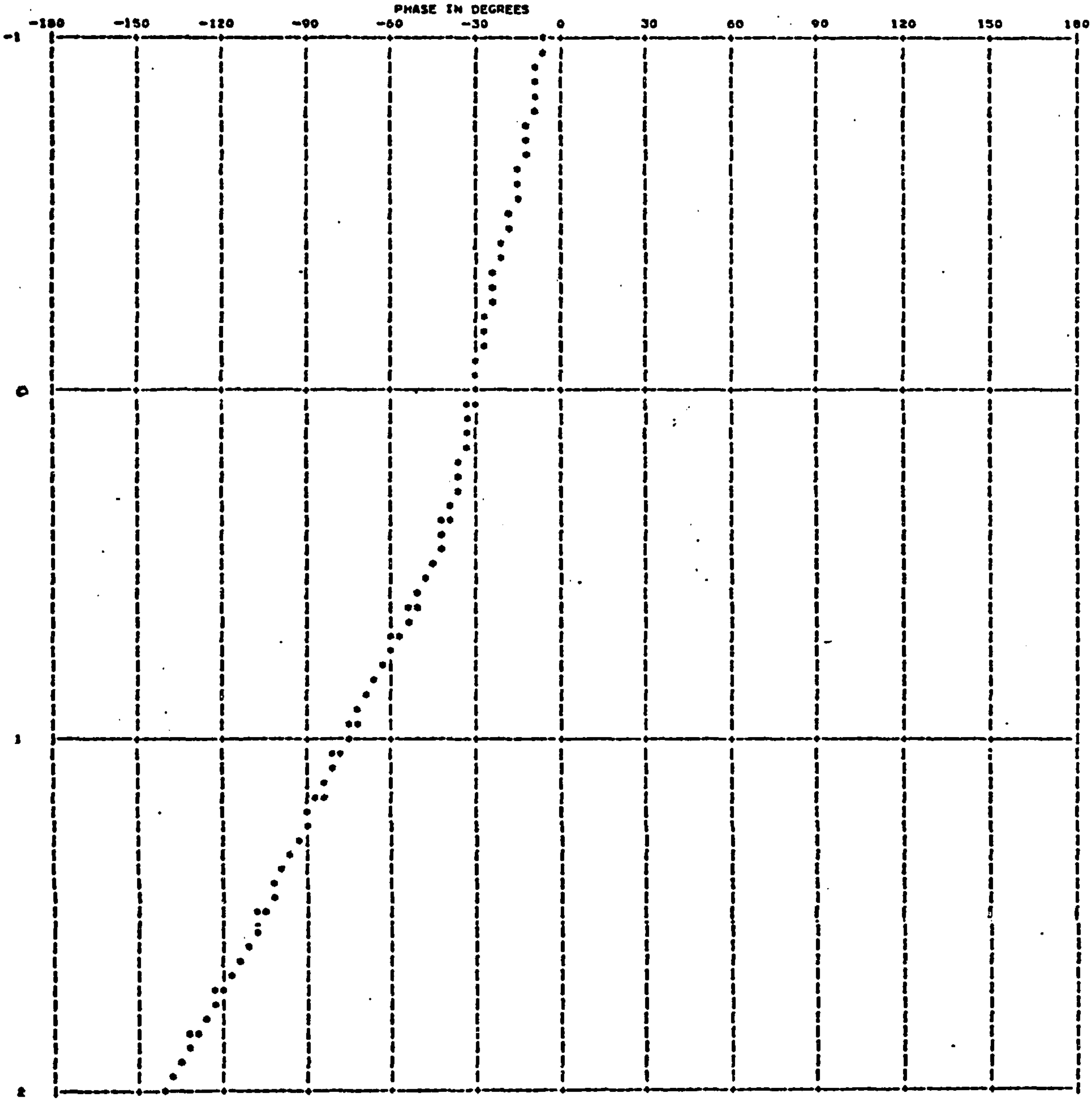


FIGURE 3-26
BODE DIAGRAM FOR EXCITER TYPE I

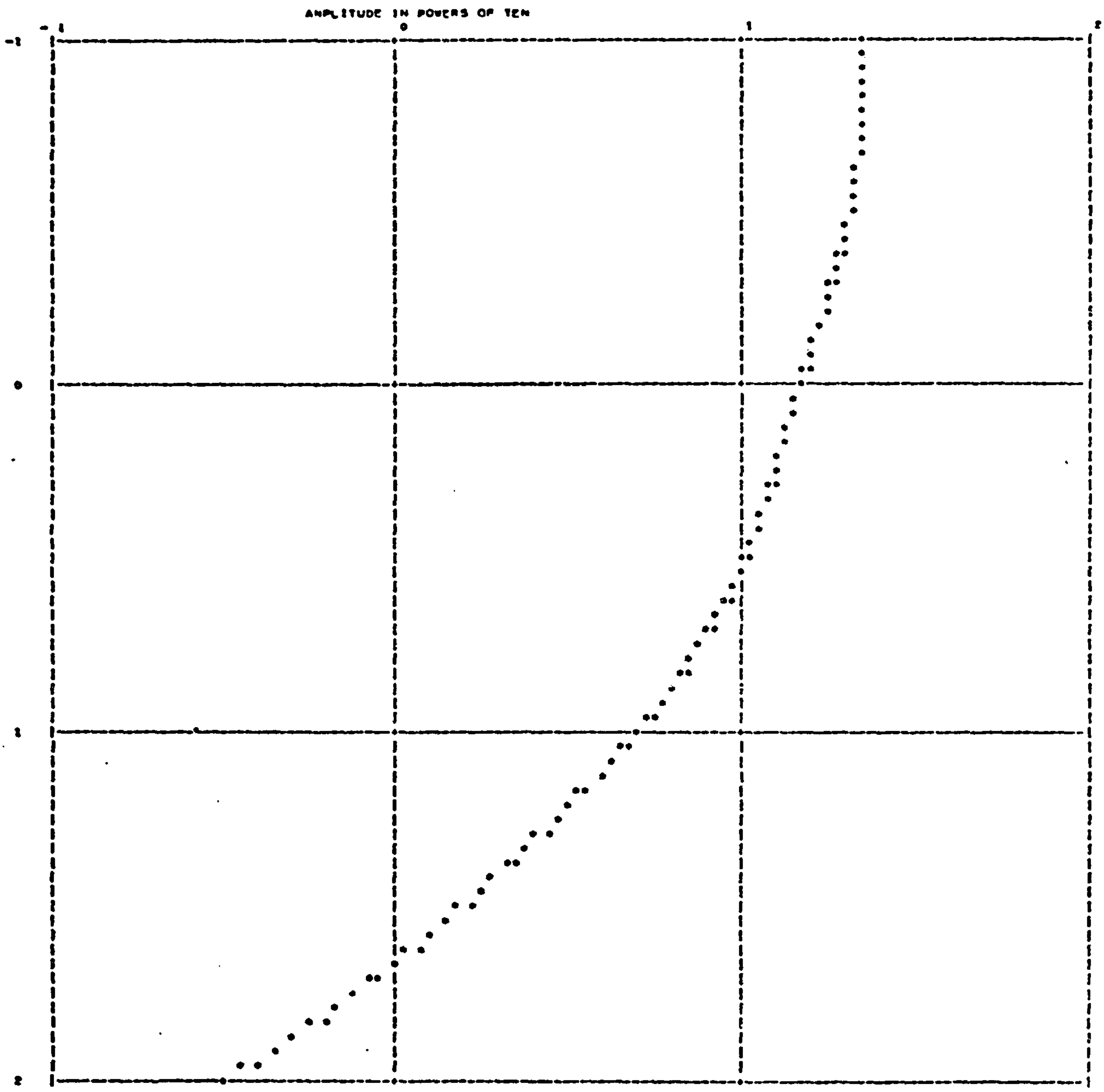


FIGURE 3-27
BODE DIAGRAM OF EXCITER TYPE I

Figure (3-28) shows the root locus of exciter type II behavior of given values of the exciter parameter. There are three poles and one Zero located at the S-plane with the Zero located at the value S = 0.0. Therefore, a segment of the root locus exists on the real axis between S = 0.0 and S = -.917 which is the first loci. The second segment of the root locus exists on the real axis between S = -.917 until breakpoint, at S = -10.5, at real axis and goes to positive infinity which is the second loci. The third segment of the root locus exists on the real axis between S = -20.0 until breakpoint, at S = -10.5, at real axis and goes to negative infinity, which is the third loci. An arrow shows the direction of loci in the curve. Fourteen different sets of data have been conducted; these data have been already used on C.S.M.P. simulation on exciter model type II. It has been found that as the exciter parameter increases incremently the resulting breakpoint increases too. The loci breakpoint varies from S = -10.5 to S = -1.25. This shows that as the exciter parameter values increase, they become more dominant. Thus, exciter model type II is stable in the sense of root locus analysis in which all loci, of the fourteen sets of data given (two of which are not stable) in the C.S.M.P. simulation program, is at the left side of the S-plane which is the necessary condition to satisfy the stability of any system. Again the slower response in exciter model type II controls the characteristic equation of the exciter system. The faster response has a less effect on the characteristic equation of the exciter model.

Figure (3-29) and (3-30) show the Bode diagram of the exciter model type II behavior of a given data set of exciter parameters. The gain and phase margin are easily evaluated from the Bode diagram. The

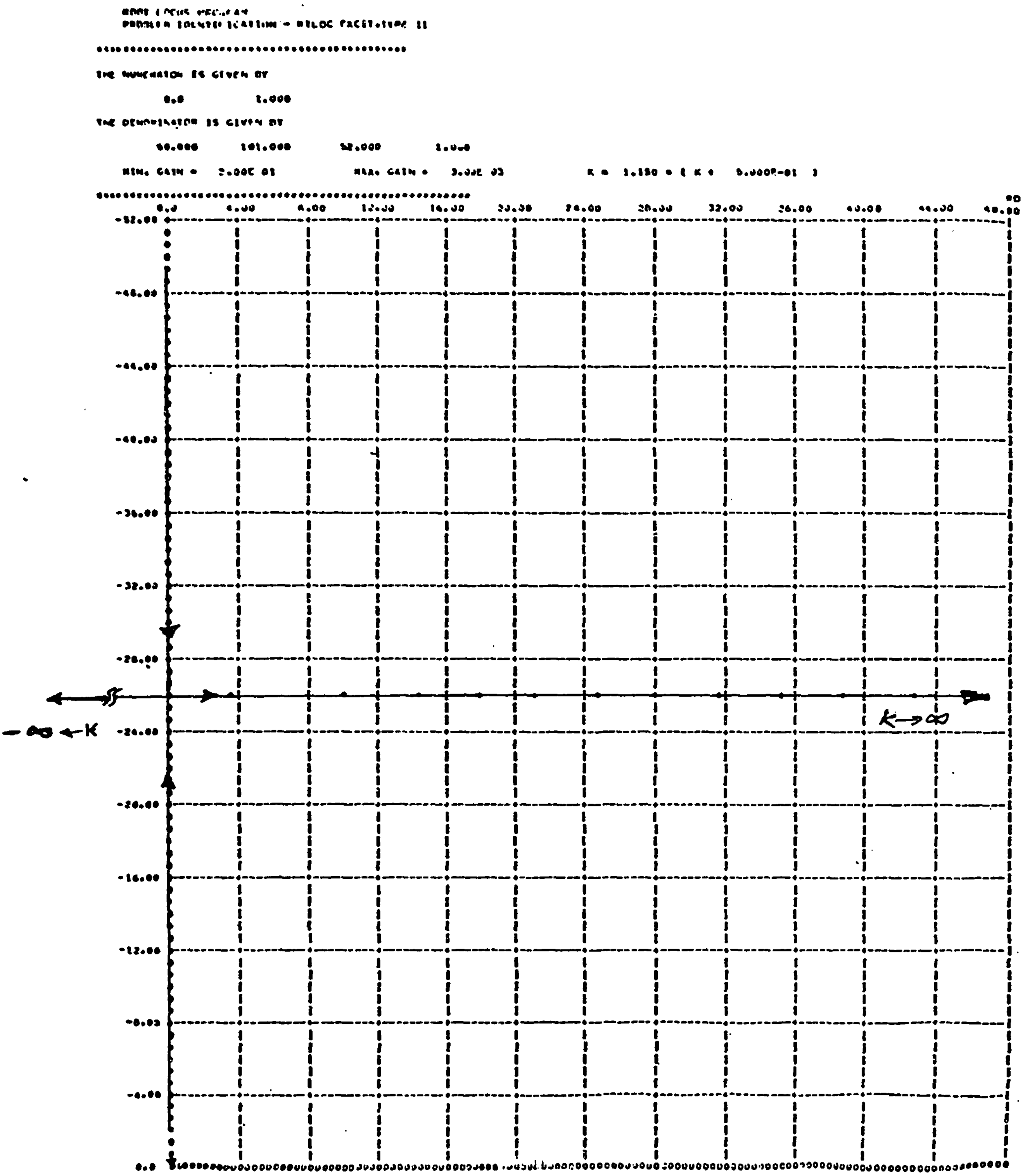


FIGURE 3-28
ROOT LOCUS OF EXCITER TYPE II

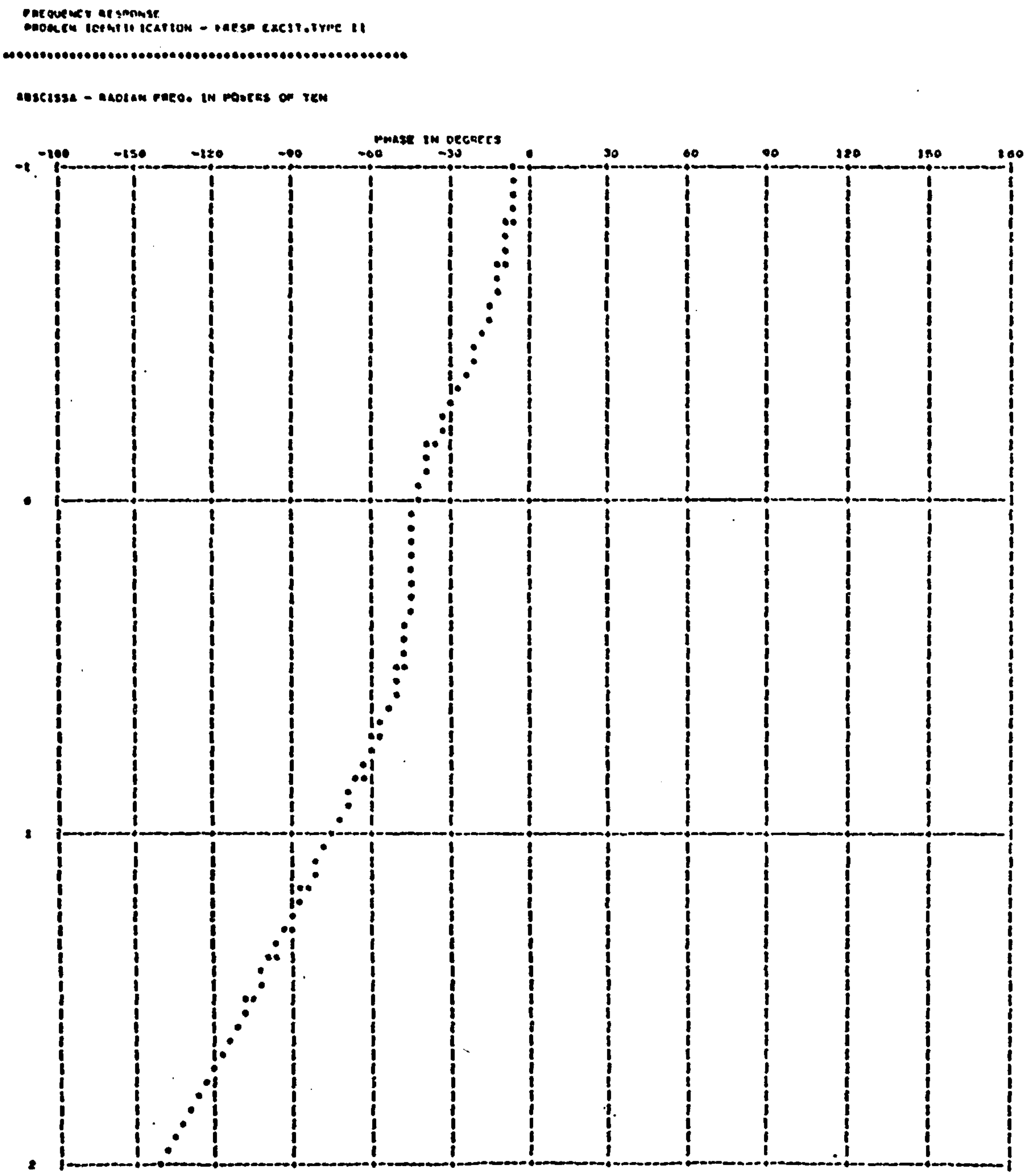


FIGURE 3-29
BODE DIAGRAM OF EXCITER TYPE II

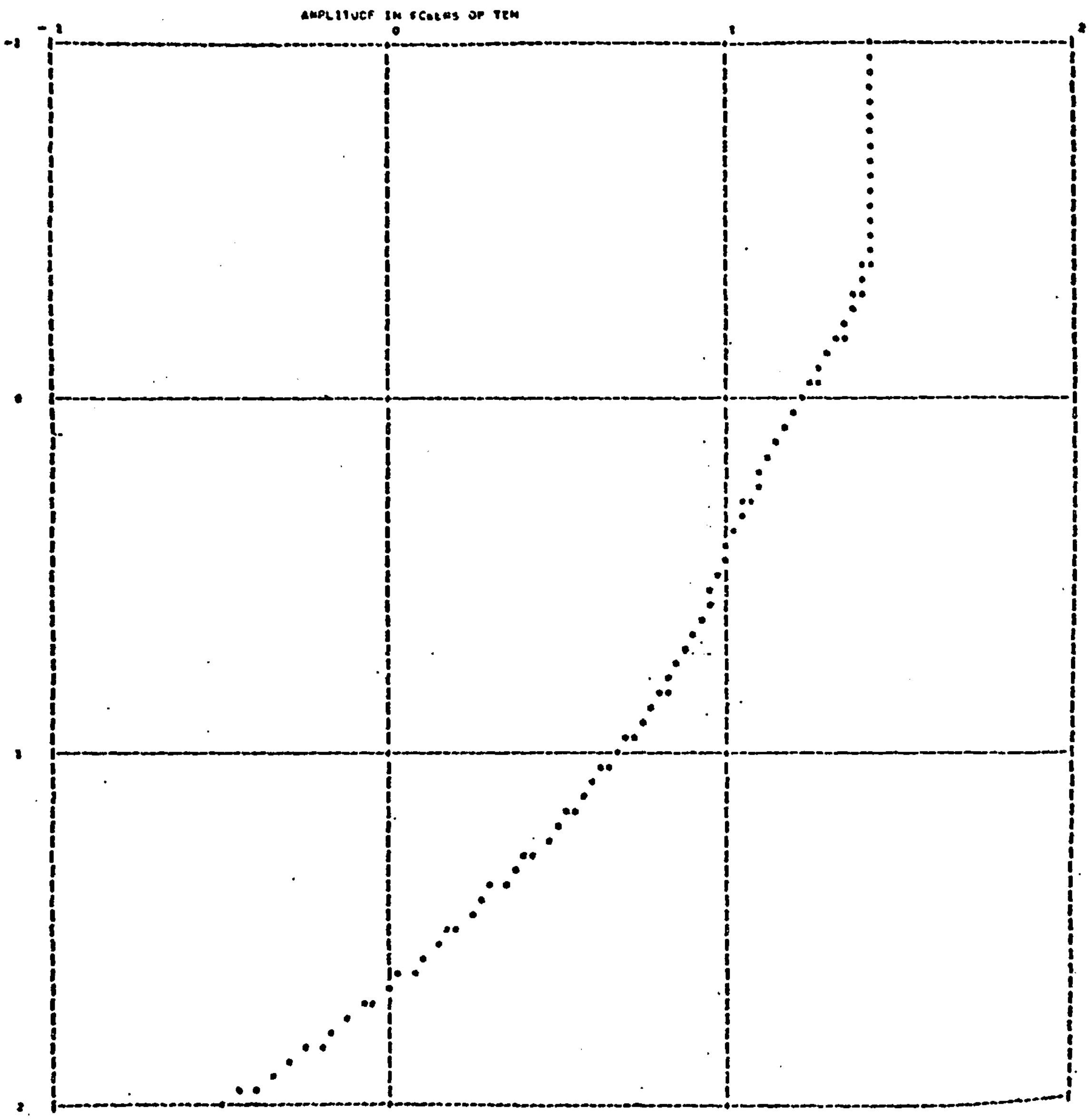


FIGURE 3-30
BODE DIAGRAM OF EXCITER TYPE II

above mentioned figures represent the results of data sets given, these data sets have been used in C.S.M.P. simulation of exciter model type II, which shows phase margin was 35^{o}. While the gain margin is high, the conclusion is that this system is stable with this data set. In addition, there has been fourteen data sets conducted. Also, these data sets have been used in C.S.M.P. simulation of exciter model type II. Their results were varied. The first two data sets show that the system is not stable because poles were located at the right hand of the S-plane. The other set shows a variance in the phase as well as an amplitude of the Bode diagram, hence this causes the critical points to vary also. The phase margin, of fourteen sets of data, is tolerated between 20^{o} and 35^{o} and that shows that the system is a less degree of stability than exciter type I. The computer output listing of this section is in Appendix D.

3-7 Introduction - Prime-Mover

The second essential part of the machine's controller is the prime-mover. It is this input that causes a speed deviation of the rotor. We need to understand the importance of the prime-mover regarding the stability study and recognition of the effect of the governor-turbine data on the system stability. Therefore, the study of the behavior of the turbine-governor model is recommended in which we are trying to see the impact of each parameter of the governor-turbine to its response. By the aid of the digital computer, C.S.M.P. package[12], it enables us to simulate the mathematical representation of the governor-turbine model. (See appendix E.) This includes the physical layout of the mechanical-hydraulic hydrogovernor and the mathematical models of the speed governing hydro system, the speed governing system for steam turbine, tandem compound double reheater, and PECO governor turbine system. The study of the behavior of the tandem compound double reheater model and the PECO governor turbine system model is the subject of this section. Listing of computer output is provided in appendix F. The program provided the results of the effect of each governor-turbine parameter variation to its response.

The governor-turbine model's behavior regarding certain given data, table (3-2), will be discussed for the tandem compound double reheater and PECO model (see appendix E).

3-8 TCDR-Type

Figure (3-31) shows the behavior of the governor-turbine model, tandem compound double reheater IEEE type (abbreviated TCDR), upon changing the speed relay time constant, T_1. The figure shows that there is not a significant change in the turbine response upon changing the speed relay time constant, T_1. This is because of the nature of the value of T_1; it is very small. Figure (3-32) shows the behavior of the governor-turbine model, TCDR, upon changing the speed governor time constant, T_2. The figure illustrates that the output is effected slightly upon changing the speed governor time constant. The output is increased upon increasing T_2. In other words, as T_2 has a larger value, it starts to dominate the loci of the system.

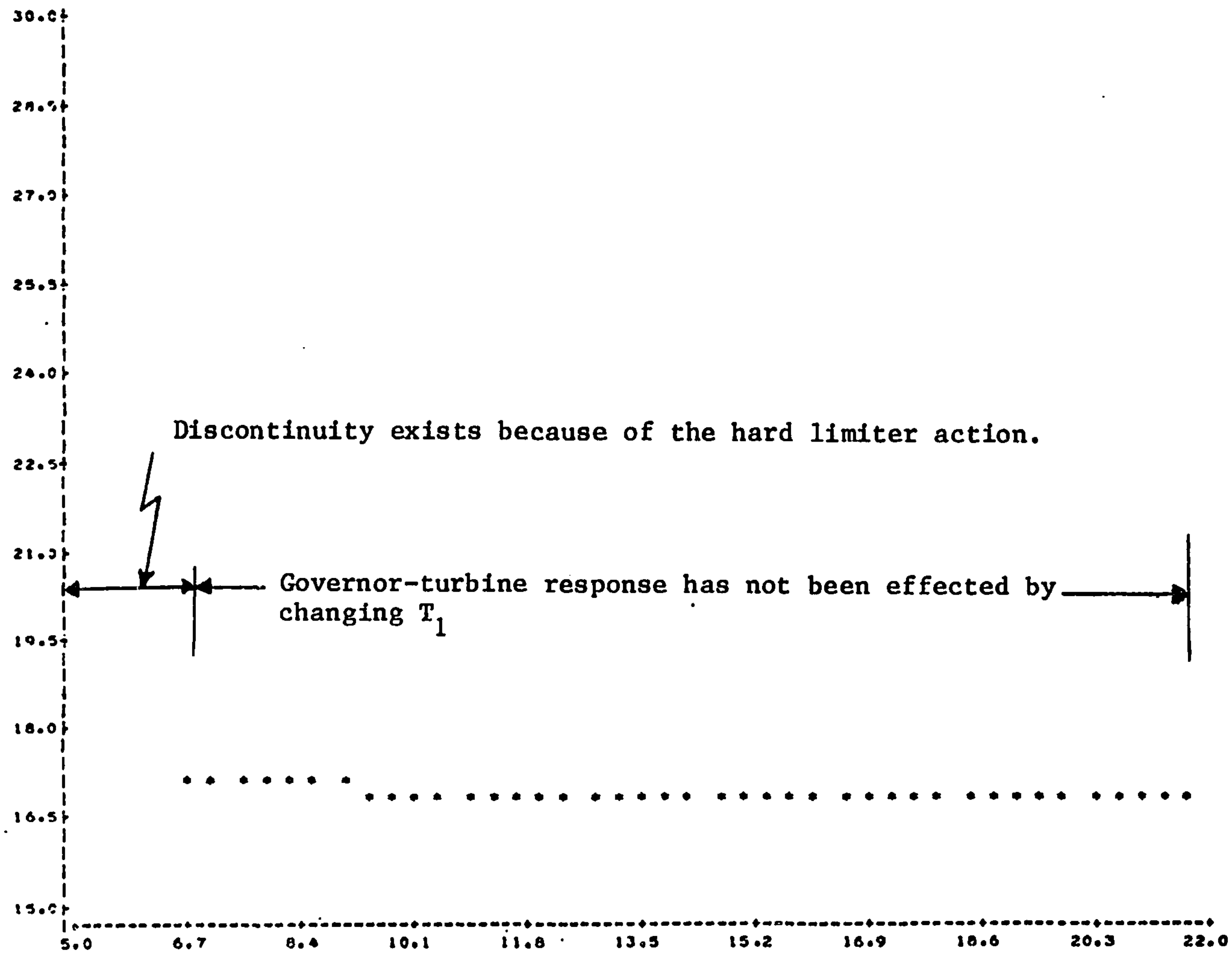
Figure (3-33) shows the behavior of the governor-turbine model, TCDR, upon changing the servo motor time constant, T_3. Again the figure shows that the output has a slight change with changing T_3. The value of this is very small, thus, its effect is apparently too small.

Parameter	PECO			TCDR		
	**	Max.	Min.	**	Max.	Min.
T_1	3.000	15.00	.050	.070	.15	0.00
T_2	5.000	15.00	.050	.125	.30	.01
T_3	.200	2.00	0.000	.125	.30	.01
T_4	.050	2.00	.050	.250	.60	.05
T_5	5.000	15.00	.000	7.000	15.00	1.00
FR	.285	-	-	-	-	-
T_{max}	-	6.87	1.335	-	-	-
T_6	-	-	-	8.500	15.00	1.00
T_7	-	-	-	.400	.99	.10
KG	-	-	-	15.000	25.00	.40
K_1	-	-	-	.220	.50	0.00
K_3	-	-	-	.220	.80	0.00
K_5	-	-	-	.300	.80	.01
K_7	-	-	-	.260	.80	.05
P_{max}	-	-	-	1.000	-	-
P_{min}	-	-	-	-1.000	-	-
Aux	-	-	-	2.000	-	-
Initp	-	-	-	6.0	-	-

**Original data

GOVERNOR AND TURBINE DATA

TABLE 3-2

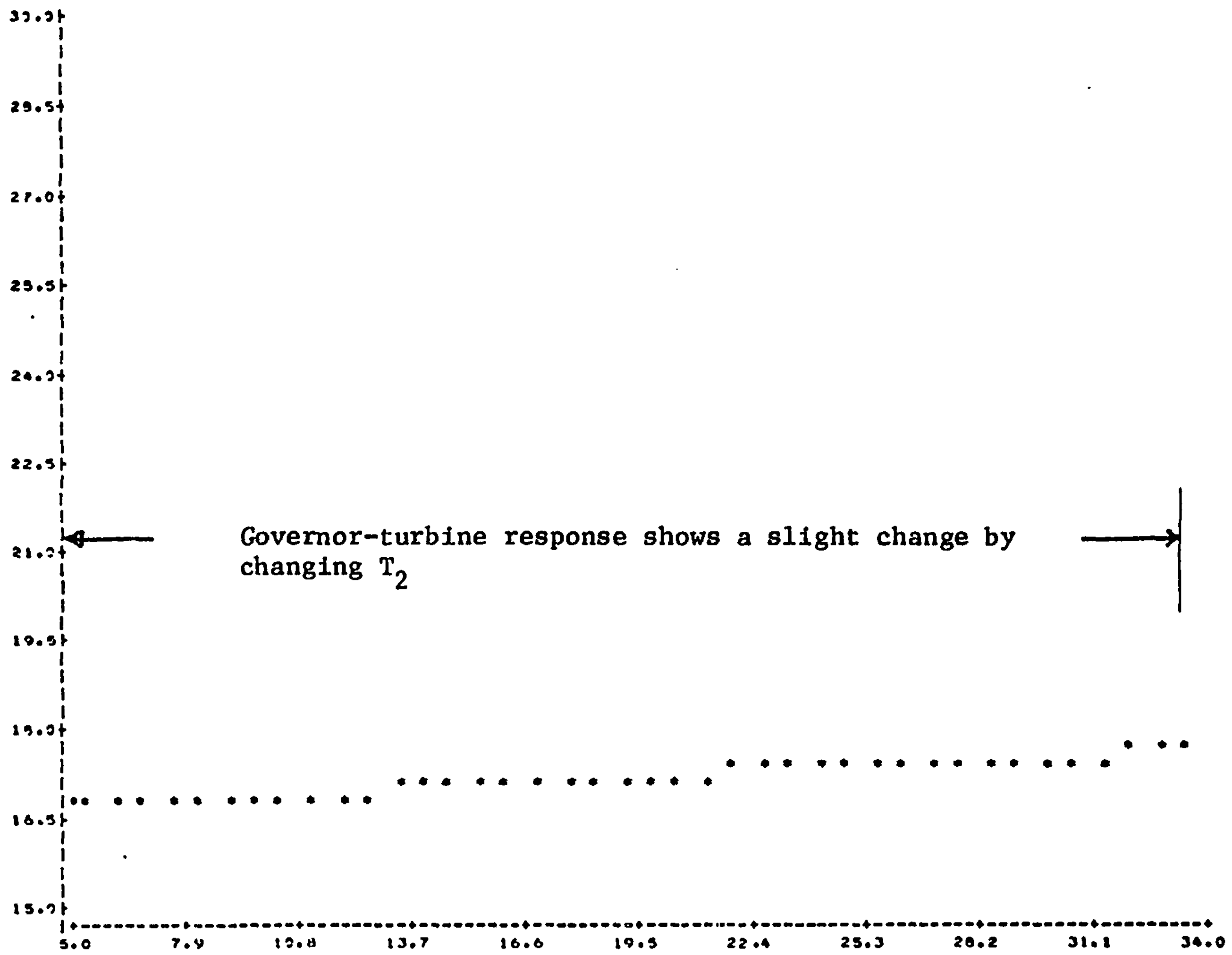


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T1 IS VARIED FROM 0.05 TO 0.15

FIGURE 3-31

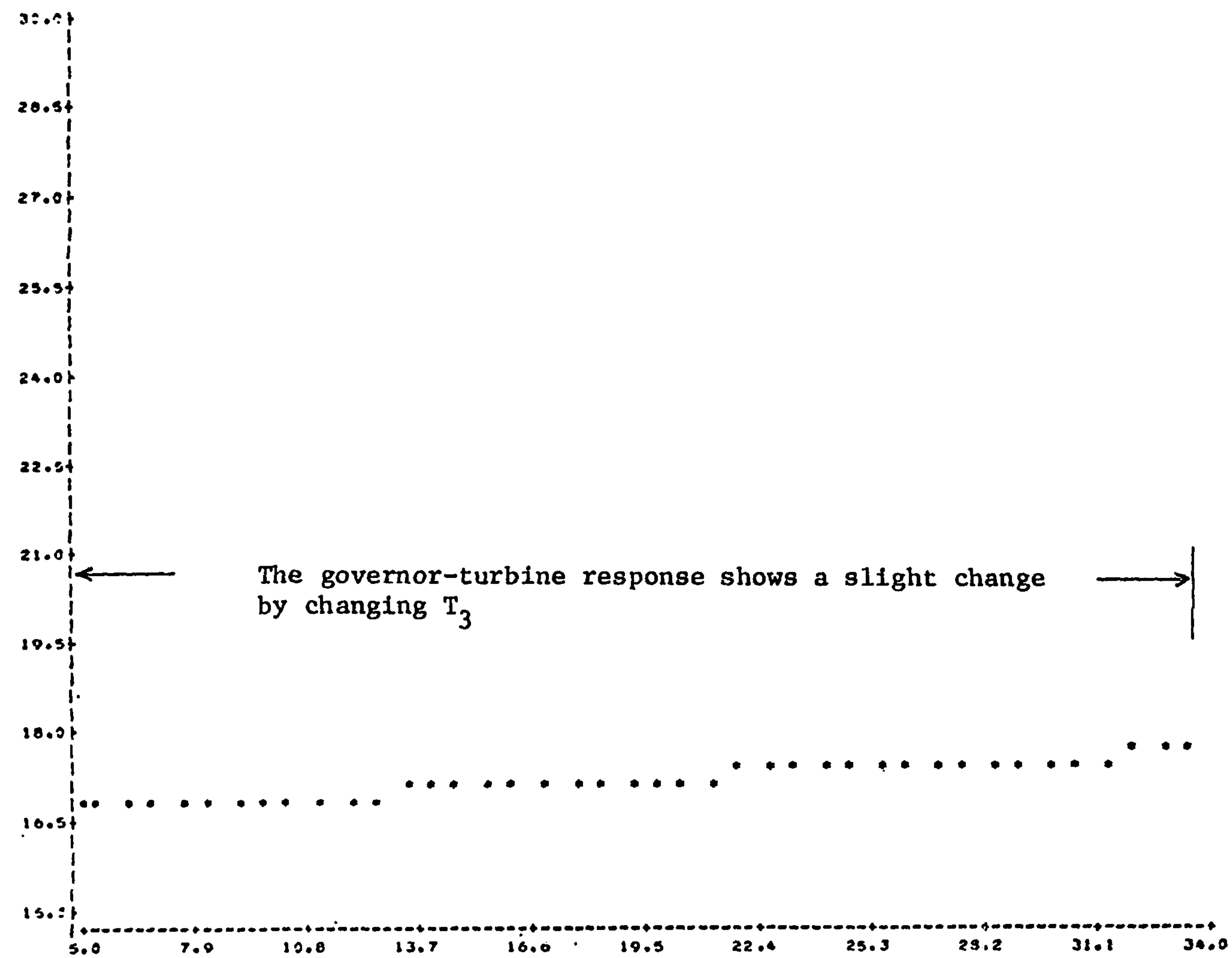


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T2 IS VARIED FROM 0.05 TO 0.2

FIGURE 3-32



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T3 IS VARIED FROM 0.05 TO 0.2

FIGURE 3-33

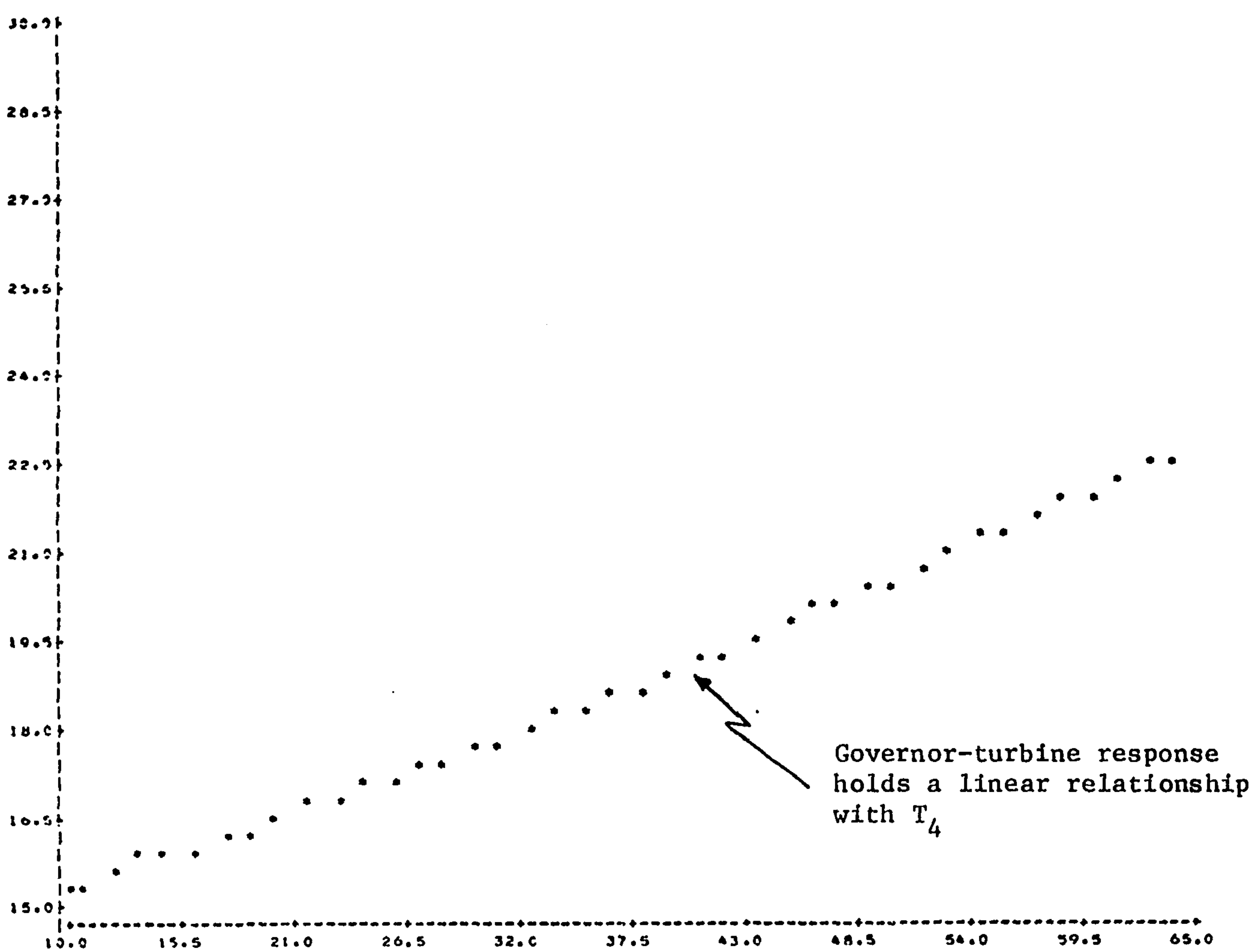
Figure (3-34) shows the behavior of the governor-turbine model, TCDR, upon changing the steam chest time constant, T_4. The figure shows that T_4 has almost a linear relationship with the output. T_4 has a larger value of the previous one and it has an effect on its characteristic equation under the assumption that the governor-turbine system is linear.

Figure (3-35) shows the behavior of the governor-turbine model, TCDR, upon changing reheat time constant, T_5. Again the figure shows that T_5 has a linear relationship with the output of the model. Its higher value is relative with the previous one. It does dominate the characteristic equation which effects the root locus.

Figure (3-36) shows the behavior of the governor-turbine model, TCDR, upon changing steady state speed regulator, K_G. Again the figure shows that K_G has a constant effect on the output of the model. The fact of its small value probably shows that there is no effect on the output of the model. Secondly, the existence of the hard limiter could have an effect of the holding of K_G effect on the output of the model.

Figure (3-37) shows the behavior of the governor-turbine model, TCDR, upon changing the limit of the hard limiter. Again the figure shows that the hard limiter variation has no significant values on the output of the model.

Figure (3-38) shows the behavior of the governor-turbine model, TCDR, upon changing the second reheat time constant, T_6. At this point there is no effect on the output of the model at the first value of T_6. But it does show a constant effect on the output of the model. This tells us that the small value of T_6 is not significant while the higher values have a significant change on the output model.

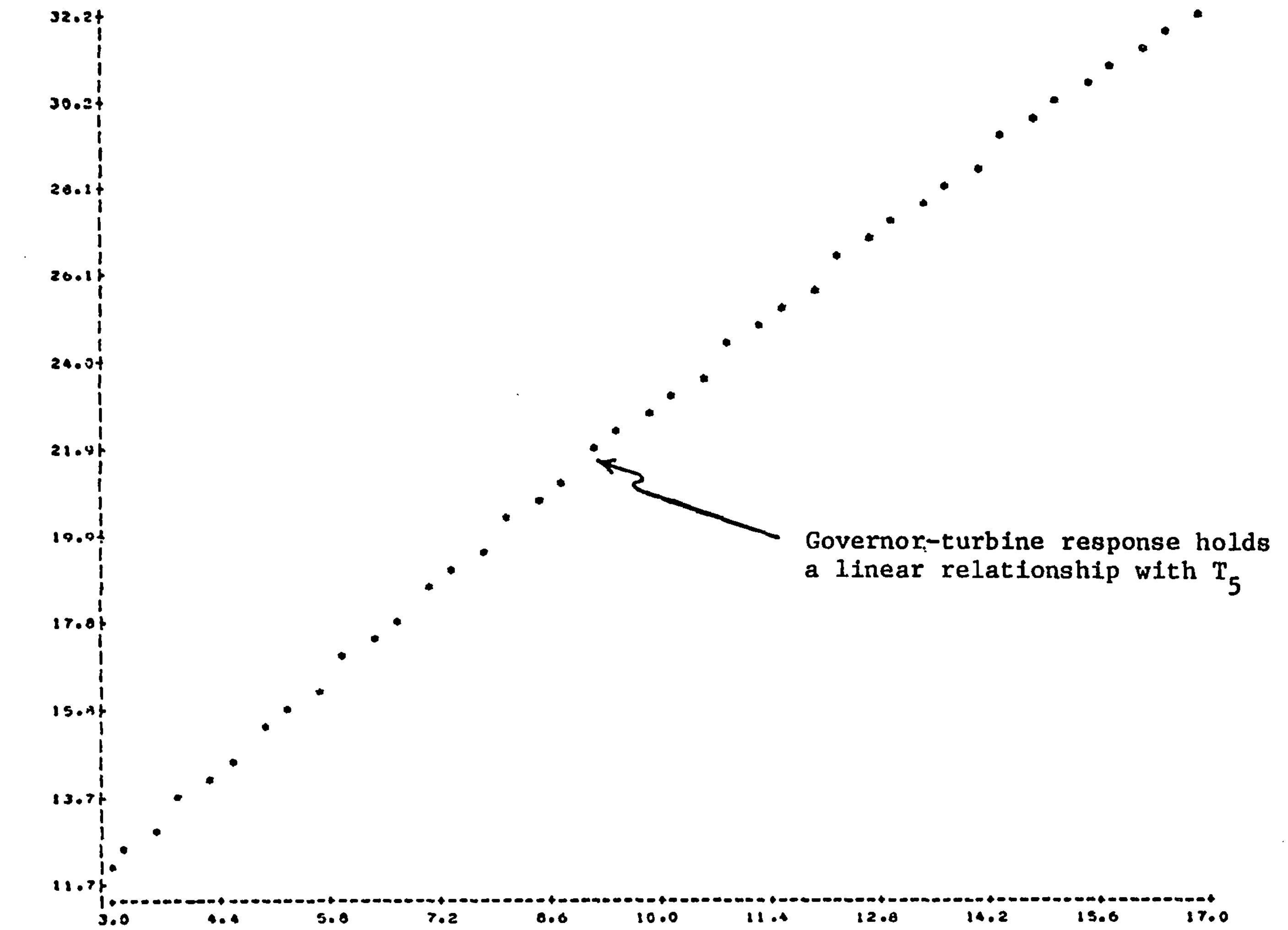


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T4 IS VARIED FROM 0.1 TO 0.6

FIGURE 3-34



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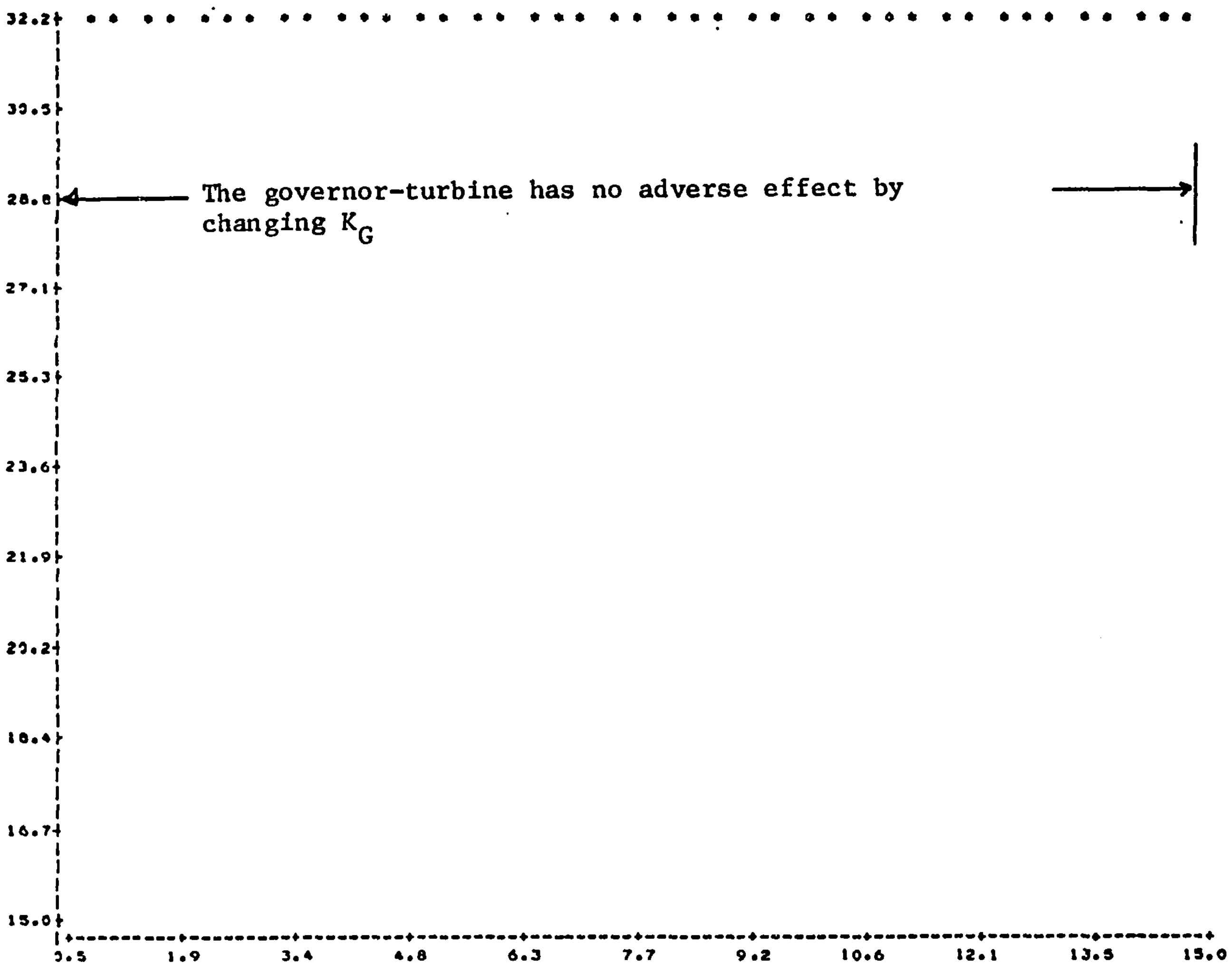
* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T5 IS VARIED FROM 3.0 TO 10.0

FIGURE 3-35



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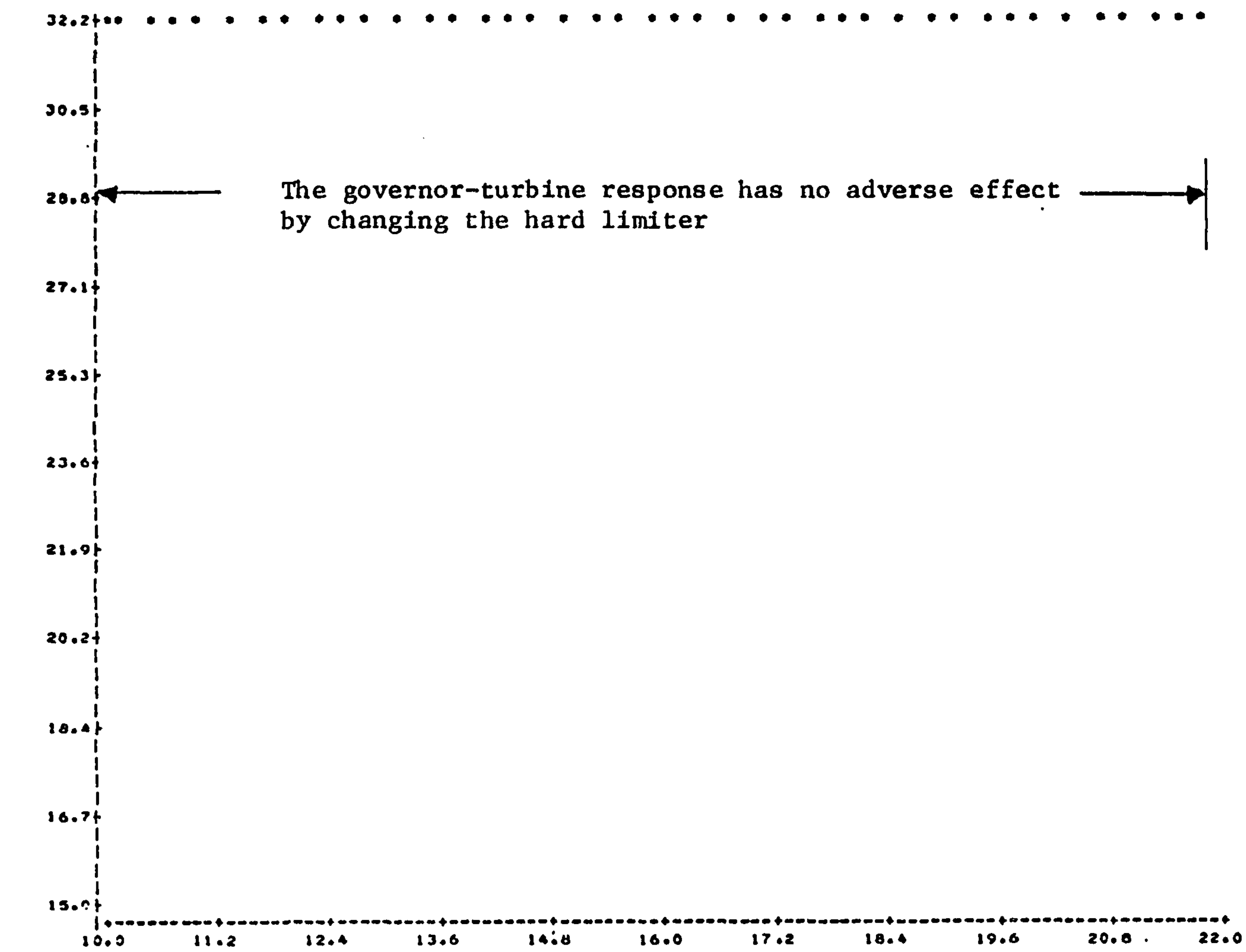
* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN KG IS VARIED FROM 0.5 TO 3.7

FIGURE 3-36

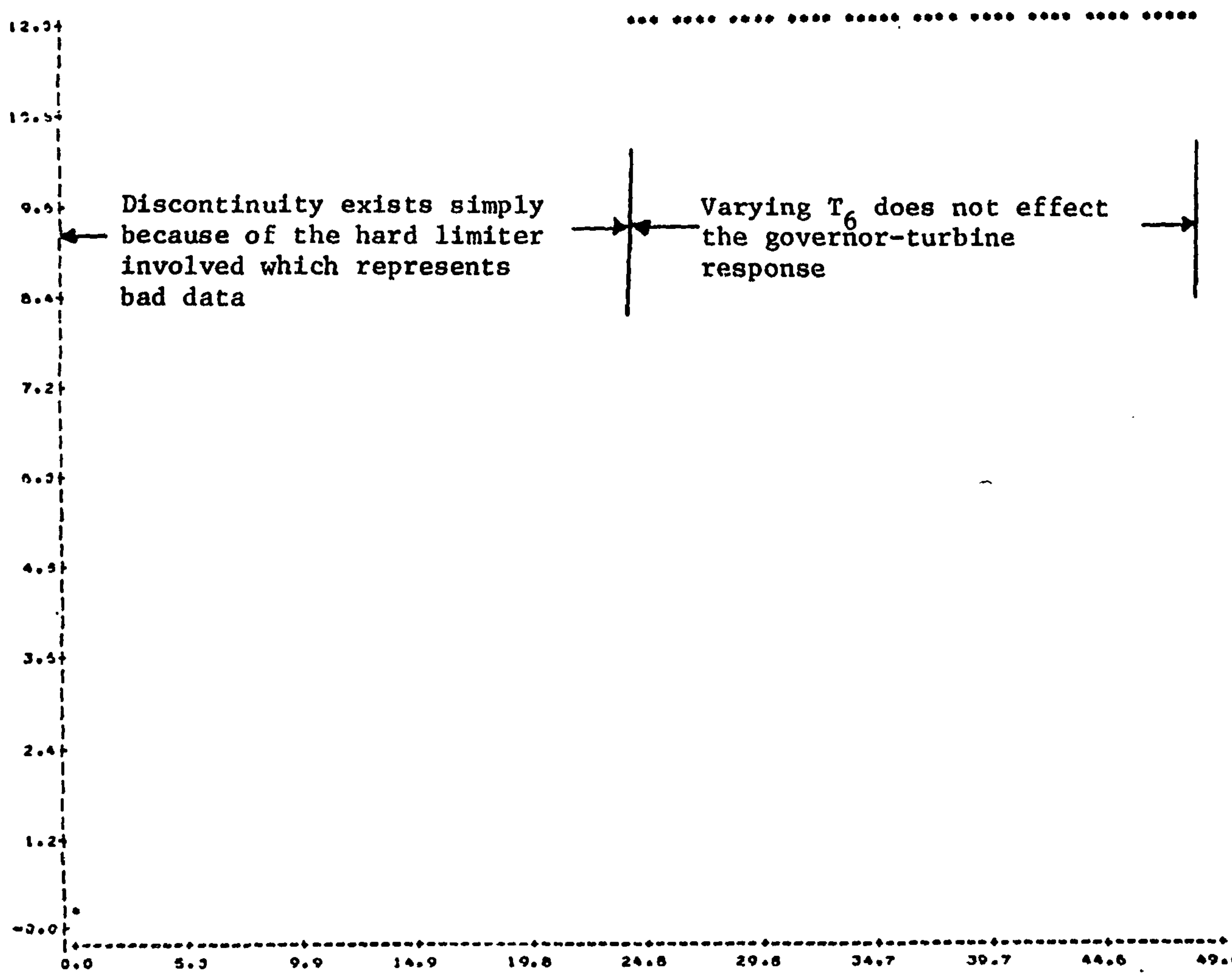


Y SCALE FACTOR USED IS 1.0E-01   X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN LIMITS OF THE HARD LIMITER ARE VARIED FROM PLUS OR MINUS 1.0 TO PLUS OR MINUS 2.0

FIGURE 3-37



Y SCALE FACTOR USED IS 1.0E-01   X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN T6 IS VARIED FROM 0.3 TO 0.7

FIGURE 3-38

Figure (3-39) shows the behavior of the governor-turbine model, TCDR, upon changing crossover time constant, T_7. The figure shows that the first portion of T_7 does not have a significant value effect on the output model while it does show an almost linear relationship with output. Thus, the small value of T_7 does not have force to drive the characteristic equation while the higher value did effect it. This implies that there is some certain degree of change in the loci.

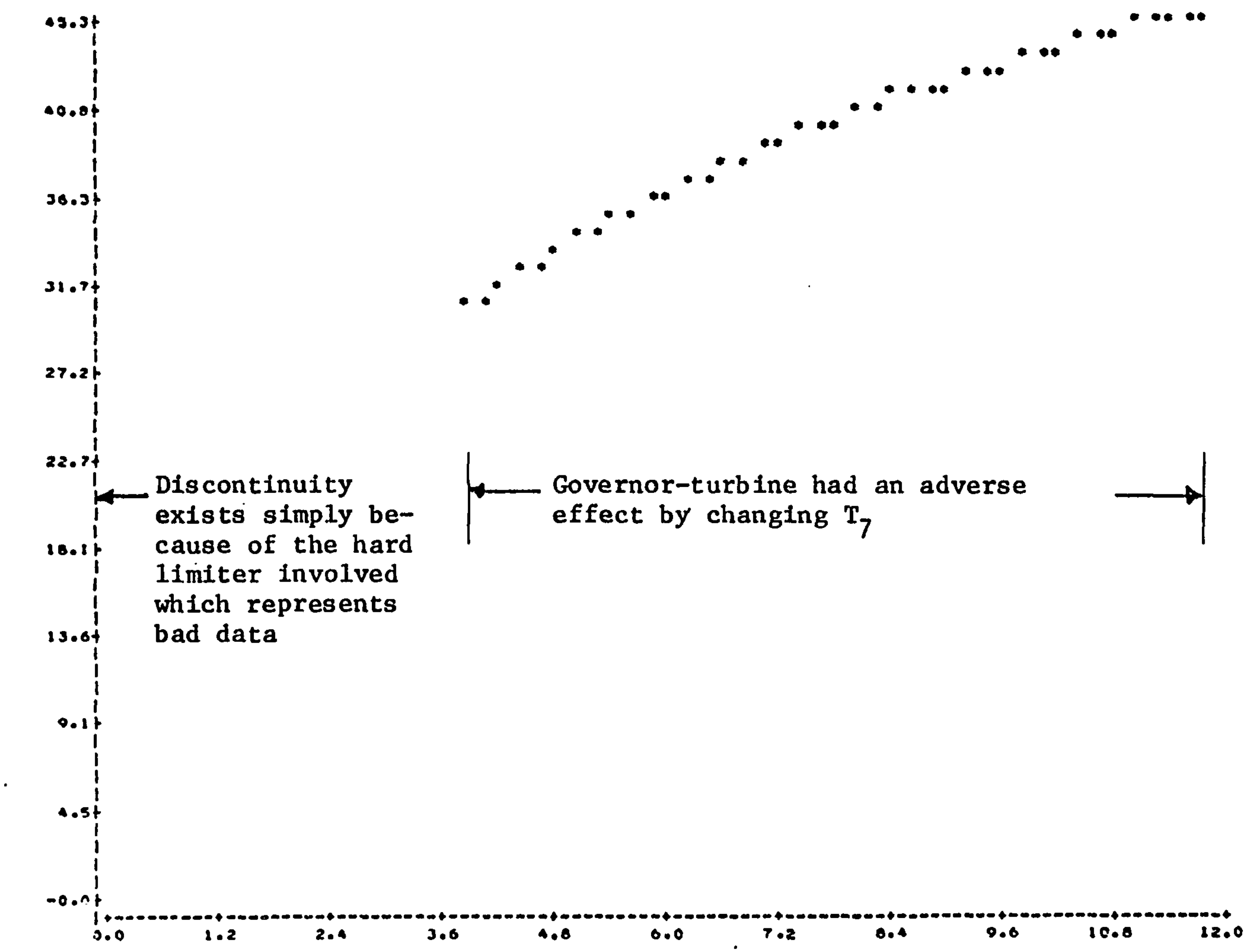
Figure (3-40) shows the behavior of the governor-turbine model, TCDR, upon changing the fraction parameter, K_3. The figure shows that K_3 does not have any significant value effect on the output of the model. Apparently, it is just a constant parameter.

3-9 PECO Type

Figure (3-41) shows the behavior of the governor-turbine model, PECO type, upon changing the time constant, T_1. The figure shows that T_1 does change the response of the PECO model at only the first portion of T_1, while it suppresses the variation of the output limiter action.

Figure (3-42) shows the behavior of the governor-turbine model, PECO type, upon changing time constant, T_2. Here the linear relationship exists between the output and time constant, T_2. The figure shows that at the higher value of T_2 there is no change in PECO response, and again the hard limiter suppresses that change.

Figure (3-43) shows the behavior of the governor-turbine model, PECO type, upon changing the time constant, T_3. T_3 has an exponential relationship with the model response. It appears that it has the most influence at first on small values while with a higher value of T_3 it does decay its effect. This is probably

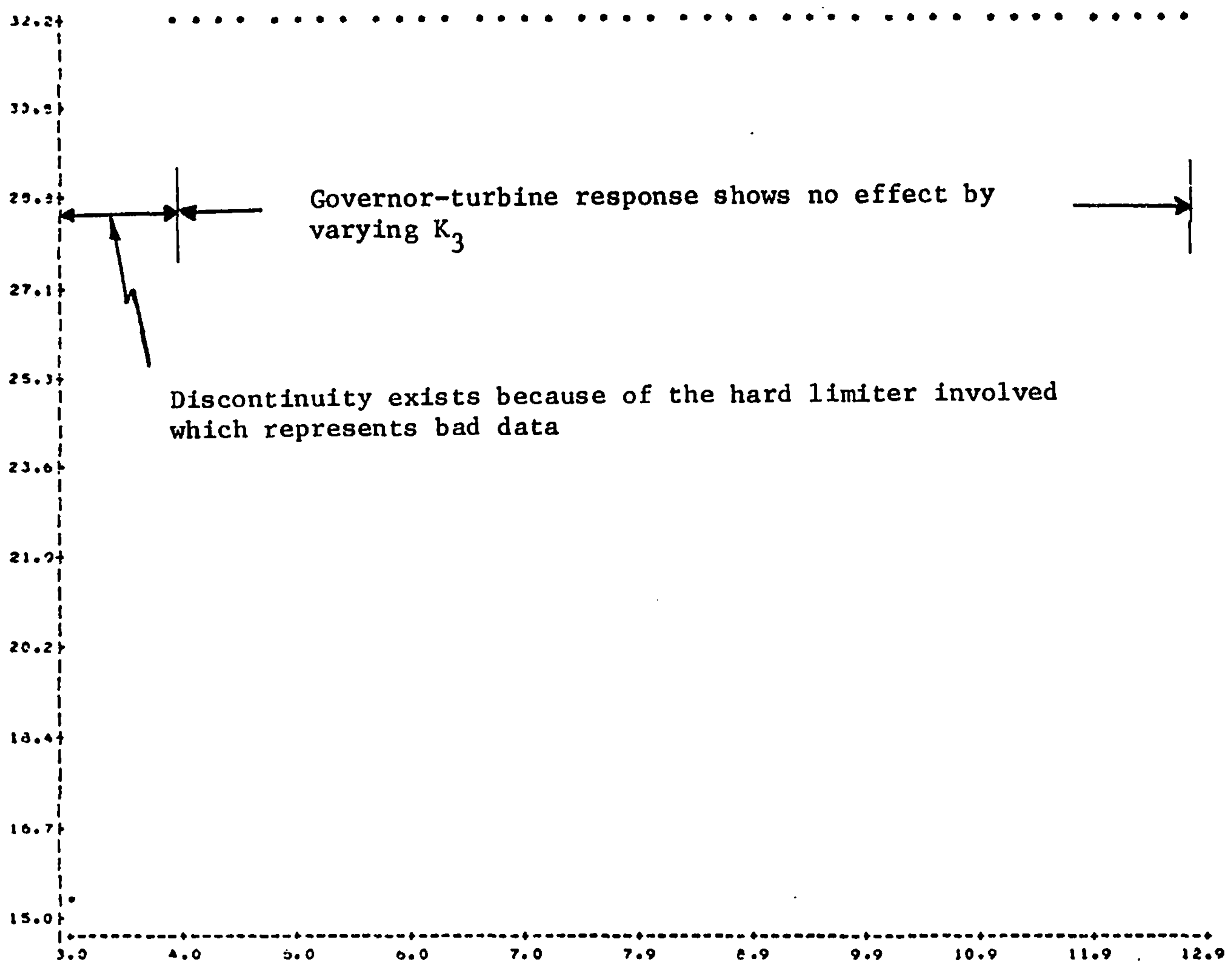


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T7 IS VARIED FROM 3.0 TO 10.0

FIGURE 3-39

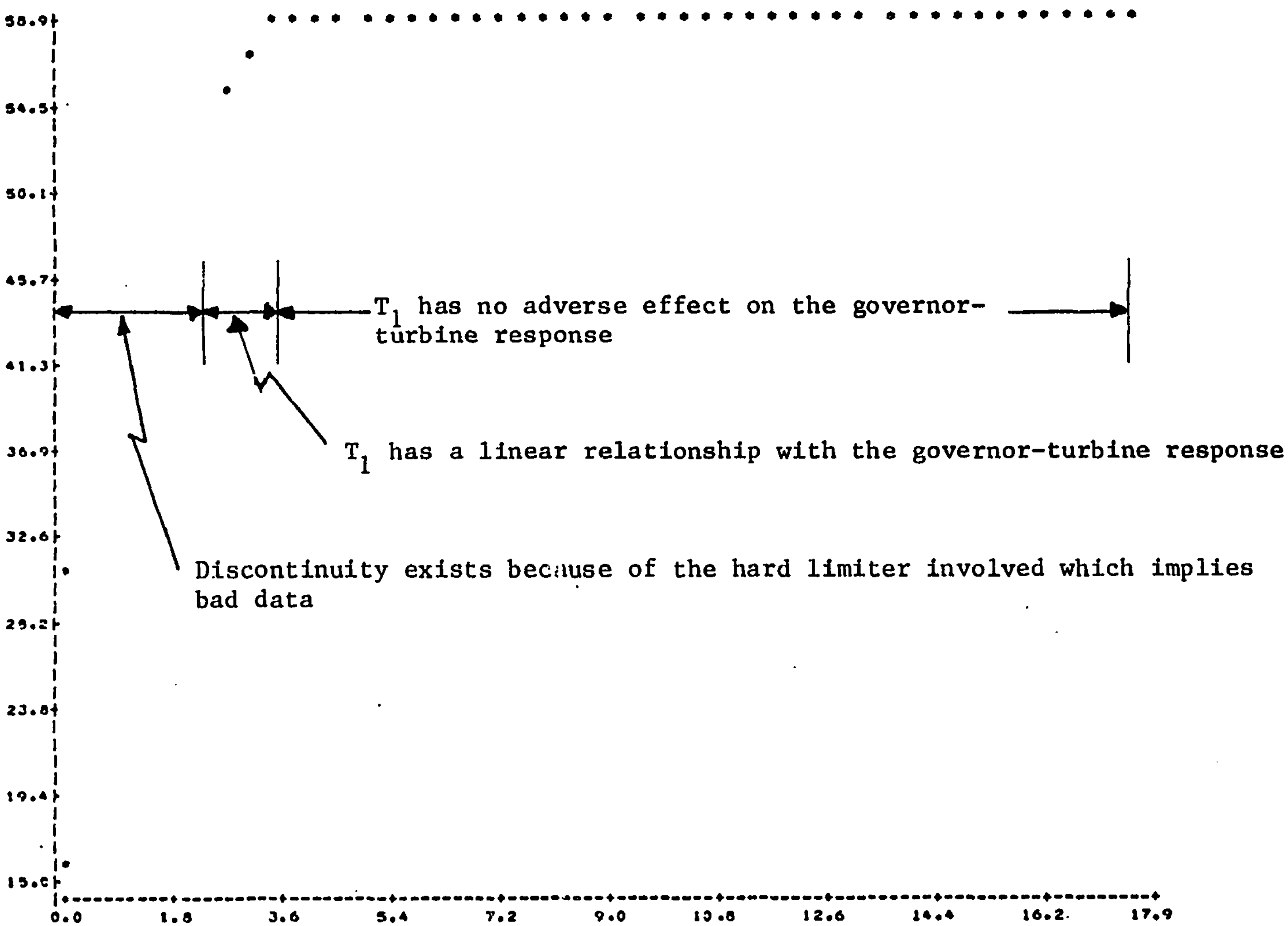


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN GAIN K3 IS VARIED FROM 0.3 TO 0.7

FIGURE 3-40



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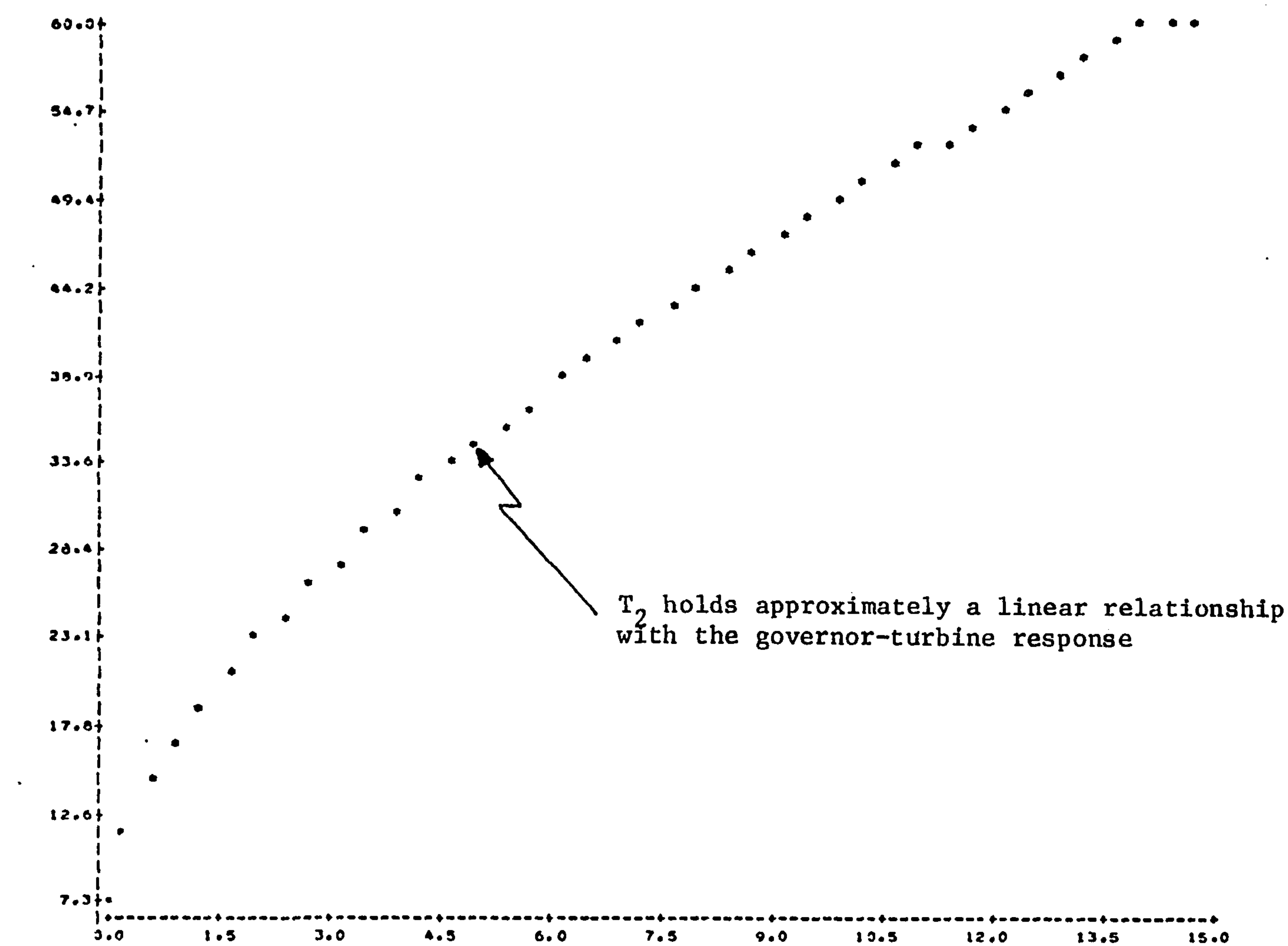
• IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T1 IS VARIED FROM -.01 TO 1.05

FIGURE 3-41

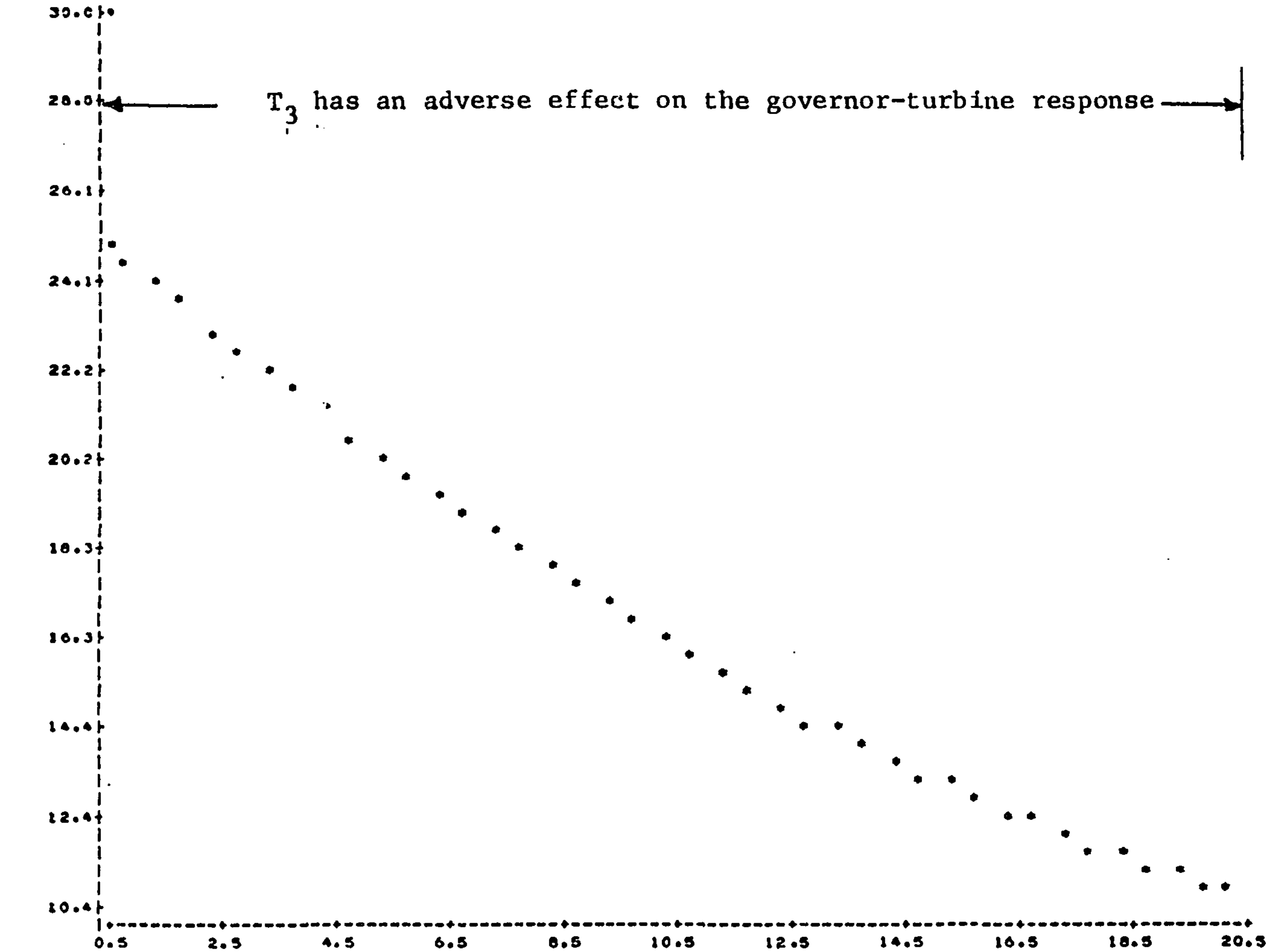


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T2 IS VARIED FROM 0.00 TO 2.0

FIGURE 3-42



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T3 IS VARIED FROM -1.0 TO 1.0

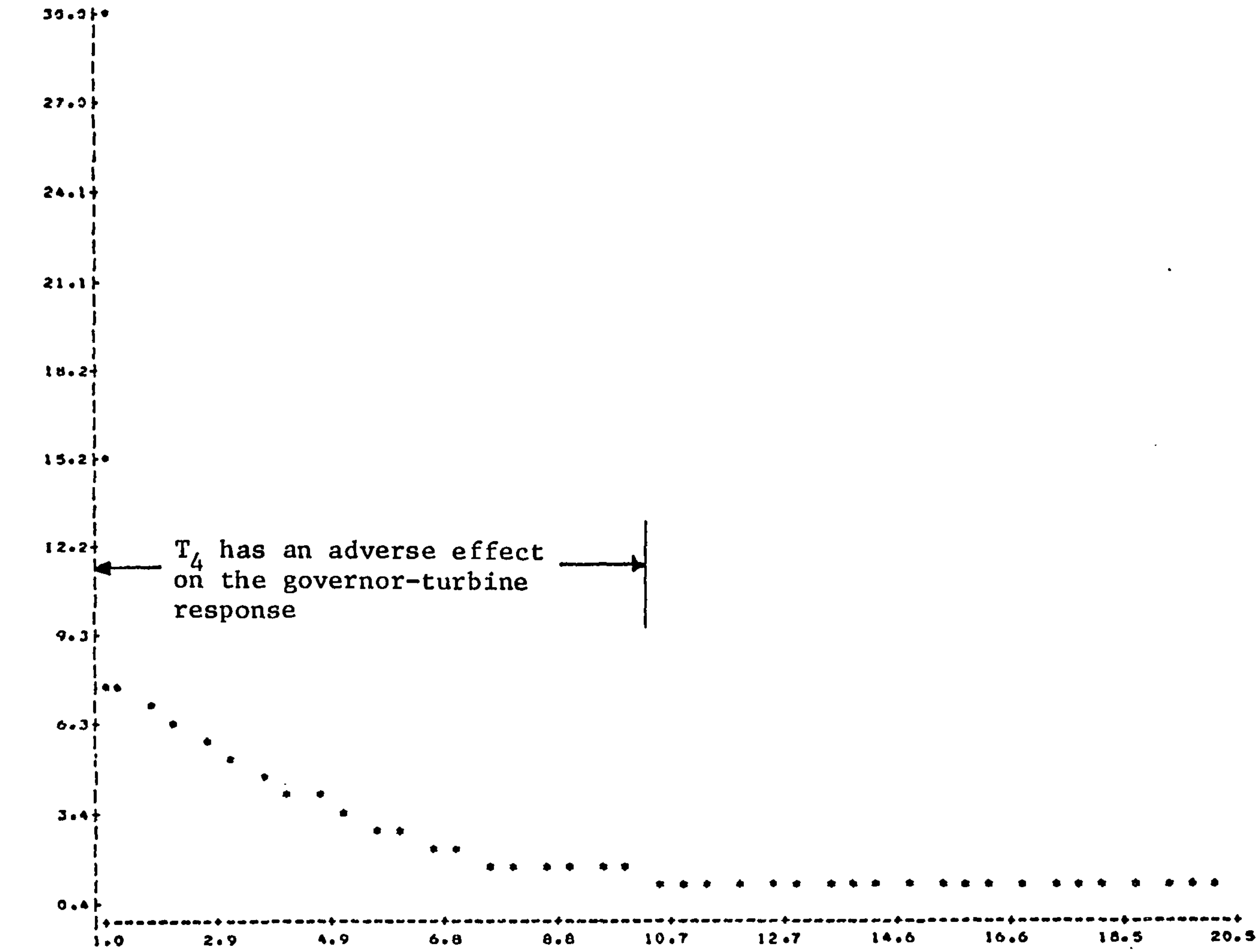
FIGURE 3-43

due to the effect of the poles when they start to dominate and reduce the Zero effect.

Figure (3-44) shows the behavior of the governor-turbine model, PECO type, upon changing time constant, T_4. It acts exactly like the previous one with the same reason.

Figure (3-45) shows the behavior of the governor-turbine model, PECO type, upon changing time constant, T_5. T_5 does not have any influence on the system response. Its value probably does not have the range to effect the output of the system.

Figure (3-46) shows the behavior of the governor-turbine model, PECO type, upon changing the hard limiter. This kind of data causes no action to the hard limiter at the first portion of the curve, while it does act constantly at a later value of the hard limiter. So it is simply that the data action causes the model to behave like this.

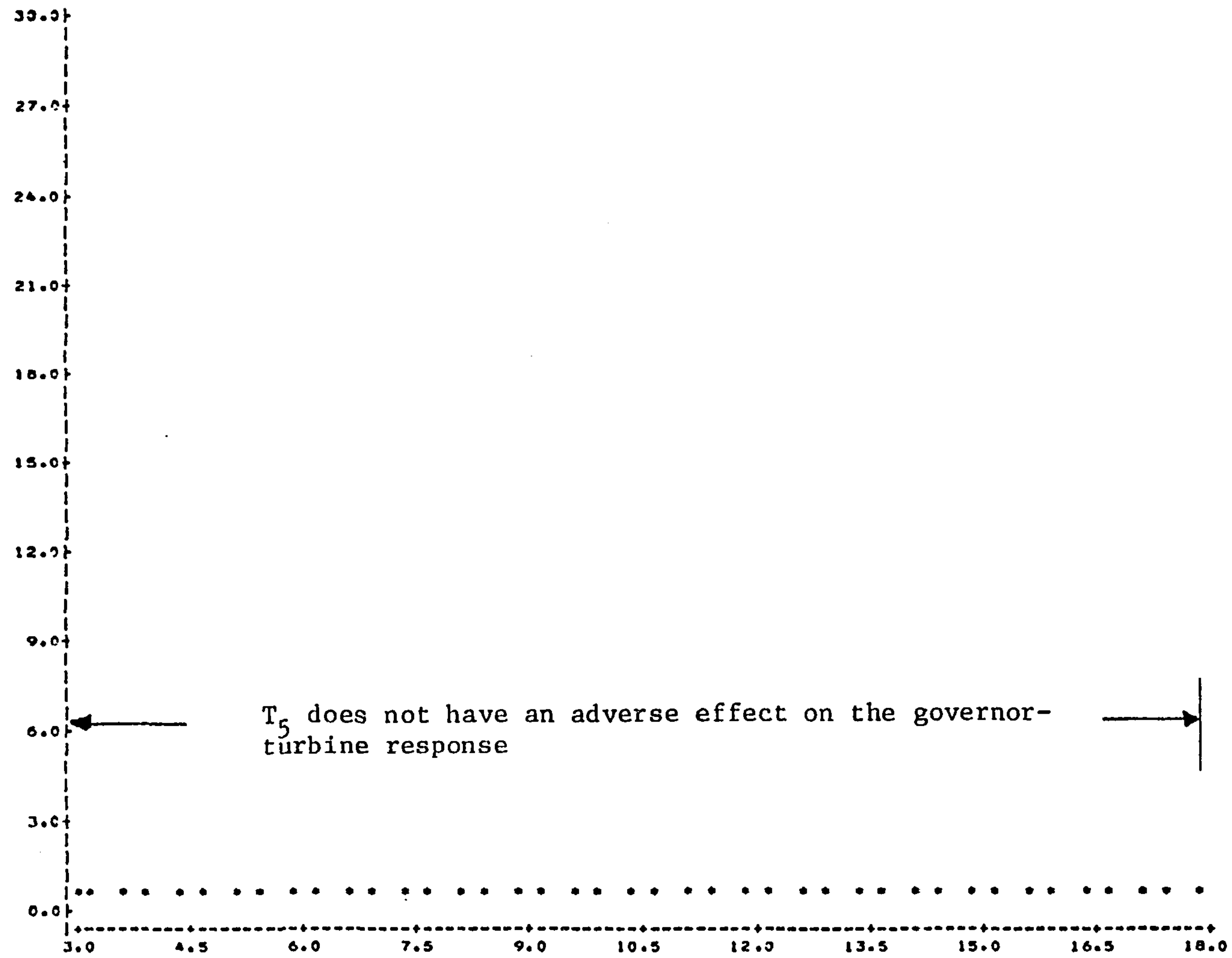


Y SCALE FACTOR USED IS 1.0E-01   X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T4 IS VARIED FROM -5. TO 15.0

FIGURE 3-44

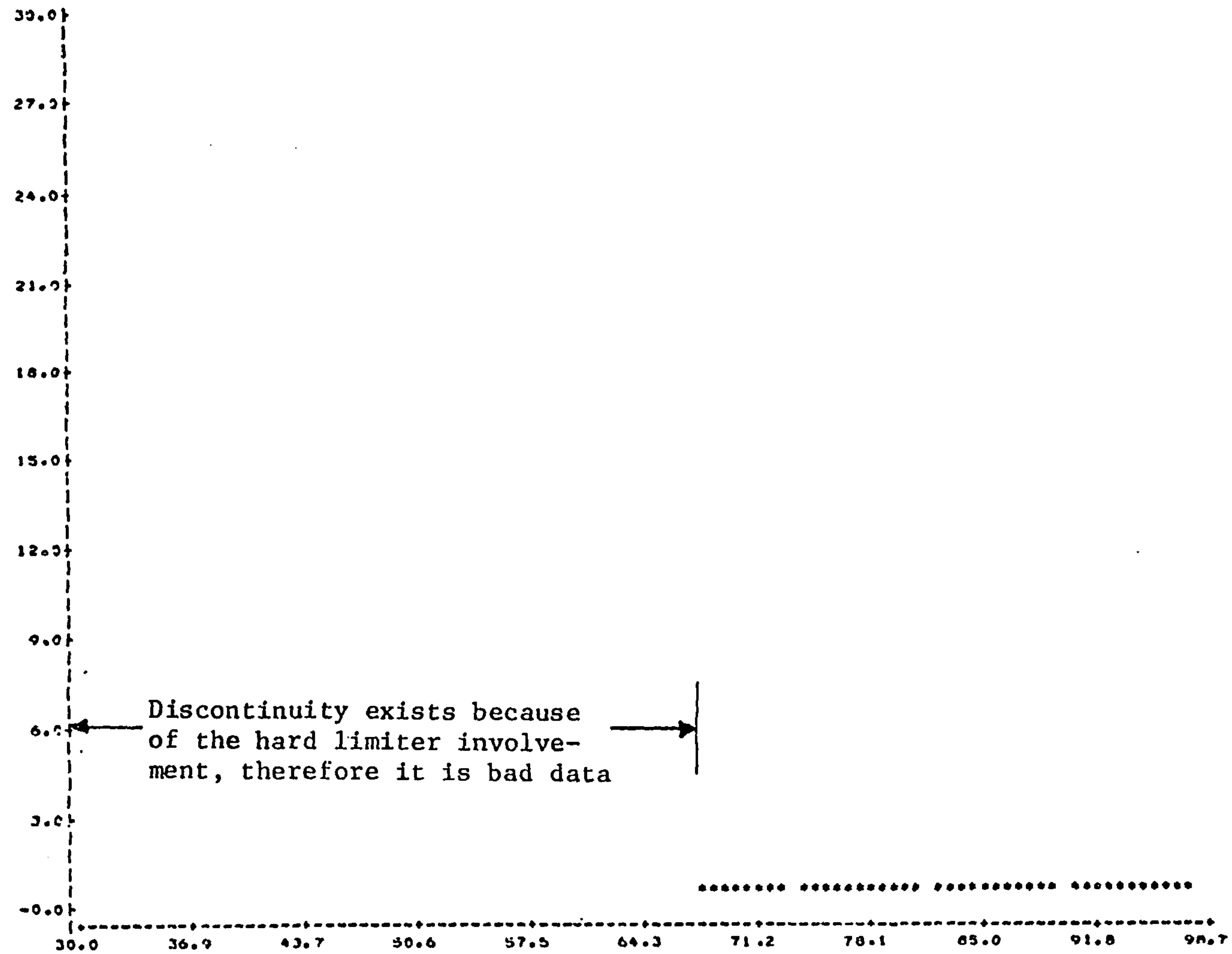


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TS IS VARIED FROM 0.0 TO 20.

FIGURE 3-45



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNORAND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN LIMITER TMIN AND TMAXVAIRED FROM 3.0 TO 10.

FIGURE 3-46

CHAPTER IV

IMPACT OF MACHINE DATA ON THE OVER-ALL STABILITY STUDIES

4-1 Introduction

Power system stability is concerned with maintaining the synchronous operation of all inter-connected generation and load so the loss-of-synchronism operation may be caused by loss of system components resulting in structure instability or by sudden load changes, energy imbalance, resulting in dynamic instability. Structure instability results from loss of capacity which can be initiated by such things as:[57]

1) mechanical or thermal failure and maybe both,

2) relaying action either for desirable protection or due to a wrong setting or misoperation,

3) neutral phenomena (for example, lighting),

4) and human errors as well as intentional errors.

Dynamic instability can result from any of the following causes:

1) improper regulation,

2) self-excitation,

3) inadequate synchronizing power,

4) and inadequate dynamic reserve.

If an operation condition carries the presence of one of the first two causes above, it takes only a small imbalance (perturbation), which is usually present, to initiate the corresponding dynamic instability. The third cause takes a large disturbance, such as a short circuit cleared by tripping a line to initiate the corresponding (transient) instability.[57] The instability can occur during the first swing or second swing if the inadequacy of synchronizing power is the real reason of transient instability. Major failure can happen in an island separated from the inter-connection with gross generation-load imbalances by inadequate dynamic reserve. In a situation like this, it is not enough to have sufficient spinning reserve in an island, because dynamically it may be too slow and therefore, generation can be lost due to the speed protection's relay against unacceptable system frequency deviation.[57]

One of the primary objectives of electric utility industries is to maintain a satisfactory power supply to its customers all the time under any circumstances. This can be achieved by a well-coordinated plan and operation of the system. Therefore, one of the most important quantities of the power system is the machine data. The past history of electric power systems shows unsufficient study on machine data. You will find some machine's data given by manufacturers which is actually reflected in a physical system being used. But what happens is that you take the manufacturers machine data and switch these data in the simulation program. Thus, you may end up with an unstable system.

Several reasons can be pointed out to why this happens. First of all, the simulation program may have errors; secondly, the data given probably was wrong; and thirdly, both data and simulation programs can have errors. The machine data given by the manufacturer may be wrong due to the measurement of the machine's parameters or the method of measurement that has been used. Therefore, it is worth investigating the machine's data and how it influences the stability studies. Especially up to this date, there has been no unified method to measure the machine data under operating conditions.[60] It is true that today teh trend is to adapt a unified method to measure the machine's quantities, but the ieda of investigating the impact of machine's data is highly recommended. This chapter will investigate the impact of the machine's data on the over-all system stability studies.

As we know at this time power systems are large and complex. Therefore, most of the stability studies in power systems are done by simulation. This consists of step-by-stop integration of the system differential equations by using one of the many numerical techniques. Thus, the simulation program[53] will be used in this study.

4-2 Study of the System

In order to see the impact of changing the machine 5 data on an over-all system, a sample system was chosen. It is a model of a 345 KV transmission system typical of Northeast utilities in figure 4-1.[58] This consists of 10 machines being equipped with an IEEE type I excitation system[8] and a Philadelphia Electric Company (PECO) generalized steam and hydro model.[61] It is the EPRI 39 bus, 46 line, 10 generator.[62] Machine data, bus data, line data, excitation system data, and turbine-governor system data are given in appendix G. This system has been used by several investigators on the ERC-RP-90.[58]

The studies in this chapter will consider the sampling system subject to a .075 second three phase fault on the 26-29 line side of bus 29. The fault location is shown in figure 4-1. "The location and level of the disturbance was based on the following:"

1) "The fault was placed on the high side of the machine transformer, slightly distant from the machine, thus, avoiding the level of d-c components that would be established by a closer fault to machine 9."

2) "Machine 9 is loosely coupled to the system through the line (26-28), (28-29) and (26,29). Hence, a fault at bus 29 would serve to exhibit the model test under severe and small disturbance conditions, bus 29 being severely disturbed and the remainder of the system buses having only moderate disturbance."

3) "The clearing action, removal of line 26-29 further serves to loosely couple the machine 9 to the rest of the system."[53]

Therefore, simulation will carry on under the above situation. Machine 5, of system figure 4-1, was chosen to vary its parameters. The attempt was made to see the impact of machine 5 parameters on the overall system stability studies. Those parameters are: direct axis synchronous reactance, x_d, direct axis transient reactance, x_d', direct axis subtransient reactance, x_d'', quadrature axis synchronous reactance, x_q, quadrature axis transient reactance, x_q', quadrature axis subtransient reactance, x_q'', direct axis transient open-circuit time constant, T_{do}', direct axis subtransient open-circuit time constant, T_{do}'', quadrature axis transient open-circuit time constant, T_{qo}', quadrature axis subtransient open-circuit time constant, T_{qo}'', and inertia constant, H. The machine will be simulated by machine model 5, model 4, model 3 and model 2.

The comparative of the machine model's performance will be considered. There are several machine quantities to observe upon changing the machine parameters; for instance machine rotor angle, field voltage, terminal voltage, electrical power output, quadrature axis voltage, direct axis voltage, mechanical torque and turbine power. The quantities which are sufficient to tell the behavior of the system are: rotor angle, field voltage and quadrature axis voltage which will be used.

Next x_d will be varied, of machine 5 of a given system (figure 4-1), n times and at the same time keeping the rest of the parameters and initial condition of the machine unchanged. The major change on the machine quantities is seen upon changing only the x_d parameter. The same thing can be done for the rest of the other machine parameters mentioned previously. Per unit quantities are being dealt with; machine parameters are in per unit. The per unit value of any quantity is defined as the ratio of quantity to its base value expressed as a decimal. For instance, if a base voltage of 120 KV is chosen, voltages of 108 KV, 120 KV and 126 KV become 0.90, 1.00 and 1.05 per unit, or it can be in a percentage scale in which the above quantities would become 90, 100, and 105 percent.[4] The per unit system is adapted as a log in the industry's system, therefore, it is used internationally in the simulation of any power system problem. Hence, a small variation of any parameter in per unit will reflect a large quantity in scale of ohms, voltage and current. Therefore, a very sensitive scale is being dealt with, for instance, x_d to n + 1 set of data cannot be used. This is because

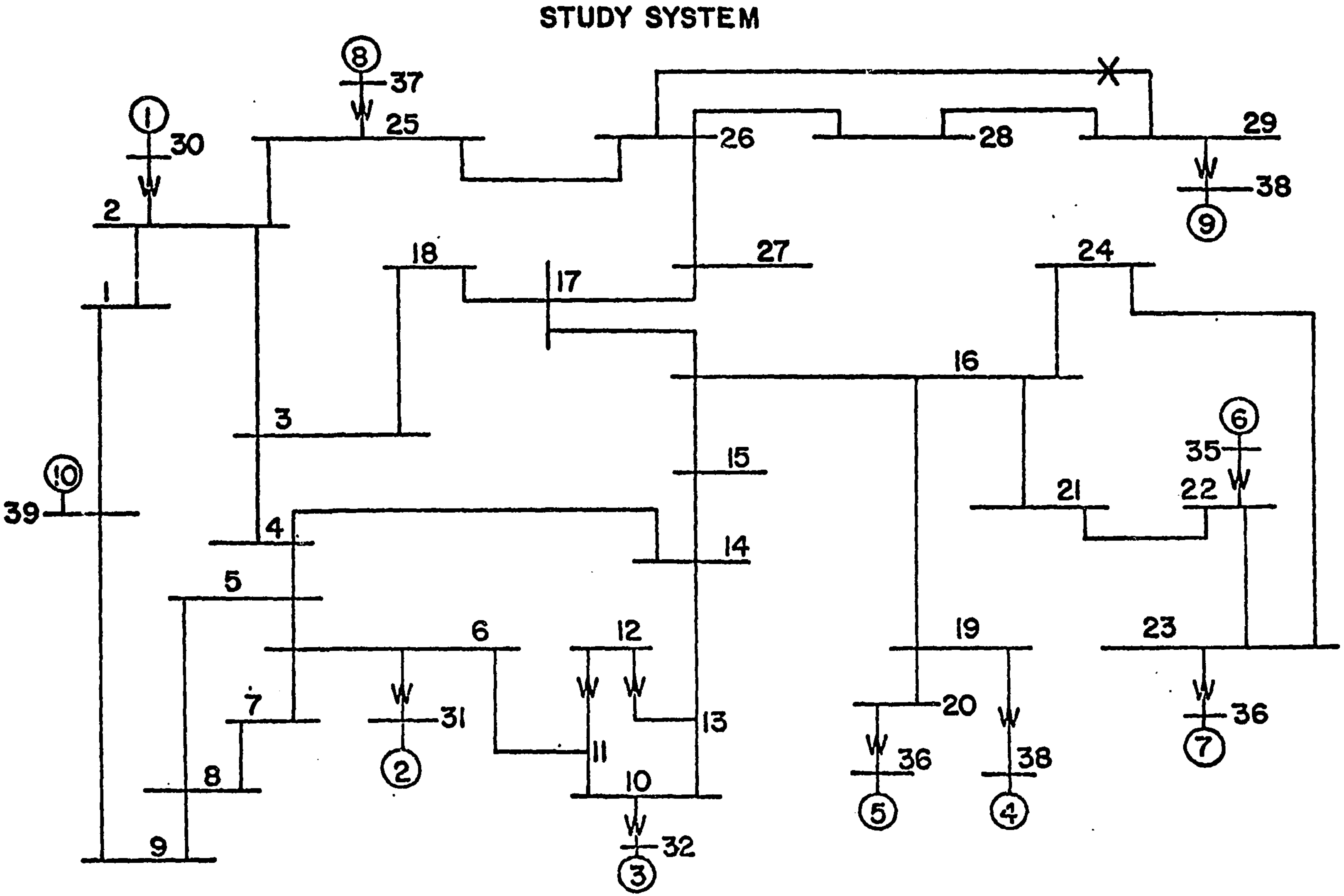


FIGURE 4-1
SAMPLE TEST SYSTEM

the system will become unrealizable in the engineering design point of view. Therefore, there is a limited ceiling for x_d which must be considered and that is when the system becomes unrealizable. Sampling the n set of data of x_d is enough to see the machine quantities behavior as well as its impact on the rest of the system.

Another point needs to be mentioned which is x'_d cannot exceed x_d, which is well known. Also, x''_d cannot exceed x'_d. The same thing is true for x_q, x_q is more or equal to x_q' and x'_q is more or equal to x''_q. There is another relation that is well defined, that is x_d is more or equal to x_q. Therefore, precautions need to be taken of the basic relationships of these parameters in the sense that x'_d cannot be more than x_d, hence, n set of data has to be defined for the x'_d variation. The same is true for x''_d, x'_q, and x_q. Other parameters such as the inertia constant H and machine time constants T'_{do}, T'_{qo}, T''_{do}, and T''_{qo} have to be limited to n set of data. Simply this is that n + 1 causes the system to be unrealizable in the sense of the design point of view.

Simulation has also been done which in this case perturbated the initial terminal voltage of machine 5 and investigates the impact of the variation of the machine data on the over-all system stability studies. Another case of simulation has been done which has perturbated one of machine 5 parameters and varies the other one parameter up to n set of data. Table 4-1 reflects that the machine 5 data has been simulated.

4-3 Result Analyses of the Machine's Models Performance

It needs to be pointed out that the stability or instability of the system will be evident as the swing curves are carried on. For

MACHINE 5 PARAMETER	SAMPLE VALUE PER UNIT	MINIMUM VALUE PER UNIT	MAXIMUM VALUE PER UNIT
x_d	.67000	.62000	2.0000
x'_d	.13200	.10000	.4000
x''_d	.05400	.01000	.1750
x_q	.62000	.18000	.7000
x'_q	.16600	.10000	.6000
x''_q	.11620	.01000	.1600
T'_{do}	5.40000	1.00000	15.0000
T'_{qo}	.44000	.01000	1.0000
T''_{do}	.05400	.01000	.8000
T''_{qo}	.05400	.01000	.4000
H	26.00000	12.00000	40.0000
R	.00014	.00010	.0015

TABLE 4-1
SIMULATED MACHINE PARAMETER

stability the relative angular displacement of the machine groups should tend to return to or oscillate about a position or relative equilibrium, that is no one machine group should increase indefinitely in relative angular displacement with respect to the other groups.

Base to simulation has been done to the four machine models under variation to the machine 5 parameters. It was found that some instability occurs due to changing the data of machine 5 parameters. The reference simulation curve for all cases is shown as curve N in figures 4-2 to 4-45; this is the simulation of the study system data given in appendix G. It needs to be mentioned here that it is sufficient to observe the performance of the system study of the following machines: machine 5 (the data of this machine has been tested); machine 9 (the nearest one to the three phase fault on the system study); machine 1 (the furthest one from the tested machine); and machine 2 (some where in the middle of the system). Machine 1 was represented in simulation by curve A, machine 2 by curve B, machine 5 by curve E and machine 9 by curve I. Figures 4-2 to 4-45 reflected machine model 5 performance while the other machine models used a statement of their performance.

4-4 Performance of Machine Model with Changing x_d

Figure 4-2 and 4-3 are a plot of the system's transient rotor angle. It plots for several values of the x_d parameter. The plot shows that the rotor angle of machine 5 is sensitive to the change of x_d. x_d causes machine 5 to be unstable at the value of 1.8 per unit. It was found that the rotor angle is directly proportional to x_d, and this is expected because x_d is an element of the A matrix. x_d causes machine 1 rotor angle to change conservatively noticing that the curve is degraded

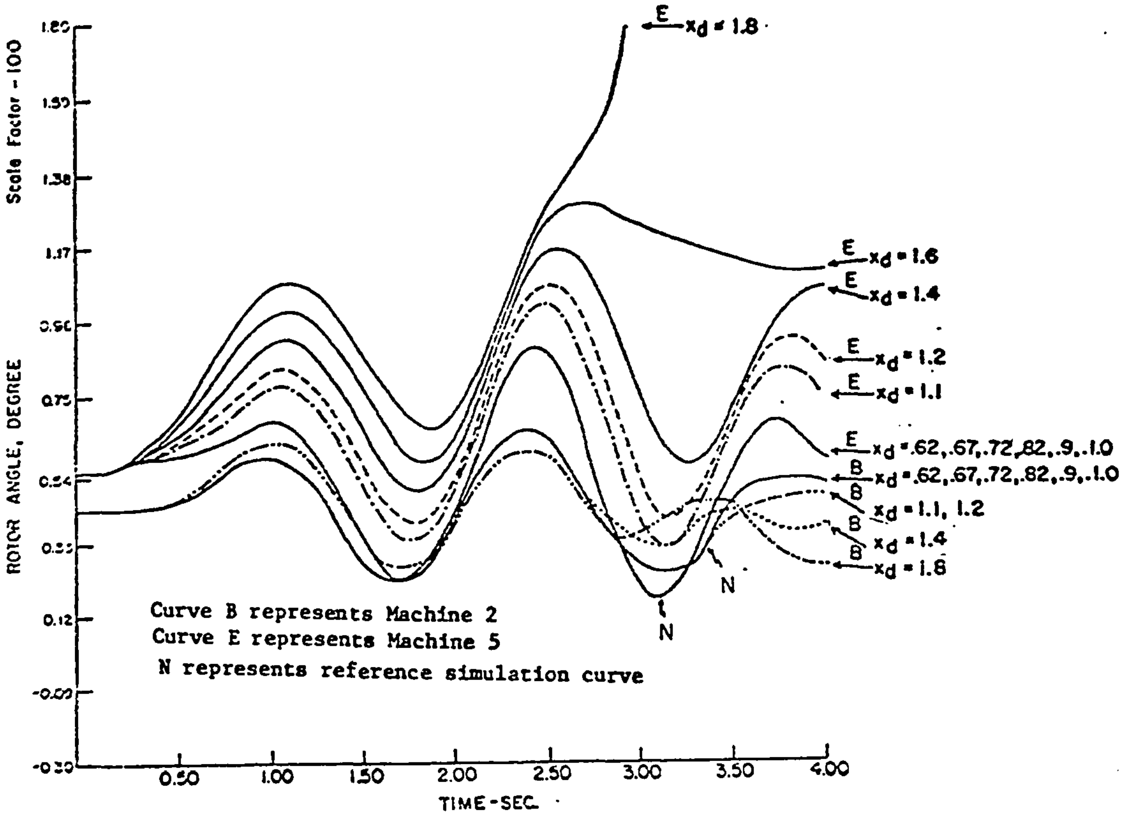


FIGURE 4-2
TRANSIENT ROTOR ANGLE UPON CHANGING x_d

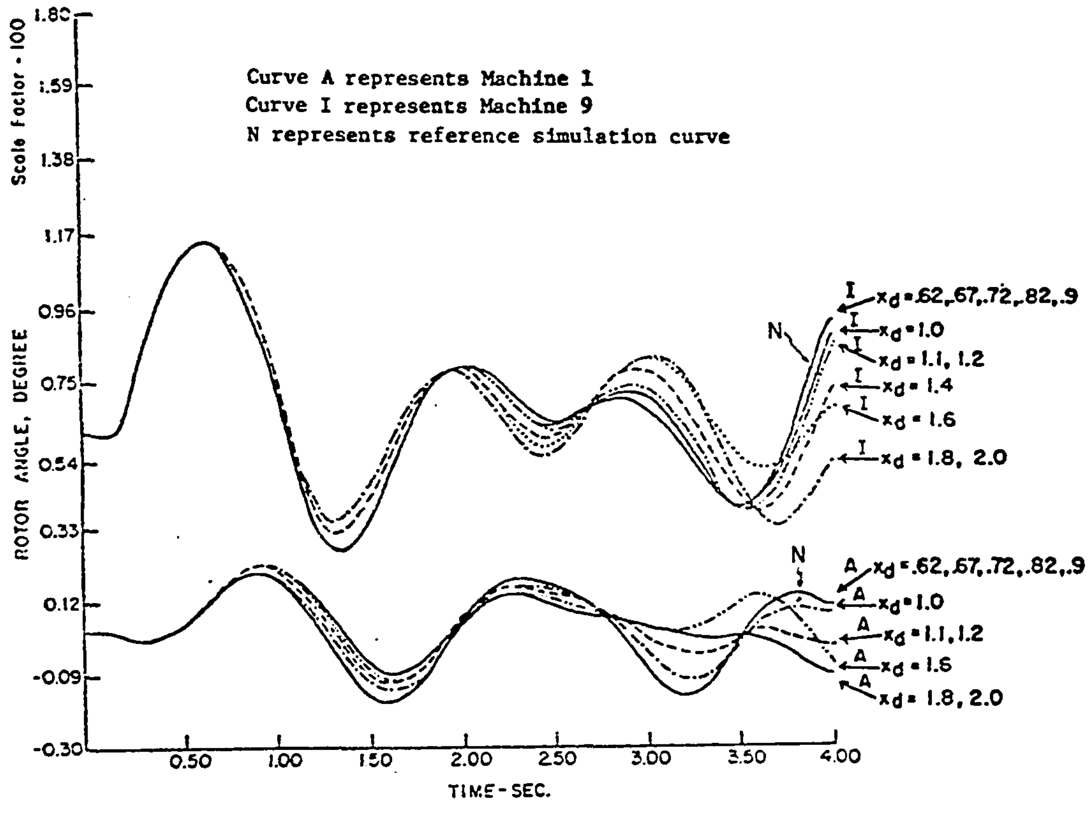


FIGURE 4-3
TRANSIENT ROTOR ANGLE UPON CHANGING X_d

from reference curve N. As the value of x_d increases this causes the machine 9 rotor angle to slightly change from the reference curve. Changing x_d of machine 5 does influence the rotor angle of the tested machine as well as other machines to change.

The same test of x_d parameter applies to machine model 4 simulation. The system's transient rotor angle plots for several values of x_d parameters. Its amplitude has increased over machine model 5, increasing the value of x_d. x_d drives machine 5 to unstable limits at the value of 1.6 per unit while it was unstable at x_d equal to 1.8 per unit at machine model 5. This is due to representation of more damping winding assigned to model 5 than was assigned to model 4. So machine 5 is sensitive to the change of x_d under machine model 4 simulation. As the value of x_d is increased it causes the rotor angle of machine 1 to be degraded than the reference curve N, which acts the same as machine model 5 simulation. The rotor angle of machines 2 and 9 have a very slight change upon changing x_d.

The same test of the x_d parameter applies to machine model 3 simulation. The system's transient rotor angle plots for several values of x_d parameter. Its amplitude has increased over machine model 4. This is because there is less damping winding in machine model 3 than machine model 4. Increasing the x_d value drives machine 5 to instability at the value of x_d equal to 1.1 per unit while machine model 4 at x_d equals 1.6 per unit. Changing x_d parameters has influenced the change of the rotor angle. The rotor angle of machine 1 and machine 9 show change starting at 2.0 seconds.

The same test of x_d parameter applied to machine model 2 simulation. The system's transient rotor angle was plotted for several values of x_d parameter. It appears that machine 9 acts unstable for all x_d values. Changing the value of x_d drives machine 5 to instability at the value of x_d equal to 1.0 per unit. The rotor angle of machines 1 and 2 has changes that are relatively small. Therefore, changing x_d is proportional to the rotor angle of the machines as it was stated earlier.

Figure 4-4 is a plot of per unit field voltage E_{fd} of the exciter system. It plots for several values of x_d parameter, machine model 5 simulation, comparing the reference curve N with other curves. This results in that almost each value of x_d causes the field voltage to be different from the referenced curve N. This implies that the amount of damping supplied by excitation system to machine 5 is changeable and depends on the x_d value as shown in figure 4-4. For instance, at x_d equal to .82 per unit, machine 5 required more damping by the exciter. At x_d equal to 1.4 per unit, it initially required tremendous amounts of field voltage while it slowed down under the normal reference curve N. This is what would be expected of field voltage to control the system. Figure 4-4 shows x_d does not provoke the field voltage of machines 1, 2 and 9. It remains constant.

The same test of x_d parameter applies to machine model 4 simulation. The per unit field voltage E_{fd} plots for several values of x_d parameter. The performance of machine model 4 holds the same behavior as machine model 5. So there is a tremendous amount of changed values of the field voltage when changing x_d parameter. In other words, the amount of damping supplied by the excitation system to machine 5 is changeable and depends on the x_d parameter's assigned value. By changing x_d parameter, it shows a slight change in the field voltage of machines 1 and 9. But it does not show any change in the field voltage of machine 2.

Again, the same test of x_d parameter applies to machine model 3 simulation. The per unit field current E_{fd} plots for several values of the x_d parameter. The field current of machine 5 is changing as x_d is changed, but it shows a less amount of change than the two previous models. Apparently this is caused by the less amount of damping supplied by the exciter of machine 5. By changing the x_d parameter, the field voltage of machines 1, 2 and 9 is not provoked. This shows a less correlation of dynamic equations in this particular part.

The same test of x_d parameter applies to machine model 2 simulation. The per unit field voltage E_{fd} of the exciter plots for several values of x_d parameter. Increasing x_d values causes the field voltage of machine 5 to increase which is the amount of damping supplied by the exciter. Comparing it with other previous models, it shows a similarity with machine model 3 in the sense of the amount of field current being used for controlling the system. There has been no significant change on the field current in machines 1, 2 and 9.

Figure 4-5 is a plot of the machine's internal voltage e'_q using machine model 5 simulation. It plots for several values of x_d parameter. The internal voltage e'_q of machine 5 shows different curves for each one value of x_d since the change in e'_q is a direct measure of the d-axis damping provided by the exciter.[53] But e'_q in the other machines re-

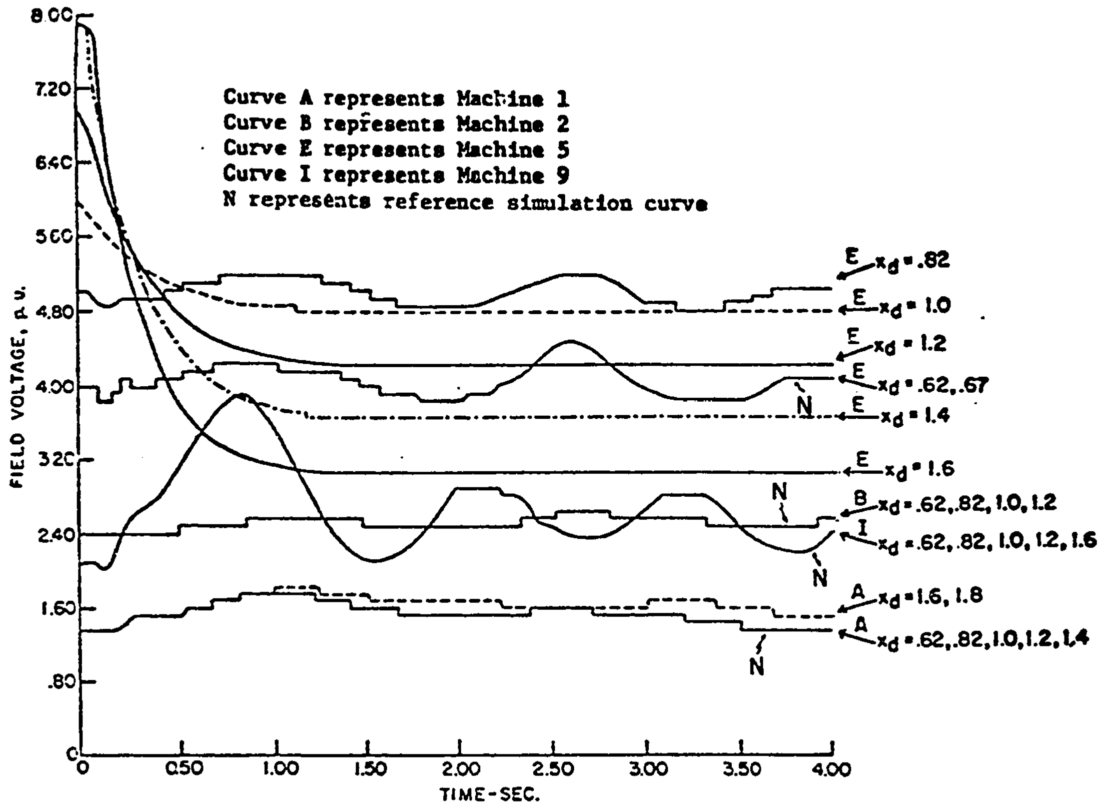


FIGURE 4-4
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING x_d

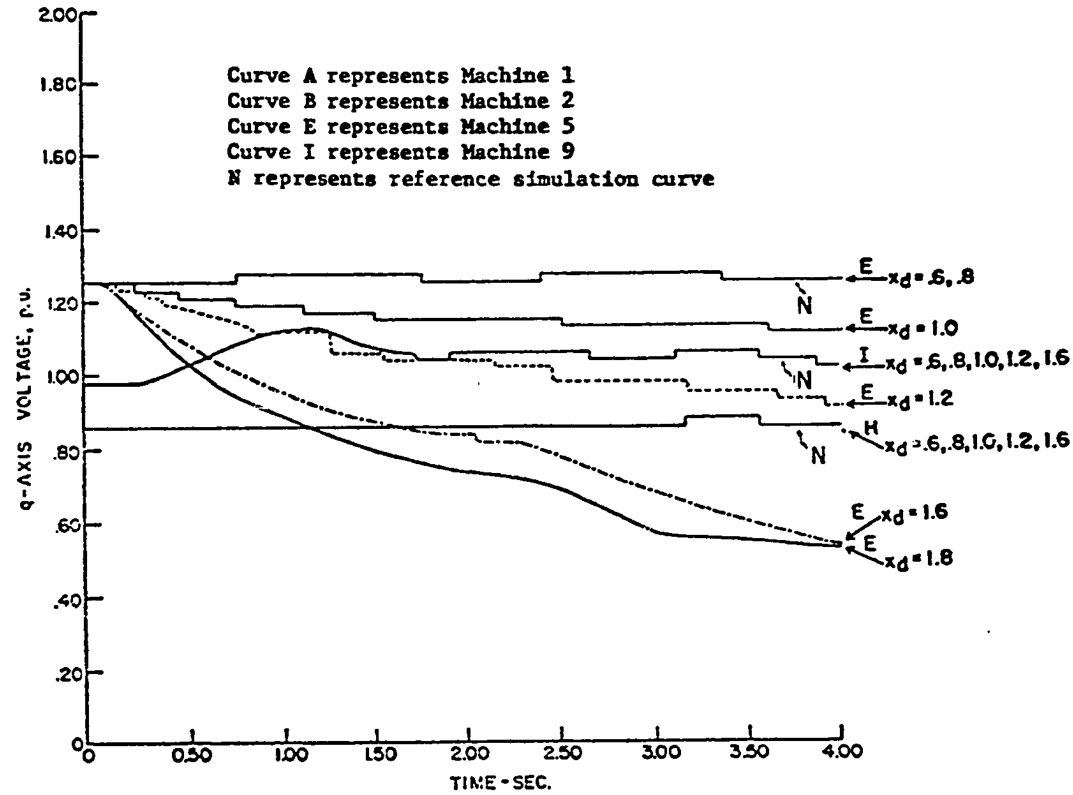


FIGURE 4-5
Q-AXIS TRANSIENT VOLTAGE e_q' UPON CHANGING x_d

main relatively uneffected by changing the value of x_d. The machine's internal voltage e'_q plots for several values of x_d parameter. e'_q of machine 5 degraded only at a higher value of x_d for all four machine models being used. Further, it shows a slight change at a smaller value of x_d for machine model 2 and 3. This is because of the influence of the exciter response over the e'_q value. Internal voltage of machines 1, 2 and 9 do not show any significant change upon changing the x_d parameter.

4-5 Performance of the Machine Models upon Changing x'_d

Figure 4-6 and 4-7 are a plot of the system's transient rotor angle. It plots for several values of the x'_d parameter, machine model 5 simulation, comparing reference curve N with other curves, which represent different values of x'_d. The rotor angle of machine 5 shows a slight change from referenced curve starting from 2.0 seconds. The rotor angle of machines 1 and 2 have been damped starting from 3.0 seconds of simulation. But machine 2's rotor angle shows a slight change upon changing x'_d. Therefore, x'_d has an influence over the machine's rotor angle of the system study.

The same test of x'_d parameter applies to machine model 4 simulation. Plots of the system's transient angle for several values of x'_d were observed. The transient rotor angle curve of machine 5 shows an increasing amplitude that is very high upon changing x'_d, while it does suppress the rotor angle of machine 9 (starting at 2.5 seconds). Also, machine 1's rotor angle has been suppressed (starting at 3.0 seconds). Machine 2's rotor angle did not significantly change.

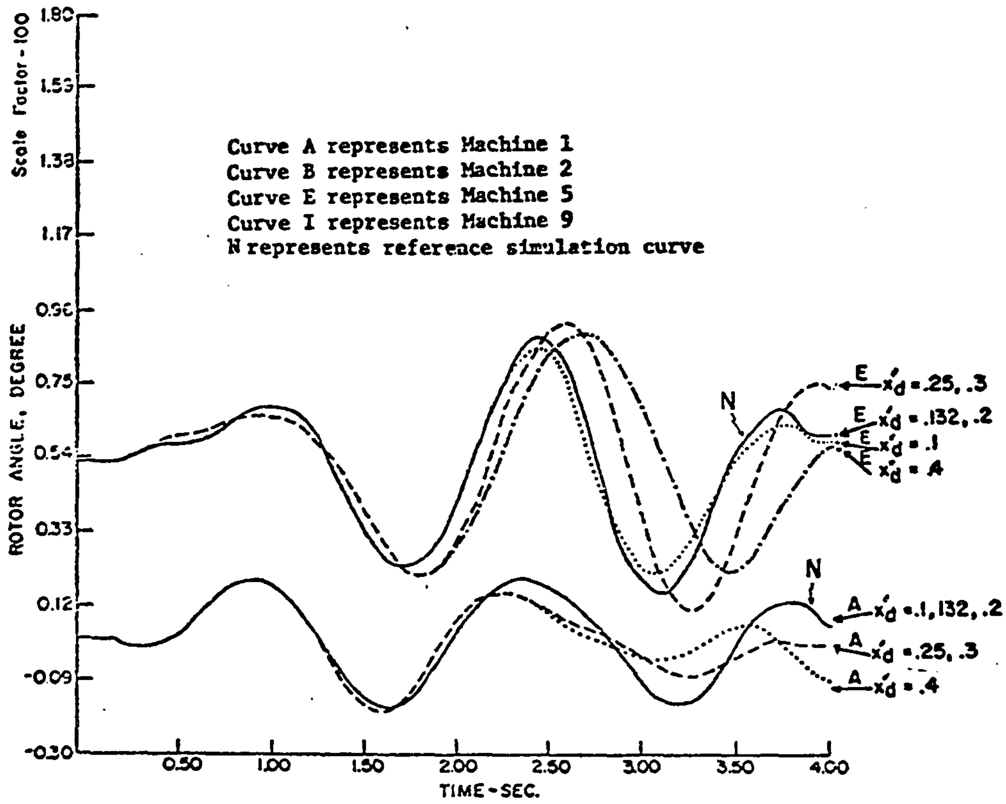


FIGURE 4-6
TRANSIENT ROTOR ANGLE UPON CHANGING x'_d

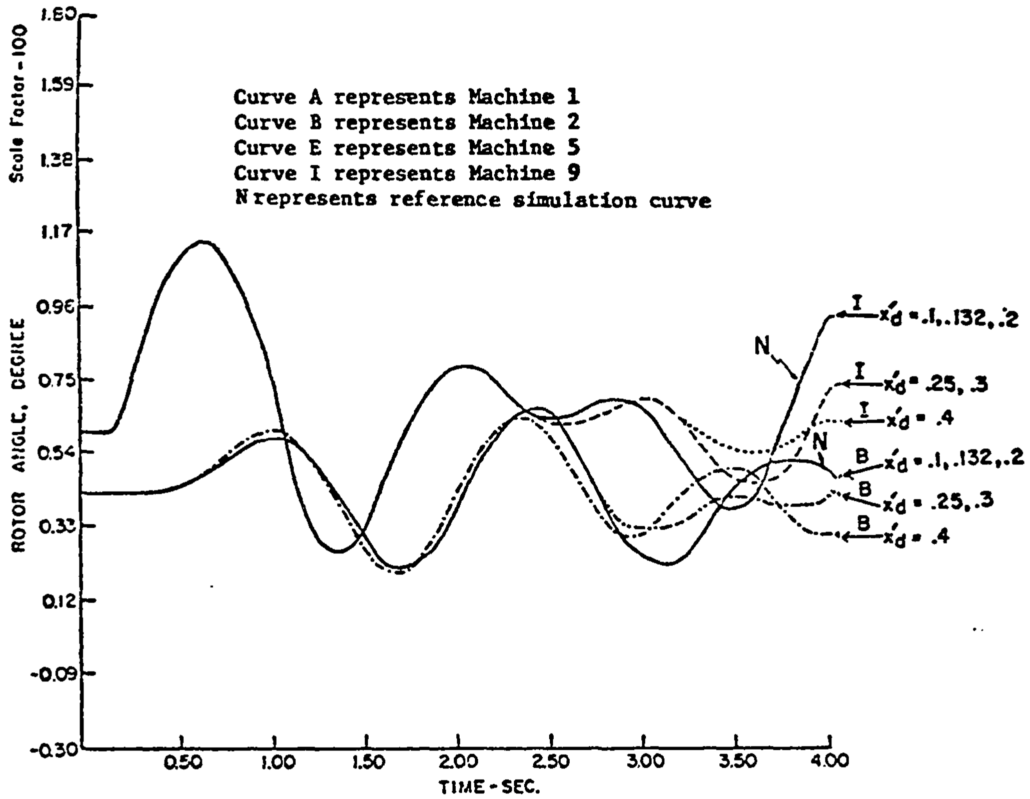


FIGURE 4-7
TRANSIENT ROTOR ANGLE UPON CHANGING x'_d

The plot of the system's transient rotor angle for several values of x_d' parameter is observed using machine model 3 simulation. The rotor angle of machine 5's amplitude is increased by increasing the value of x_d'. Machine 9's rotor angle does not change at all under varying x_d'. It's characterized by high amplitude of oscillation which is the severing of the 3-phase fault. Machine 1's rotor angle has been damped out (starting at 3.5 seconds) by increasing x_d'. So changing x_d' has an influence over the whole machine's system that can be true for other machines.

The plot of the system's transient rotor angle for several values of x_d' parameter is observed using machine model 2 simulation. Again machine 5's rotor angle increases the amplitude by increasing x_d'. This is also because of less damper winding being used for this machine model. Machine 9 was unstable for all causes tested of x_d'. Machine 1's rotor angle curves show a slight change but it is damped out (starting at 2.50 seconds) by increasing x_d'.

Figure 4-8 is a plot of the per unit field voltage E_{fd} of the exciter system using machine model 5 simulation. It plots for several values of x_d' parameter of machine model 5 simulation. Almost each value of x_d' causes the field voltage to be relatively different from the referenced field voltage of machine 5. That is because of the damping needed to suppress the system supplied by exciter. Field voltage of machines 1, 2 and 9 did not provoke it by changing x_d' parameter. This system is not dynamically correlated in this particular point of view.

The plot of the per unit field voltage E_{fd} of the exciter system, machine model 4 simulation, was observed for several values of x_d' parameter. Machine 5's field current showed oscillation as x'_d was increased. This tells us the amount of damping needed by the exciter. The field voltage of machines 1, 2 and 9 was not provoked by changing x'_d parameter. This is because the system was not dynamically correlated in this particular point of view.

The plot of the per unit field voltage E_{fd} of the exciter system, machine model 3 simulation, was observed for several values of x'_d parameter. The only machine severe field voltage was changed in machine 5, while the field voltage of machines 1, 2 and 9 did not change at all.

The plot of the per unit field voltage E_{fd} of the exciter system, machine model 2 simulation, was observed for several values of the x'_d parameter. Again the only machine severe field voltage was changed in machine 5 while the field voltage of machines 1, 2 and 9 did not change at all.

Figure 4-9 is a plot of the machine's internal voltage e'_q using machine model 5 simulation. It plots for several values of x'_d parameter. Internal voltage of machine 5 shows a tremendous amount of change as x'_d is increased. This change reflects that the change in this voltage is a direct measure of the d-axis damping provided by the exciter system.

The plot of the machine's internal voltage e'_q uses machine model 2, 3 and 4 simulation. It plots for several values of x'_d parameter. Internal voltage of machine 5 becomes larger by increasing x'_d. The internal voltage of machines 1, 2 and 9 did not show any change upon changing x'_d.

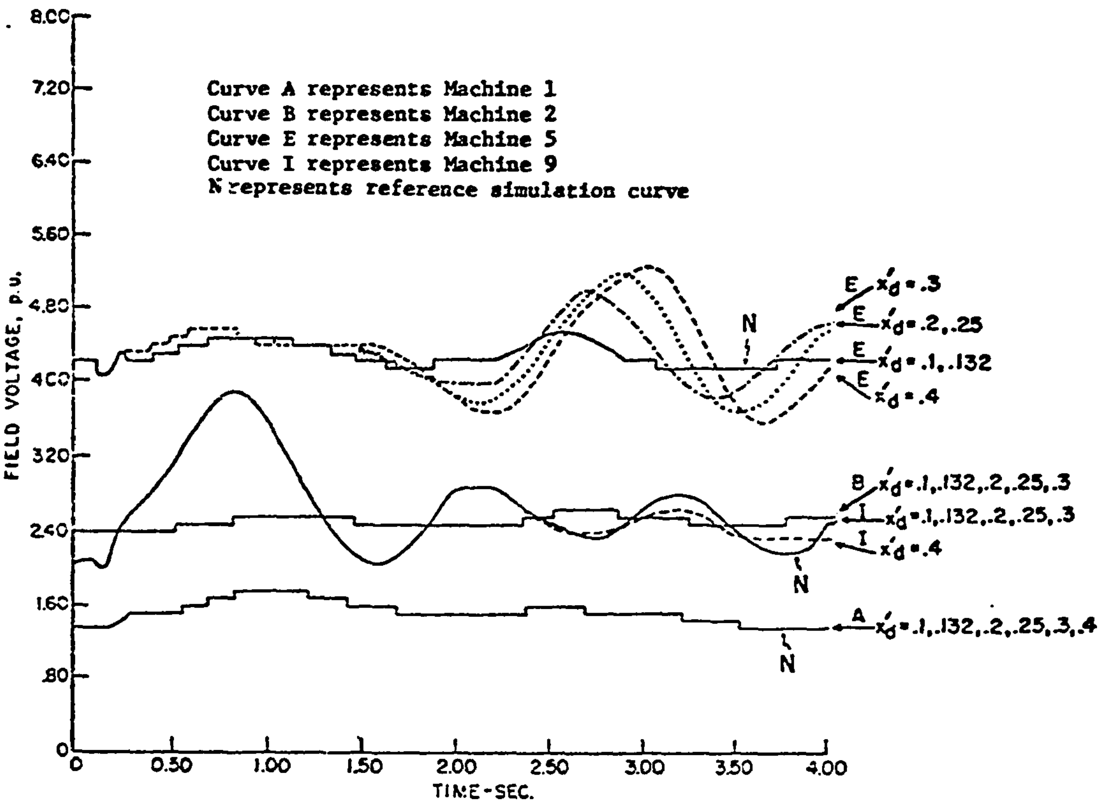


FIGURE 4-8
PER UNIT EXCITER OUPTUT E_{fd} UPON CHANGING x'_d

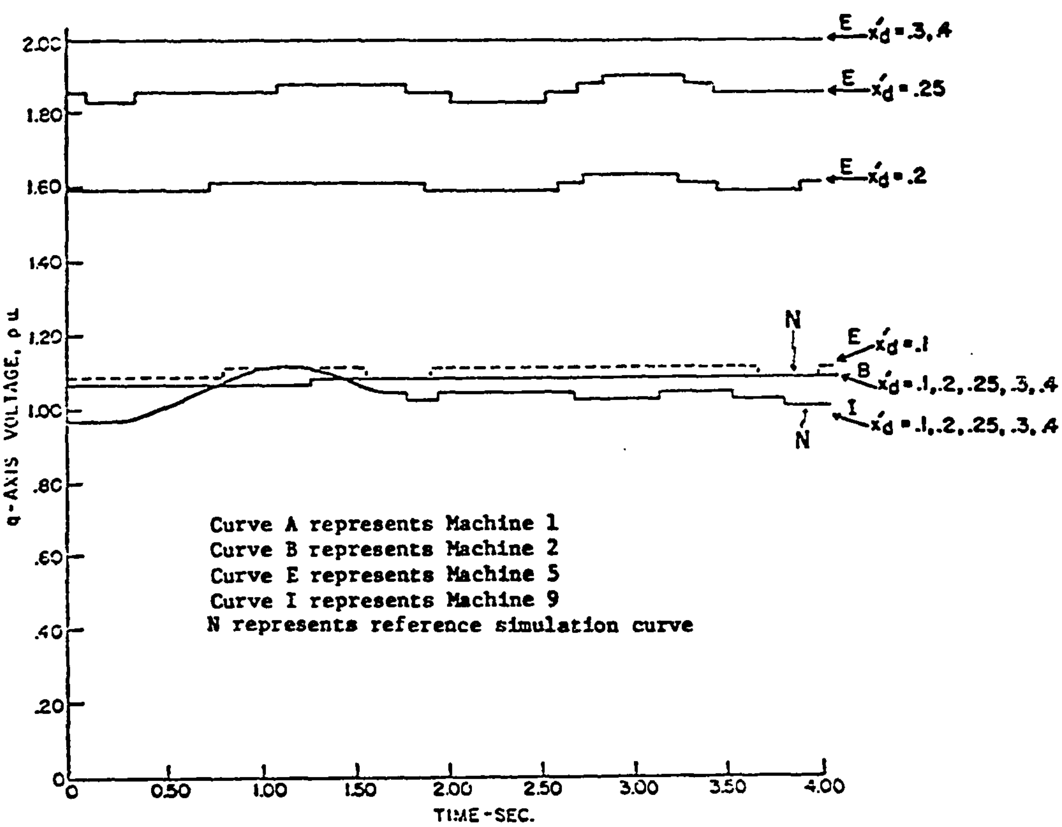


FIGURE 4-9
Q-AXIS TRANSIENT VOLTAGE e'_q UPON CHANGING x'_d

4-6 Performance of the Machine Models upon Changing x''_d

Figure 4-10 is a plot of the system's transient rotor angle. It plots for several values of x''_d parameter using machine model 5 simulation. It is found that none of the machine's rotor angles changed. Therefore, x''_d does not contribute any significant change to the whole system under the existing situation described before.

The plot of the system's transient rotor angle, machine model 4 simulation, was observed for several values of x''_d. Again there has been no change in the rotor angle of all of the machines due to the change of x''_d.

Figure 4-11 is a plot of the machine's internal voltage e'_q using machine model 5 simulation. It plots for several values of the x''_d parameter. e'_q of machine 5 shows a slight change. Internal voltage of machines 1, 2 and 9 did not show any change at all upon changing x''_d. This is because x''_d did not effect the eigen value of the system.

4-7 Performance of the Machine Models upon Changing x_q

Figure 4-12 and figure 4-13 are a plot of the system's transient rotor angle. It plots for several values of x_q, machine model 5 simulation, comparing reference rotor angle curve N with other curves which represent different values of x_q. The rotor angle of machine 5 is shown initially changing. Increasing x_q causes the transient rotor angle shaft up by constant quantity. Machine 1 does not change at all under such change of value x_q. The rotor angle of machines 2 and 9 remain unchanged too.

The plot of the system's transient rotor angle for several values of x_q is observed using machine model 4 simulation. Machine 5's rotor

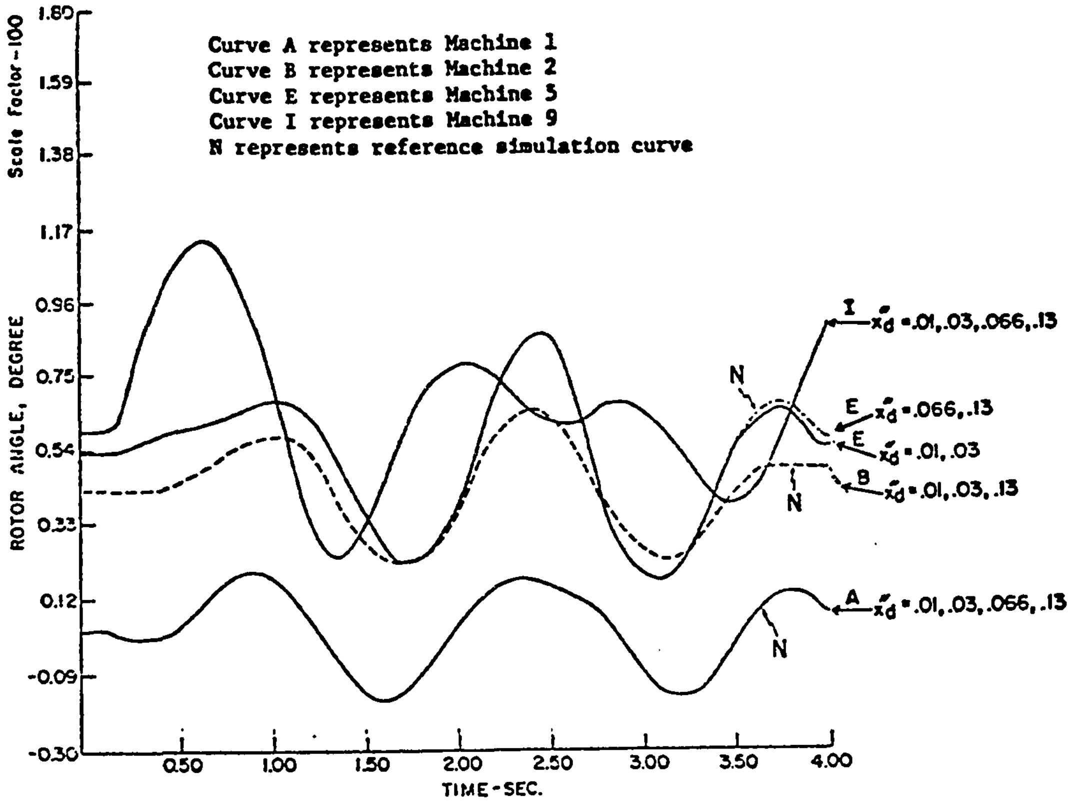


FIGURE 4-10
TRANSIENT ROTOR ANGLE UPON CHANGING x''_d

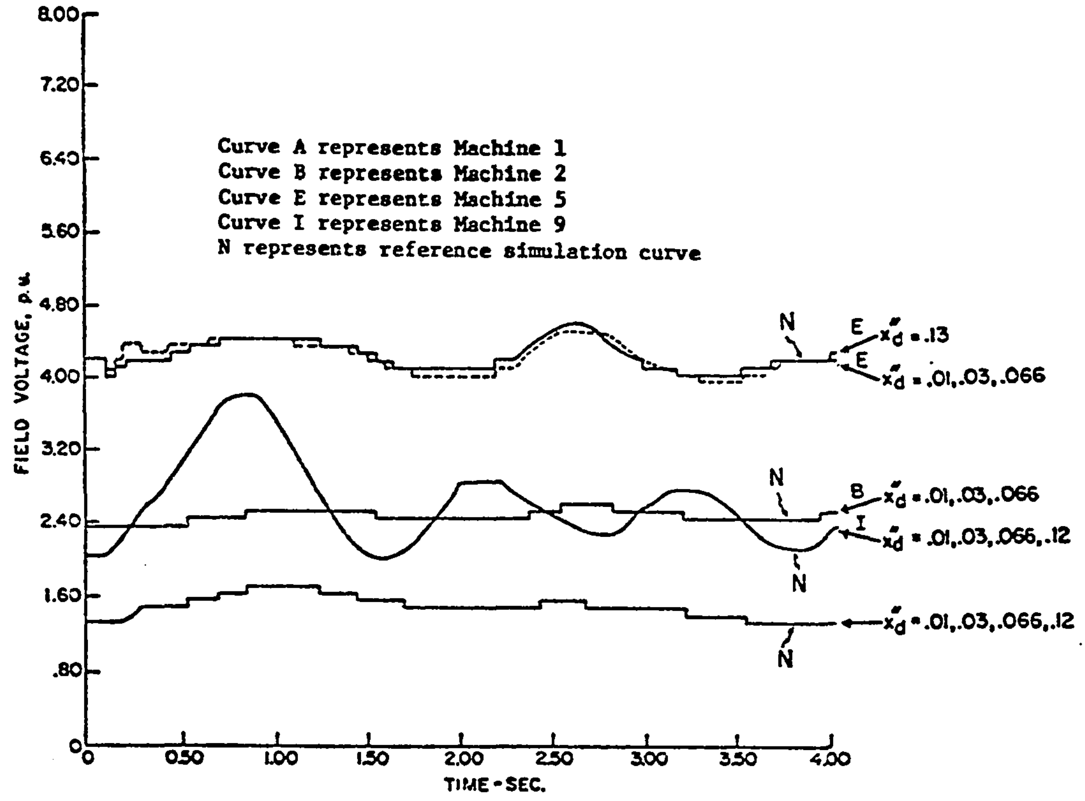


FIGURE 4-11
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING x''_d

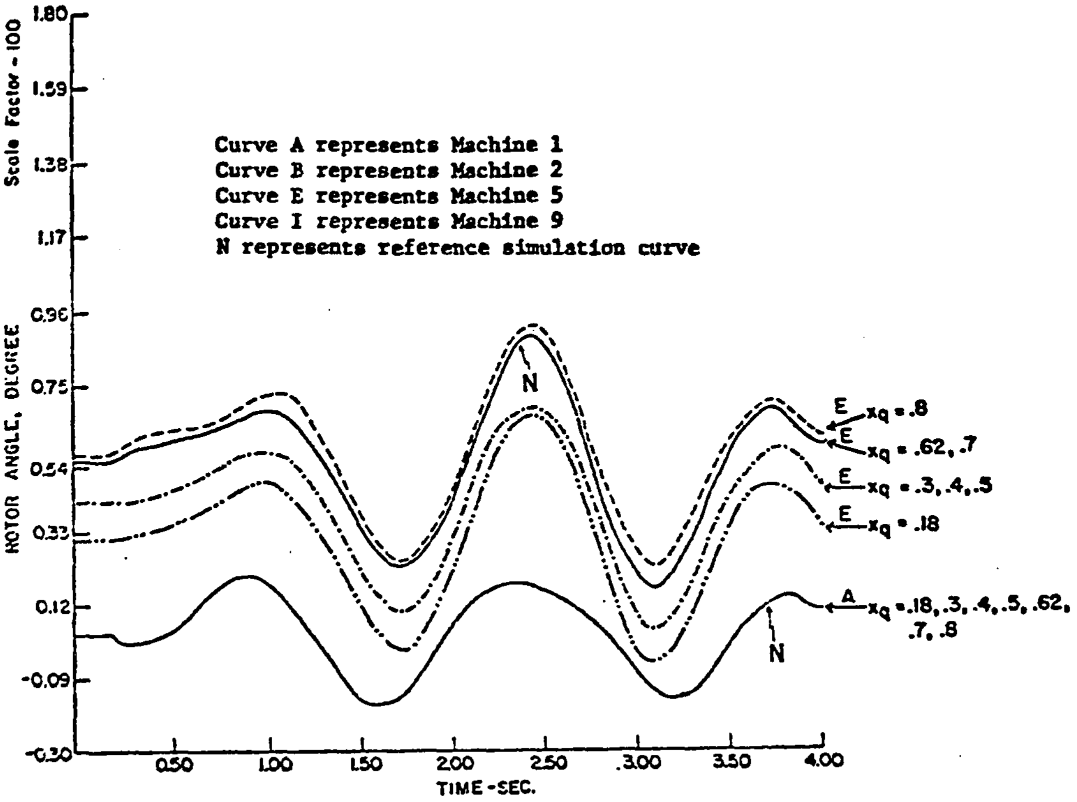


FIGURE 4-12
TRANSIENT ROTOR ANGLE UPON CHANGING x_q

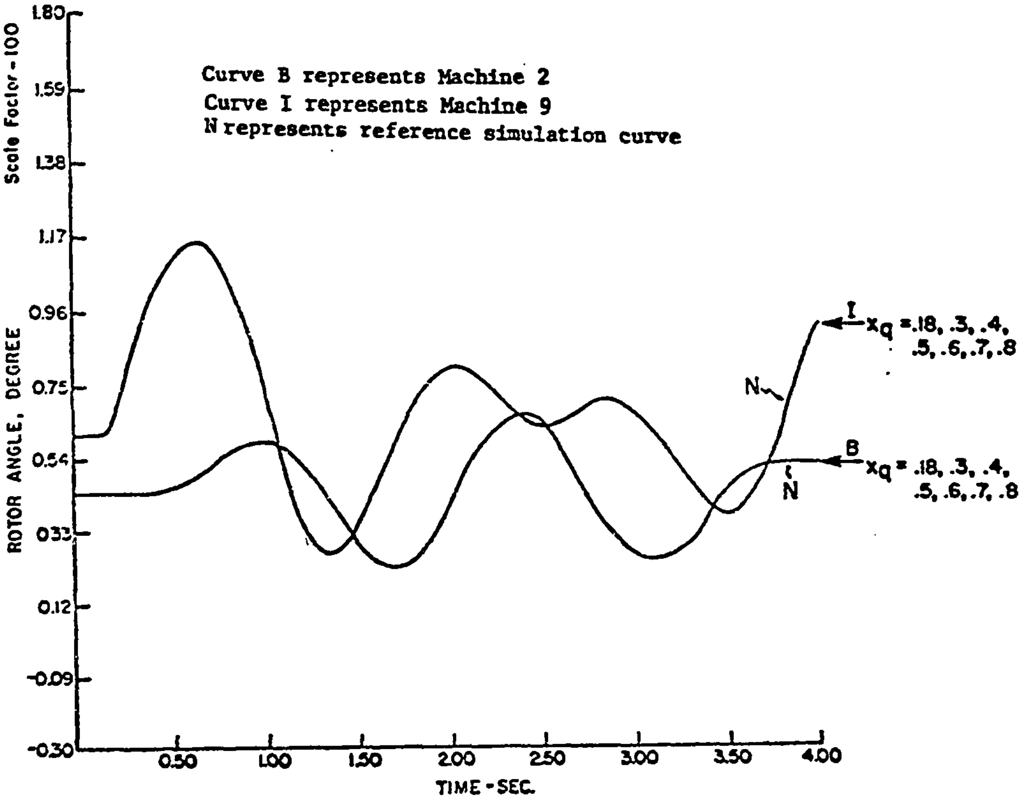


FIGURE 4-13
TRANSIENT ROTOR ANGLE UPON CHANGING x_q

angle shows a slight change upon changing x_q while the rotor angle of machines 1, 2 and 9 doesn't change at all.

The plot of the system's transient rotor angle for several values of x_q is observed using machine model 3 simulation. The transient rotor angle of machine 5 shows a high oscillation with increasing the value of x_q. But the transient rotor angle of machines 1, 2 and 9 does not show a change with the value of x_q changing.

The plot of the system's transient rotor angle for several values of x_q and x_q' was observed using machine model 2 simulation. Note that machine model 2 carried the same value for x_q and x_q'. Machine 9 was unstable and was not effected by changing x_q and x_q'. Machine 5's transient rotor angle shows a change while machines 1 and 2's rotor angle does not change by changing x_q and x_q'.

Figure 4-14 is a plot of the per unit field voltage E_{fd} of the exciter system. It plots for several values of x_q, machine model 5 simulation, comparing the reference curve N with other curves, which corresponds to different values of x_q of machine 5. It was found that the field current increased with increasing values of x_q. In other words, the system has been damped by the exciter system. The field voltage of machines 1, 2 and 9 remains uneffected with the changing of x_q.

The plot of the per unit field voltage E_{fd} of the exciter system for several values of x_q was observed using machine model 4 simulation. Machine 5's field current remained unchanged. This is the same for machines 1, 2 and 9. This shows the system dynamically uncoupled in reference to the field current.

The plot of the per unit field voltage E_{fd} for several values of x_q was observed using machine model 2 and 3. In both models the per unit field E_{fd} of machine 5 showed a slight change, while the other machine's field voltage remained unchanged with x_q changing.

Figure 4-15 is a plot of the machine's internal voltage e'_q, machine 5. It plots for several values of x_q. The figure shows e'_q of machine 5 changing slightly. The change in e'_q is direct provided by the exciter. The other machine's internal voltage remains unchanged.

The plot of the machine's internal voltage for several values of x_q was observed by using machine models 2, 3 and 4. Internal voltage of machine 5 shows the same change on machine model 5 while the other machine's internal voltage remain constant for all of the machines using machine model 2, 3 and 4.

4-8 Performance of the Machine Models upon Changing x'_q

Figure 4-16 is a plot of the system's transient rotor angle. It plots for several values of x'_q using machine model 5 simulation. It is found that all of the machine's rotor angles remain uneffected by changing x'_q. One fact is this value of x'_q is so small, it probably could not make any change to the system's eigen value.

The plot of the system's transient rotor angle for several values of x'_q was observed using machine models 3 and 4 simulation. Again all of the machine's rotor angles remain uneffected by changing x'_q. This is because of the system's eigen value was not changed.

Figure 4-17 is a plot of the per unit field voltage E_{fd} of the exciter system. It plots for several values of x'_q by using machine model 5 simulation. Here again, the field current remains unchanged for all machines.

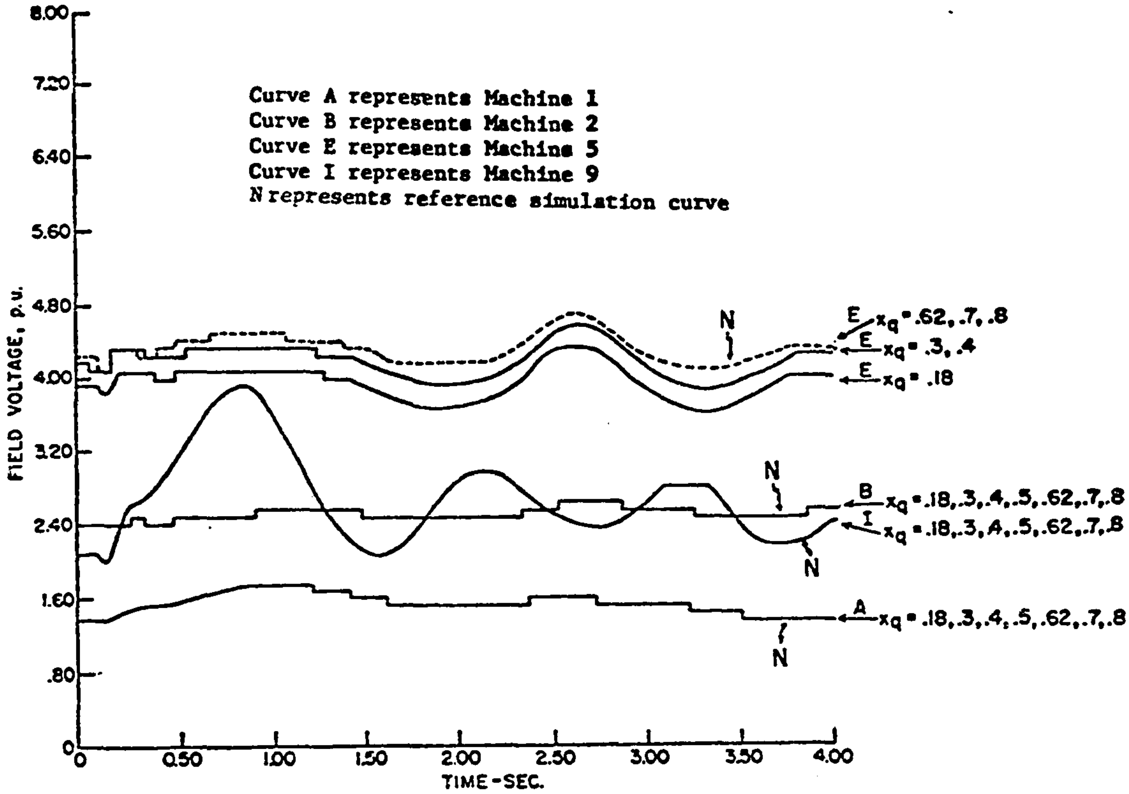


FIGURE 4-14
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING x_q

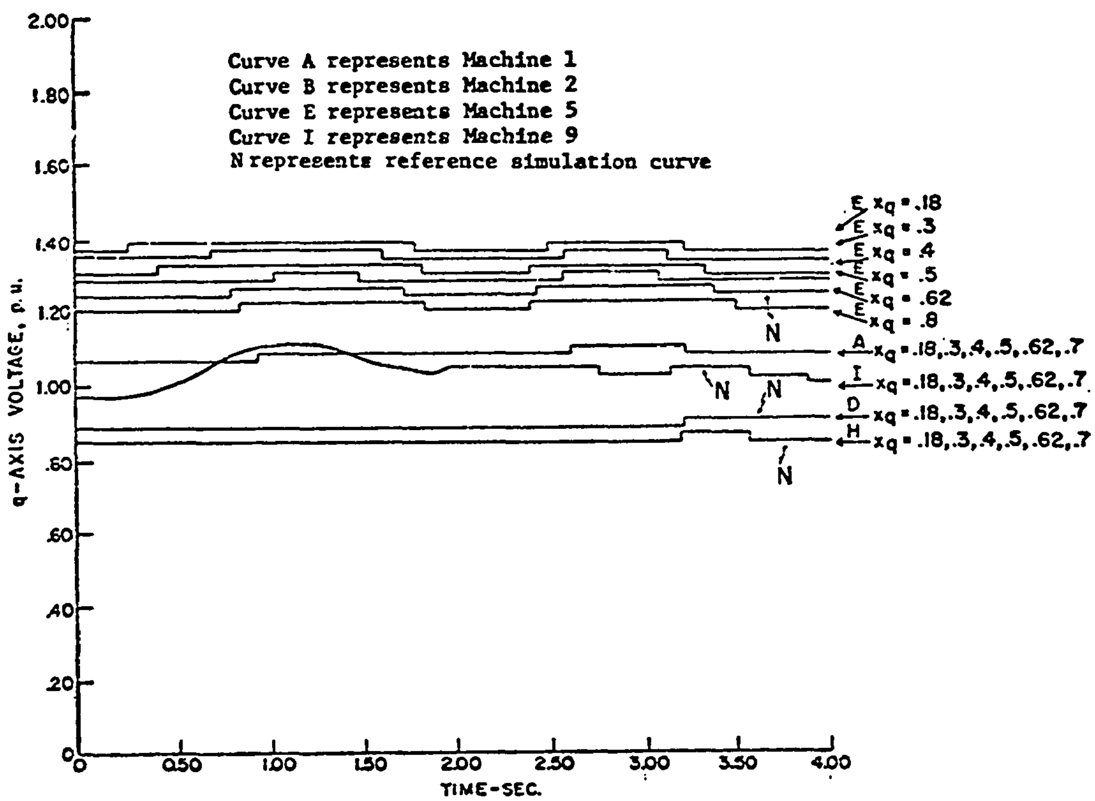


FIGURE 4-15
Q-AXIS TRANSIENT VOLTAGE e_q' UPON CHANGING x_q

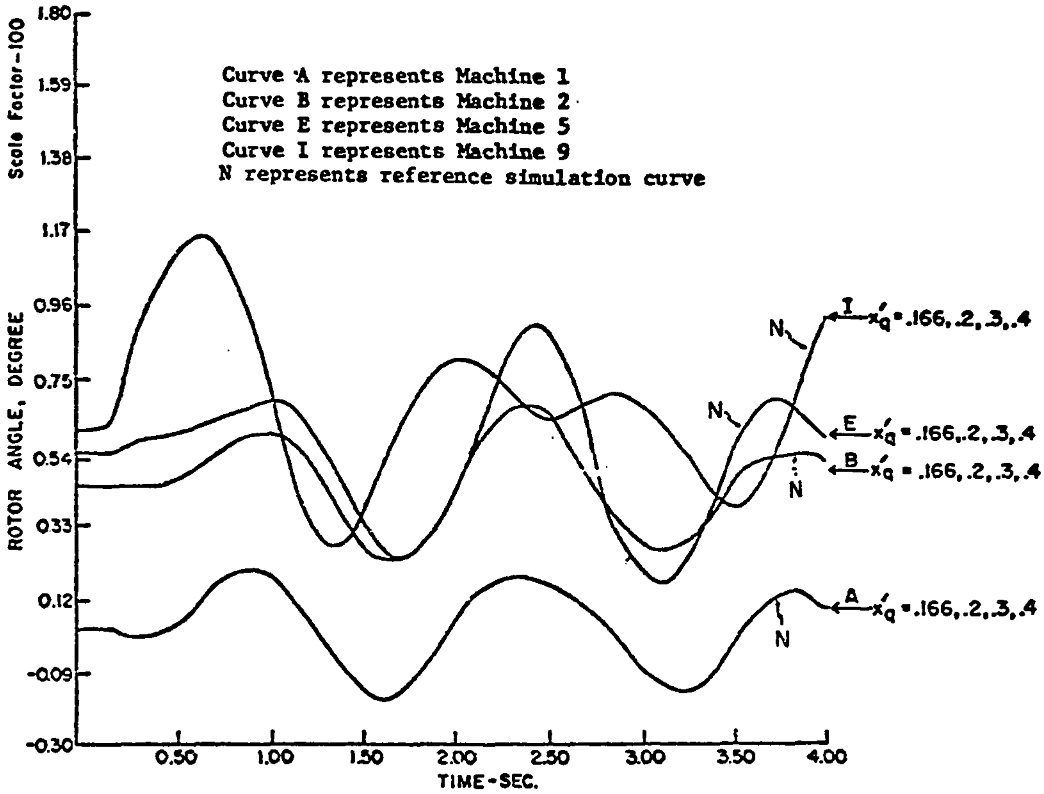


FIGURE 4-16
TRANSIENT ROTOR ANGLE UPON CHANGING x_q'

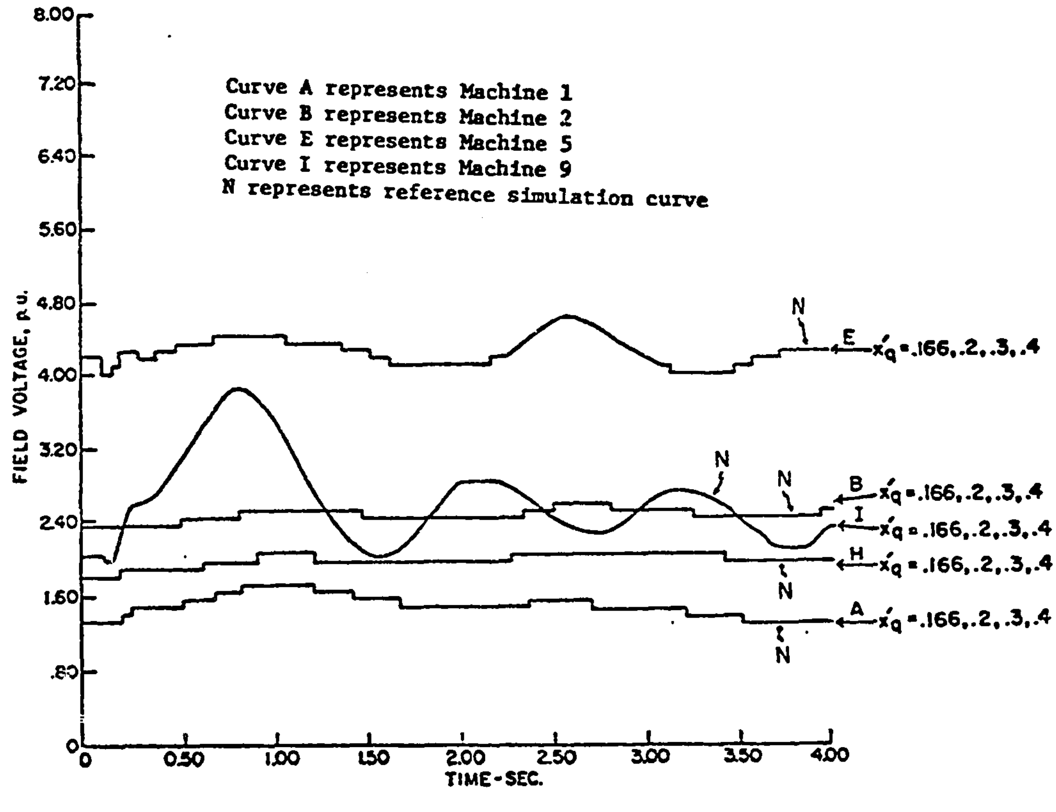


FIGURE 4-17
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING x_q'

The plot of the per unit field voltage E_{fd} of the exciter system, using machine model 3 and 4, was observed for several values of x_q'. E_{fd} of the machines remained uneffected for the same reasons mentioned previously.

Figure 4-18 is a plot of the machine's internal voltage e_q'. It is plotted for several values of x_q' using machine model 5 simulation. e_q' of the machines being tested remained constant. This is because the system's eigen value did not change by changing x_q'.

The plot of the machine's internal voltage e_q', using machine model 3 and 4 was observed for several values of x_q'. e_q' for all of the machines remained also uneffected.

4-9 Performance of the Machine Models upon Changing x_q''

Figure 4-19 is a plot of the system's transient rotor angle. It plots for several values of x_q'' using machine model 5 simulation. It was found that all of the machine's rotor angles remained uneffected by changing x_q''. This can be expected since x_q'' is a very small value which cannot contribute to changing the eigen value of the system.

The plot of the system's transient rotor angle for several values of x_q'' was observed using machine model 4 simulation. Again all of the machine's rotor angles remained uneffected by changing x_q'' for the same reasons stated above.

The plot of the per unit field voltage E_{fd} of the exciter, using machine models 5 and 4, was observed for several values of x_q''. It is found that the field voltage of machine 9 showed a slight change. Field voltage of the other machines remained uneffected.

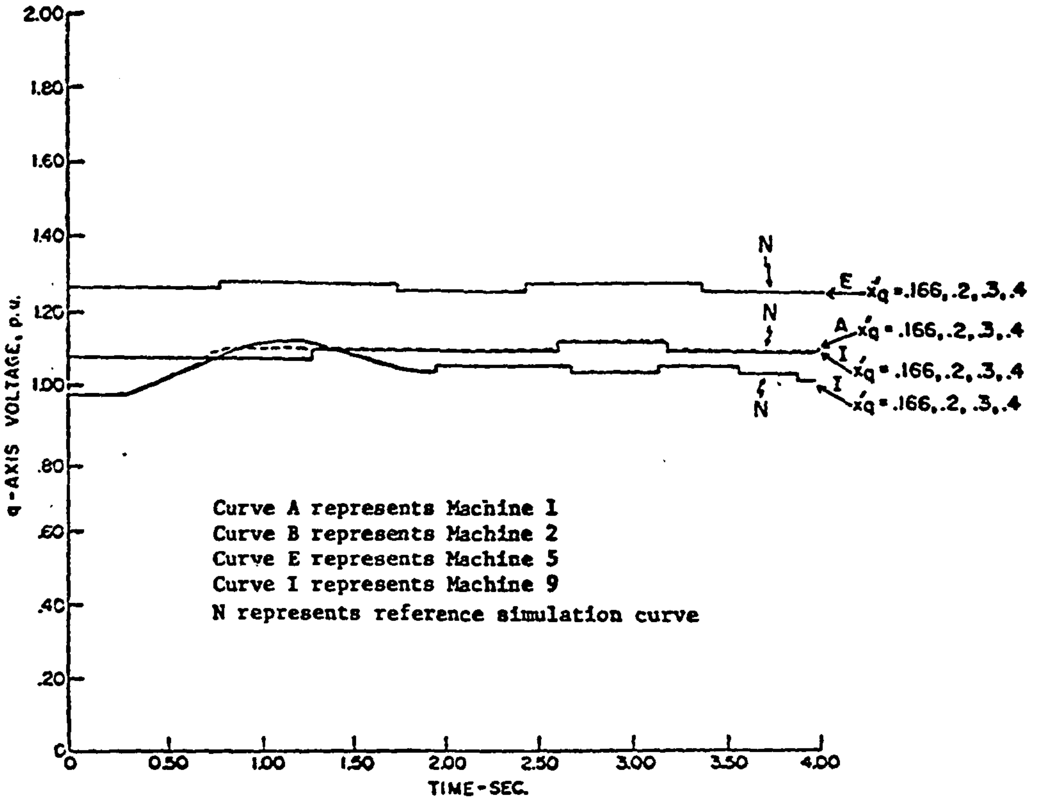


FIGURE 4-18
Q-AXIS TRANSIENT VOLTAGE e_q' UPON CHANGING x_q'

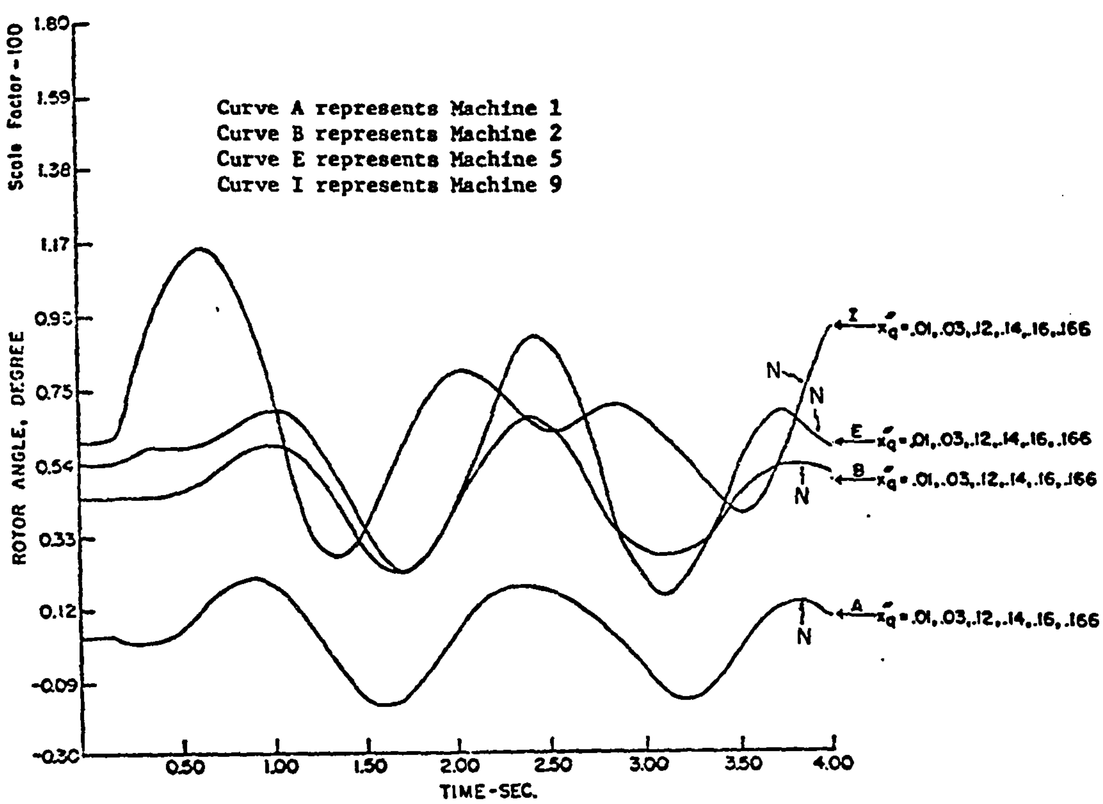


FIGURE 4-19
TRANSIENT ROTOR ANGLE UPON CHANGING x_q''

The plot of the machine's internal voltage e_q' using machine models 4 and 5 was observed for several values of x_q''. Again e_q' of the machine remained uneffected by changing x_q''.

4-10 Performance of the Machine Models upon Changing T_{do}'

Figure 4-20 is a plot of the system's transient rotor angle. It plots for several values of T_{do}' using machine model 5 simulation. Looking at the curves, it showed that the transient rotor angle remained uneffected for the machines being tested.

The plot of the transient angle, using machine model 4 simulation, was observed for several values of T_{do}'. The transient angle of machines 5 and 9 showed high oscillation upon increasing T_{do}'. The transient angle of machine 1 remained uneffected by such a change in T_{do}'. But the transient rotor angle did not show any change, by using machine model 3 simulation, on all of the machines.

The plot of the machine's transient rotor angle for several values of T_{do}', using machine model 2 simulation, was observed. The rotor angle of machine 5 did change with the decreasing amplitude. The rotor angle of machines 1, 2 and 9 did not change although machine 9 severed instability due to the fault that existed in the system.

The plot of the per unit field voltage E_{fd} of the exciter system was observed using machine models 2, 3, 4 and 5 simulation. Machine 5's rotor angle showed a slight change for all of the machine models. But the field voltage in the other machines remained uneffected by varying T_{do}'.

The plot of the machine's internal transient voltage e_q' was observed by using machine models 2, 3, 4 and 5 simulation. e_q' of machine

5 and 9 has changed slightly than the referenced curve N, while other internal voltage of the machine remained uneffected.

4-11 Performance of the Machine Models upon Changing T'_{qo}

Figures 4-21 and 4-22 are plots of the system's transient rotor angle and the per unit field current E_{fd}. The machine's rotor angle remained uneffected while the field voltage of machine 5 showed a very slight change as well as machine 9. The field current of the other machines was not effected at all.

The plot was observed for the machine's rotor angle and the field current using machine models 3 and 4 simulation. Curves of both rotor angle and field current remain unchanged which showed the mode of the system was not changed by changing T'_{qo}.

4-12 Performance of the Machine Models upon Changing T''_{qo}

Figure 4-23 is a plot of the system's rotor angle. It plots for several values of T''_{qo} using machine model 5 simulation. Comparing the rotor angle curves with N reference curve showed a very slight change on the rotor angle of machines 1 and 5. But the rotor angle of machines 2 and 9 remained uneffected. The same test was applied to machine model 4 which showed that all of the machine's rotor angles remained uneffected.

Figure 4-24 is a plot of the per unit field voltage E_{fd} of the exciter system. The field current of machine 5 fluctuated around the reference curve N in which damping was supplied by the exciter which fluctuated too. The field currents of machines 1 and 9 were changed slightly with respect to reference curve N while the field current of machine 2 remained unchanged.

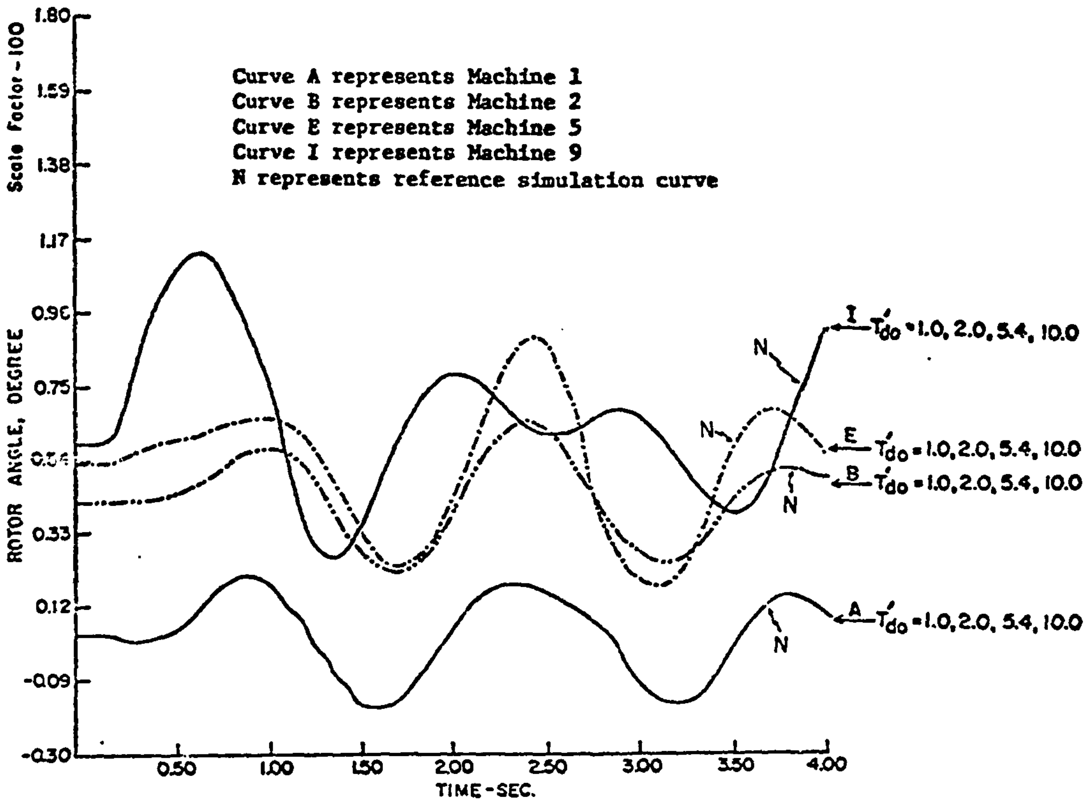


FIGURE 4-20
TRANSIENT ROTOR ANGLE UPON CHANGING T'_{do}

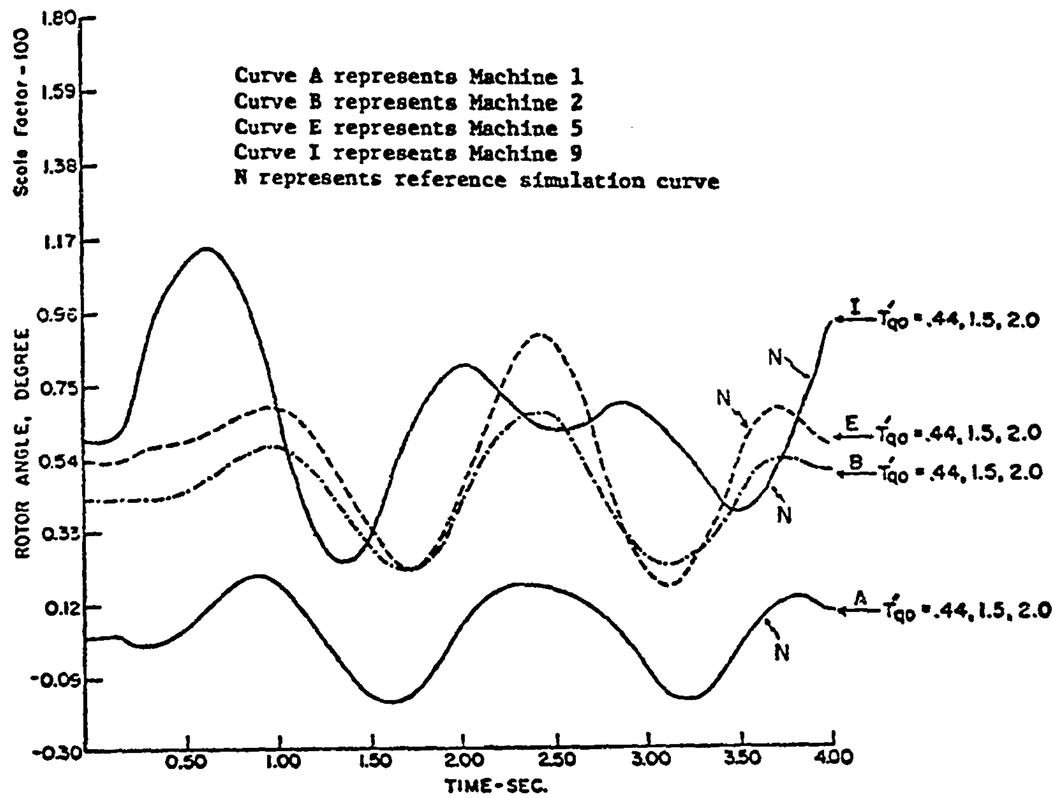


FIGURE 4-21
TRANSIENT ROTOR ANGLE UPON CHANGING T'_{qo}

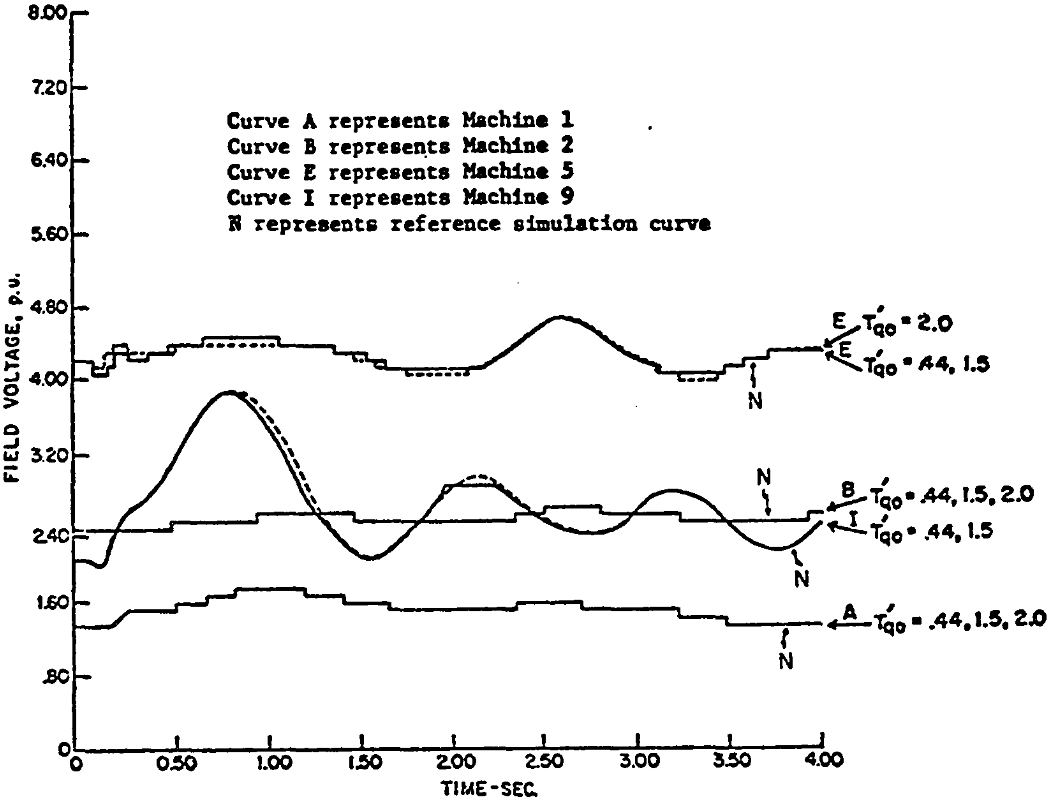


FIGURE 4-22
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING T'_{qo}

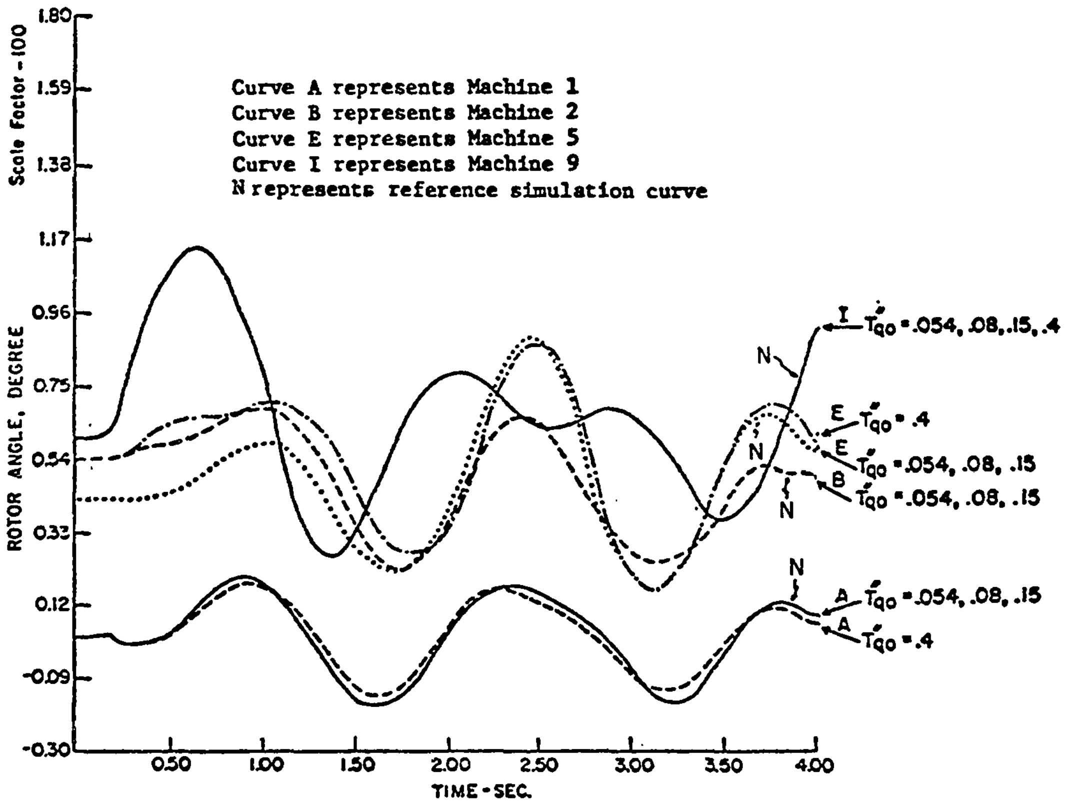


FIGURE 4-23
TRANSIENT ROTOR ANGLE UPON CHANGING T''_{qo}

4-13 Performance of the Machine Models upon Changing H

Figures 4-25 and 4-26 are the plots of the system's transient rotor angle. It plots for several values of the inertia constant H using machine model 5. Increasing the value of H causes the amplitude of the rotor angle of machine 5 to increase, while it showed a reverse on the rotor angle of machine 1, (increasing H serves to suppress the rotor angle oscillation as it was seen in figure 4-20). The rotor angles of machines 2 and 9 were suppressed too by increasing the inertia constant. Therefore, the amplitude of the rotor angle of machine 5 is directly proportional with the inertia constant.

The same test was applied to machine models 2, 3, and 4 with the system's rotor angle being observed. Generally looking at these curves, it was reflected that the rotor angle of machine 5 increased its amplitude for all of the machine models by increasing the inertia constant. It suppressed the rotor angle of machines 1, 2 and 9 by increasing H. Note that machine 9 severed the instability for all inertia values that had been assigned. This is due to the 3-phase fault at bus 29.

Figure 4-27 is a plot of the per unit field voltage E_{fd} of the excitation system. It is plotted for several values of the inertia constant H using machine model 5. The field current of machine 5 showed a slight fluctuation around reference curve N. The field voltage of machine 9 changed slightly while increasing H. The field voltage of the other machines remained uneffected. This test was applied for machine models 2, 3 and 4. The field voltage was observed during this test. It behaved relatively the same as machine model 5.

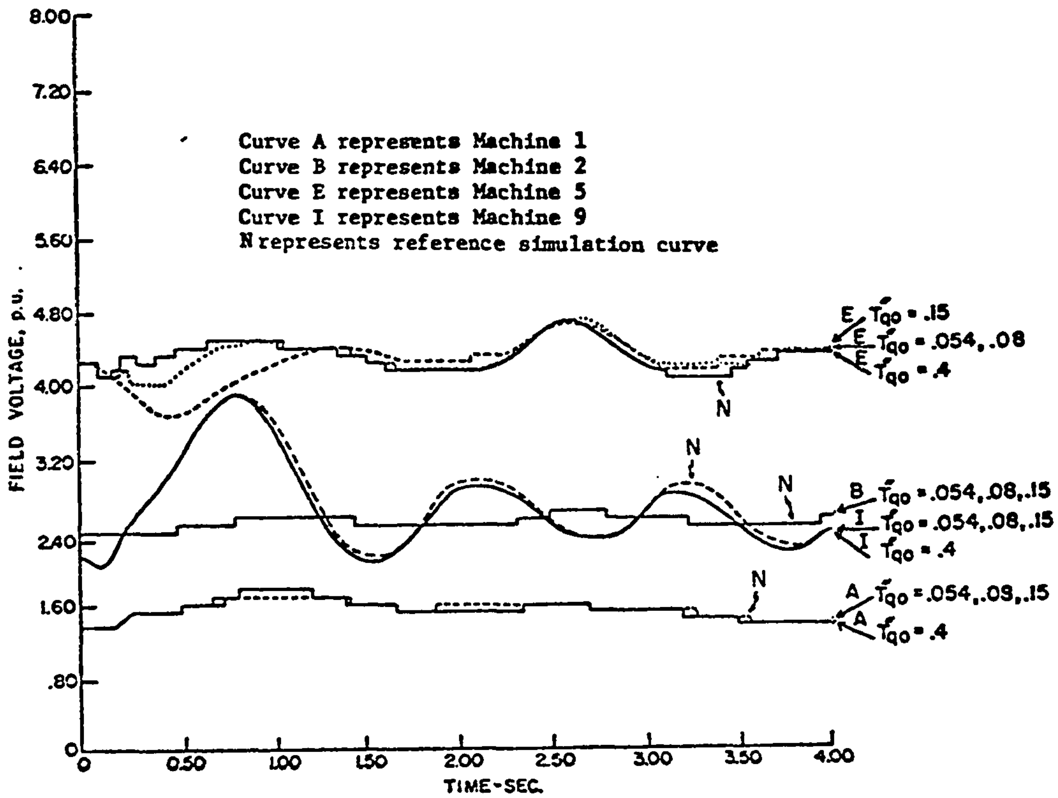


FIGURE 4-24
PER UINT EXCITER OUTPUT E_{fd} UPON CHANGING T''_{qo}

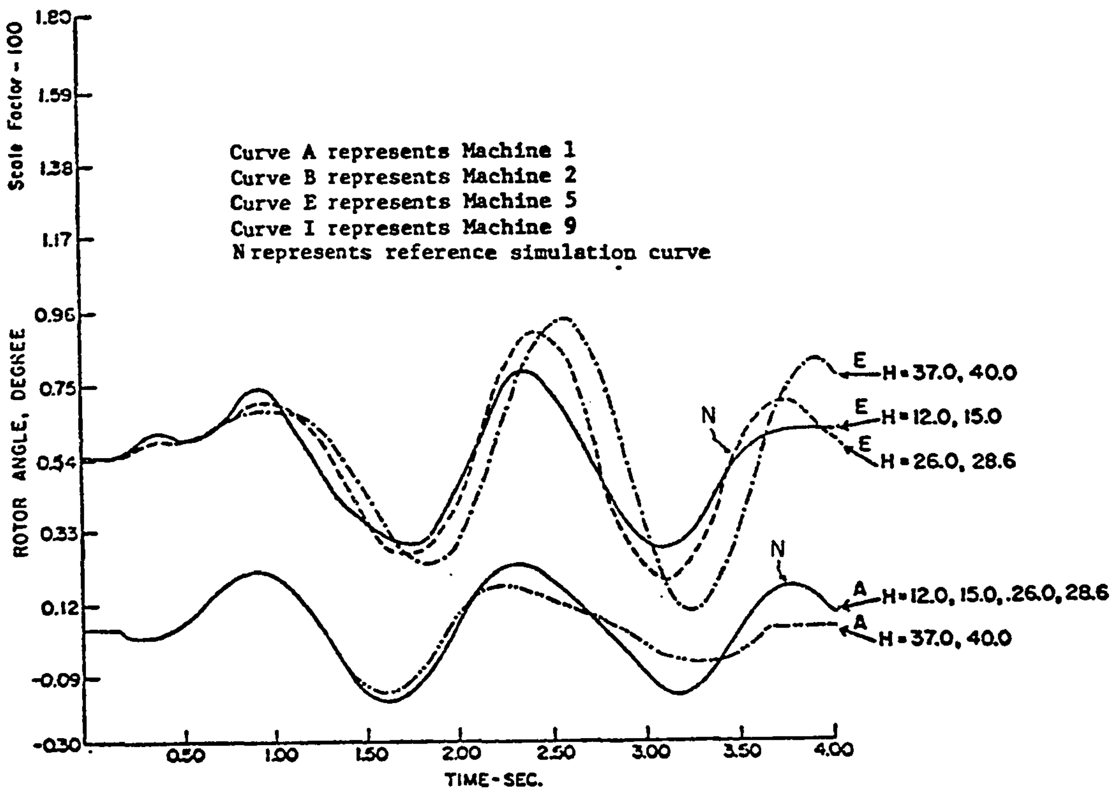


FIGURE 4-25
TRANSIENT ROTOR ANGLE UPON CHANGING H

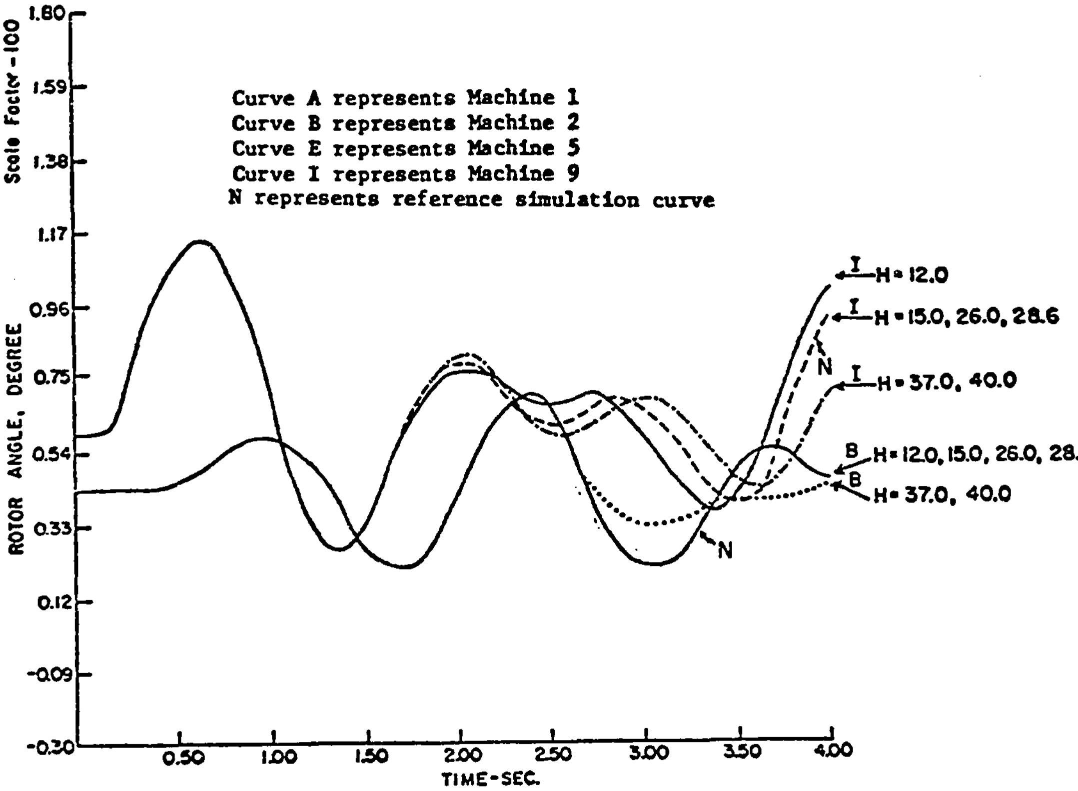


FIGURE 4-26
TRANSIENT ROTOR ANGLE UPON CHANGING H

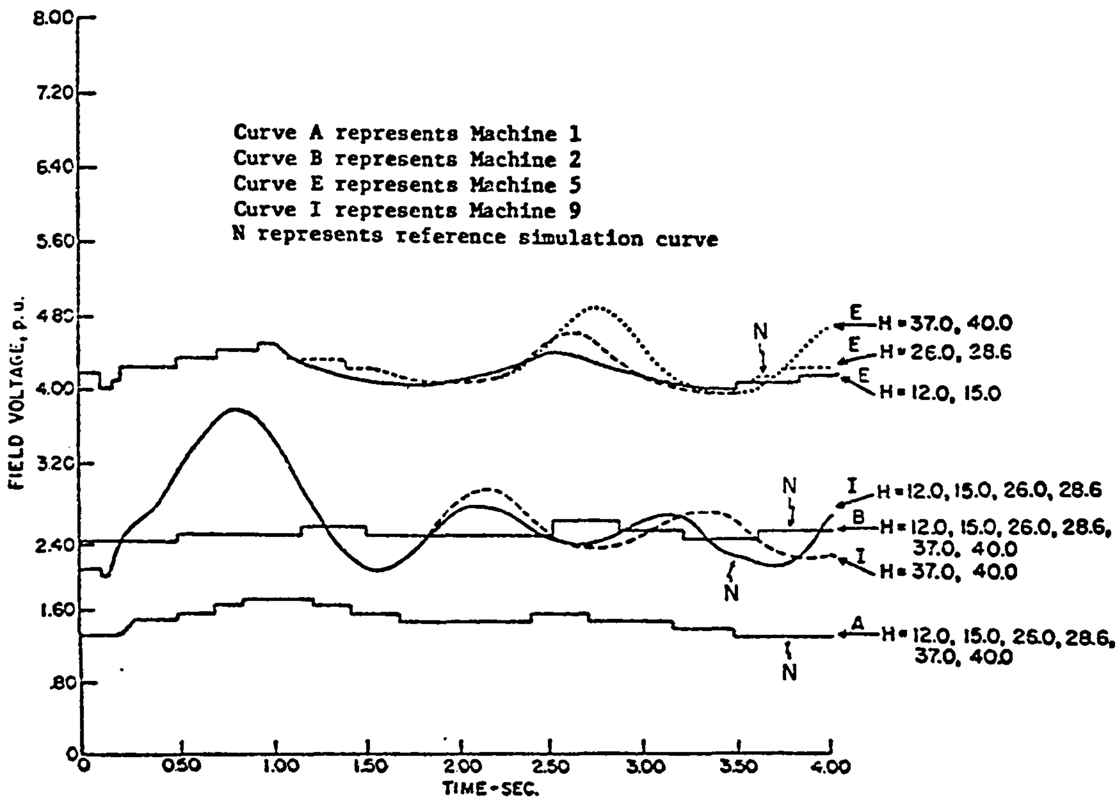


FIGURE 4-27
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING H

The plot of the turbine output power was observed for several values of x_d, x'_d, x''_d, x_q, x'_q and x''_q using machine model 5. It was found that the turbine output power was not sensitive to any of the above machine parameters. This is what would be expected. The plot of the system's rotor angle, field current E_{fd}, and the internal voltage e'_q for several values of the rotor angle was observed using machine model 5 simulation. It was found that there had been no change on the above quantities upon changing the rotor resistance. The fact is it is too small to compare it with the other parameters, hence, it would not change the performance of the system.

4-14 Performance of the Machine Models upon Changing x_q and Holding x_d with abnormal value

Simulation is carried on by holding the abnormal value of x_d and changing the x_q parameter using machine model 5. Figure 4-28 is a plot of the machine's rotor angle. Recall that figures 4-12 and 4-13 represent the machine's rotor angle simulation with varying only the x_q parameter. Comparing figure 4-28 with figures 4-12 and 4-13 you find that they are identical. The rotor angle, the field current and terminal voltage of the machine 5 are identical. The rotor angle of machines 1, 2 and 9 remain uneffected in both cases.

Again comparing figure 4-14, this is a plot of the field current upon changing x_q only, and figure 4-29, which is a plot of the field current upon changing x_q and holding x_d equal to 1.0 per unit, it showed a difference in the amount of damping used for machine 5. Figure 4-29 shows a higher field current used than in figure 4-14, this is reflected in the amount of damping supplied by the exciter to machine 5 upon changing

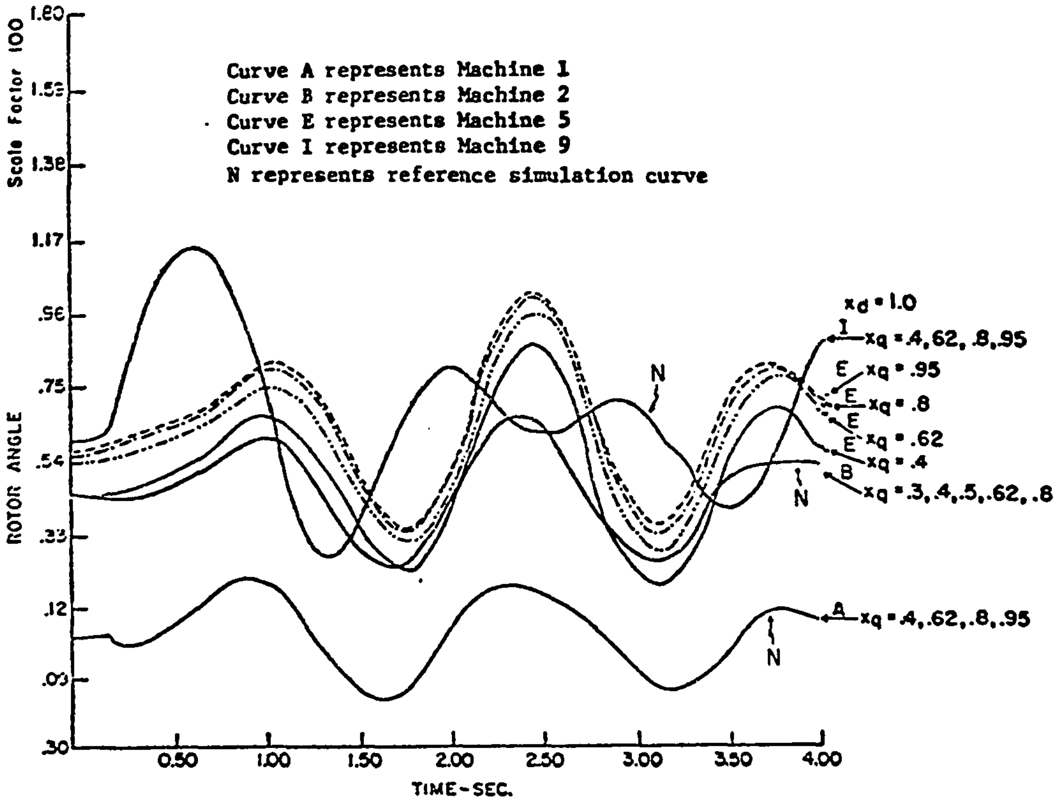


FIGURE 4-28
TRANSIENT ROTOR ANGLE UPON CHANGING x_q WITH x_d = 1.0 per unit

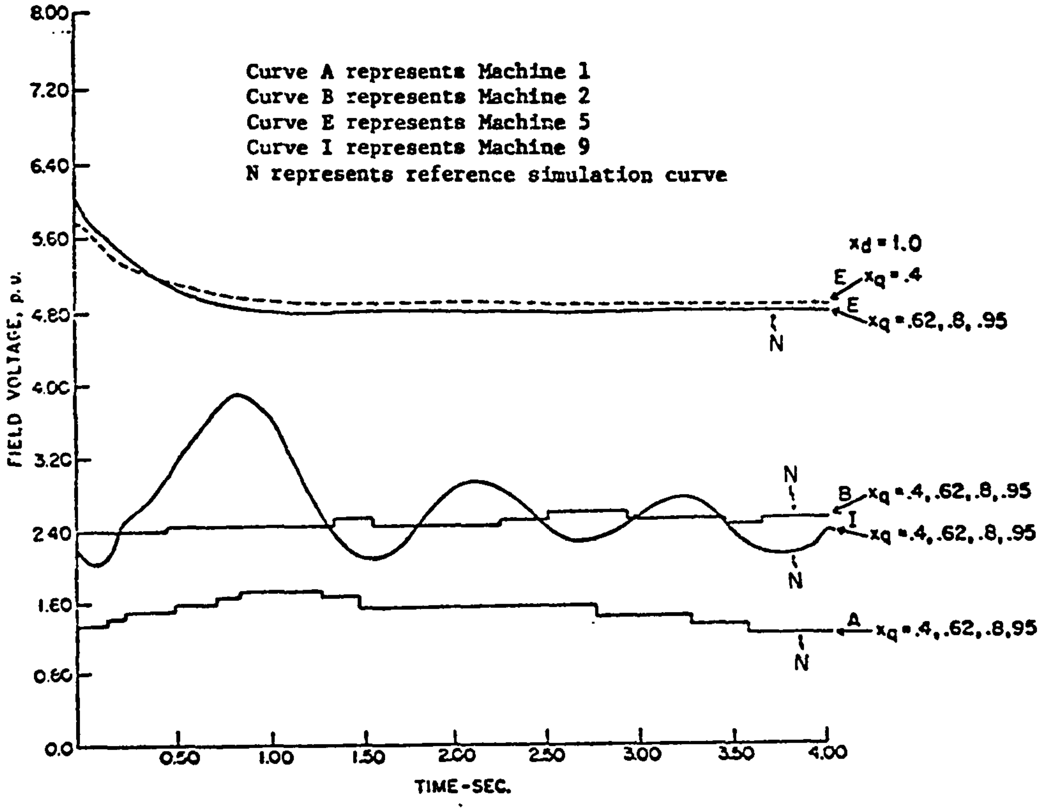


FIGURE 4-29
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING x_q WITH x_d = 1.0 per unit

x_d and x_q which is larger. The field current of machines 1, 2 and 9 remain unchanged for both cases.

Figure 4-30 is a plot of the machine's internal voltage e'_q. It is a plot for several values of x_q and holding the abnormal value of x_d. Comparing figure 4-15, which changes only the x_q values, and figure 4-30 we would find that figure 4-15, the internal voltage of machine 5, was more sensitive to the change than the internal voltage of machine 5 which was shown in figure 4-30.

4-15 Performance of the Machine Model 5 Upon Perturbation Terminal Voltage of Machine 5 as well as Varying its Parameters

The initial terminal voltage of machine 5 was 1.012 per unit, (this is given in appendix G). The simulation will consider the small perturbation of terminal voltage of machine 5 which is equal to 1.092 per unit. Figure 4-31, 4-32, 4-33 and 4-34 are plots of the machine's rotor angle, field current and internal machine voltage e'_q for several values of the x_d parameter. It was found that these curves are identical to the machine's performance by changing only the x_d parameter, this is shown in figure 4-2, 4-3, 4-4 and 4-5.

Figures 4-35, 4-36, 4-37 and 4-38 are plots of the machine's rotor angle, field current and internal machine voltage e'_q for several values of the x'_d parameter. It was found that there were no differences between this simulation and the one in which we only changed the x'_d parameter as seen in figures 4-6, 4-7, 4-8 and 4-9.

Figures 4-39, 4-40, 4-41 and 4-42 are plots of the machine's rotor angle, field current E_{fd}, and internal machine voltage for several values of the x_q parameter. By comparing these figures with figures 4-12, 4-13, 4-14 and 4-15, it was found that these figures were identical.

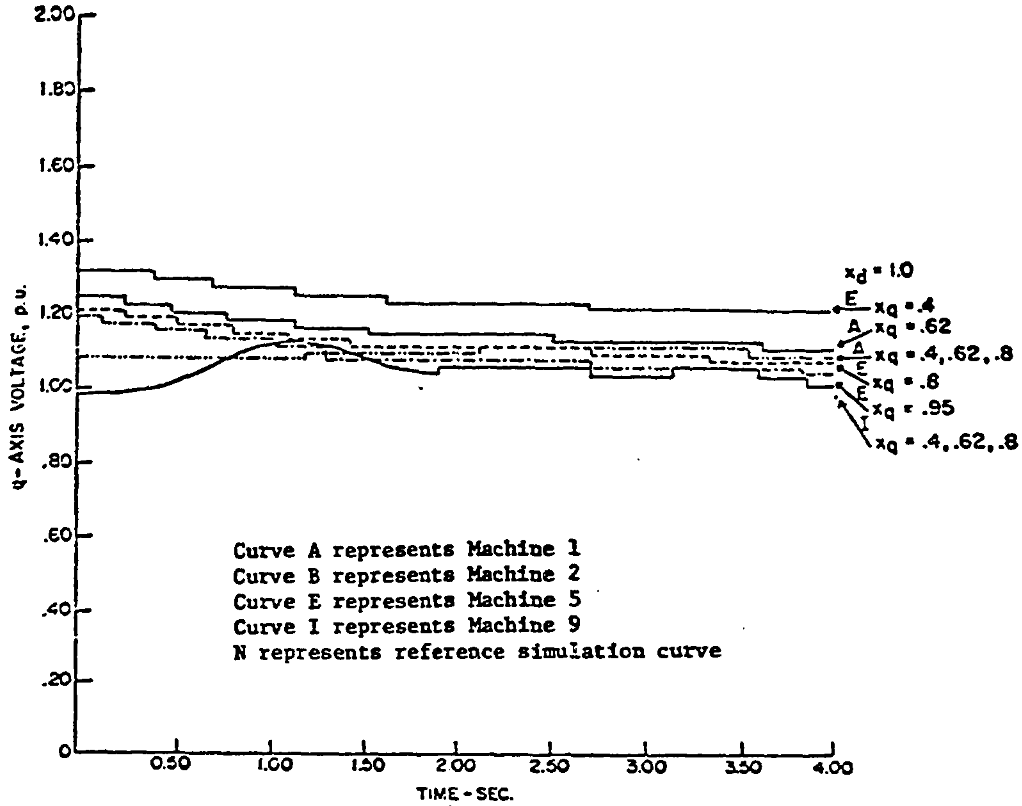


FIGURE 4-30
Q-AXIS TRANSIENT VOLTAGE e'_q UPON CHANGING x_q WITH x_d = 1.0 per unit

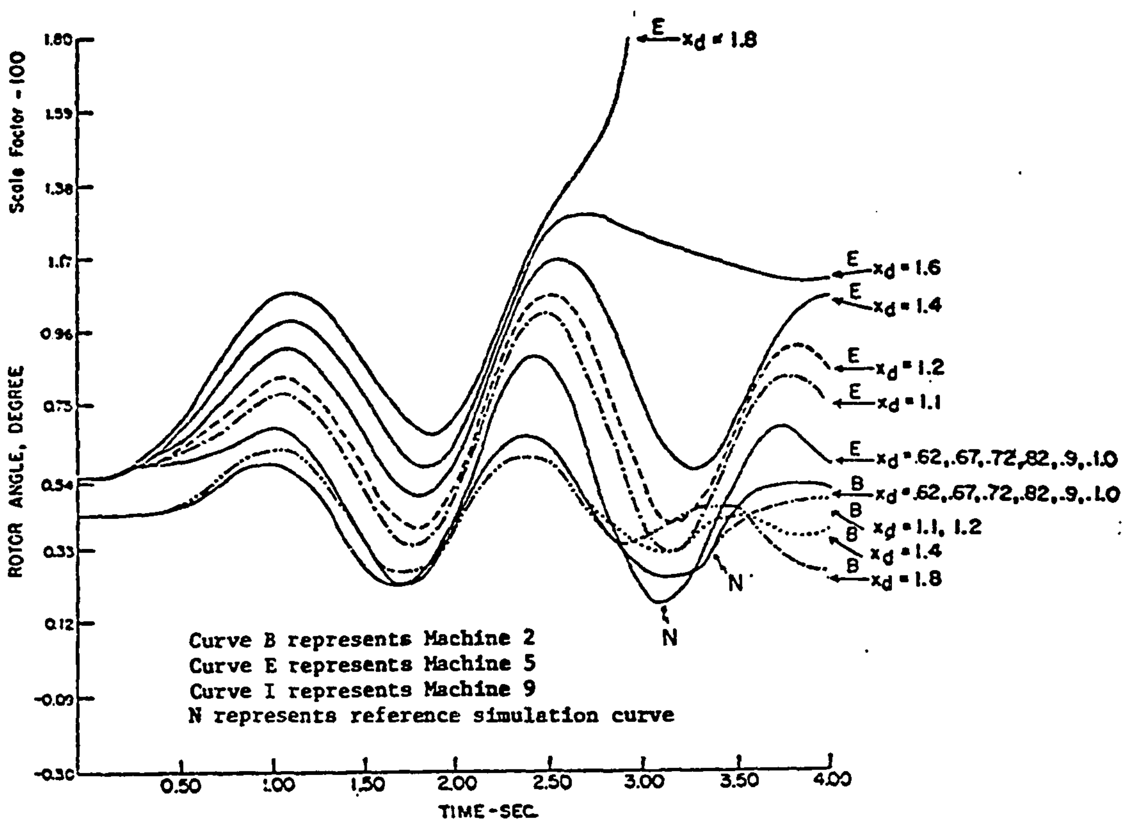


FIGURE 4-31
TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL VOLTAGE AND x_d

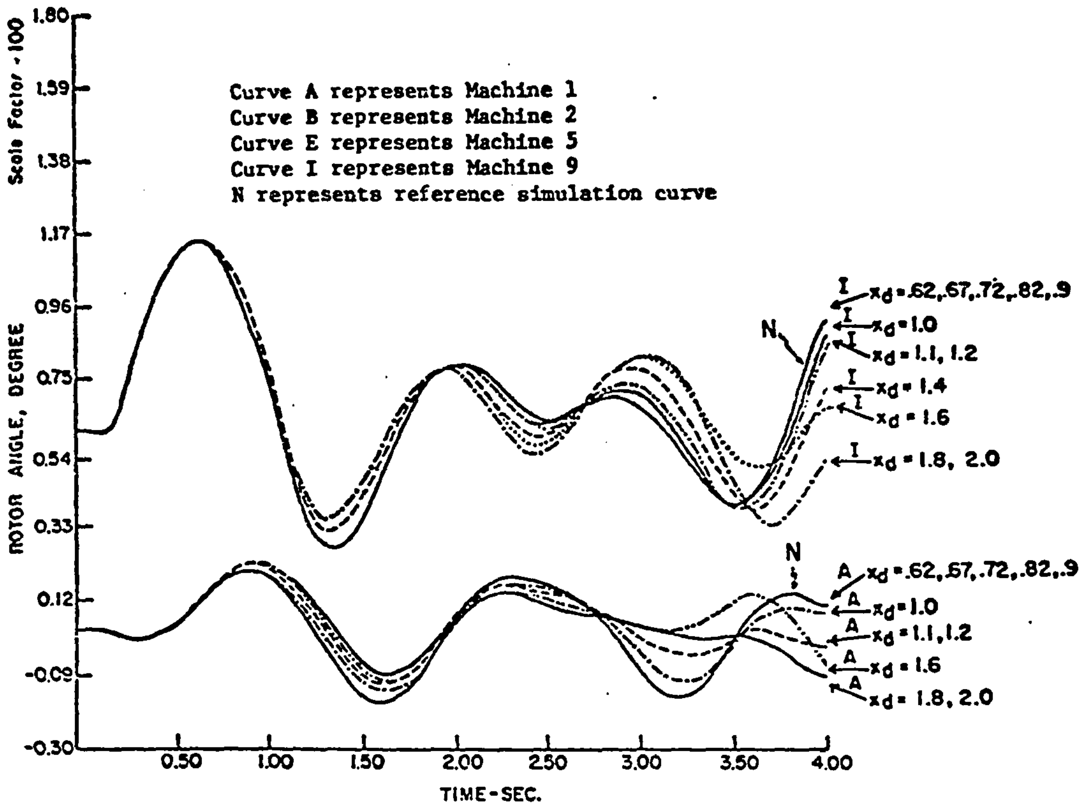


FIGURE 4-32
TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_d

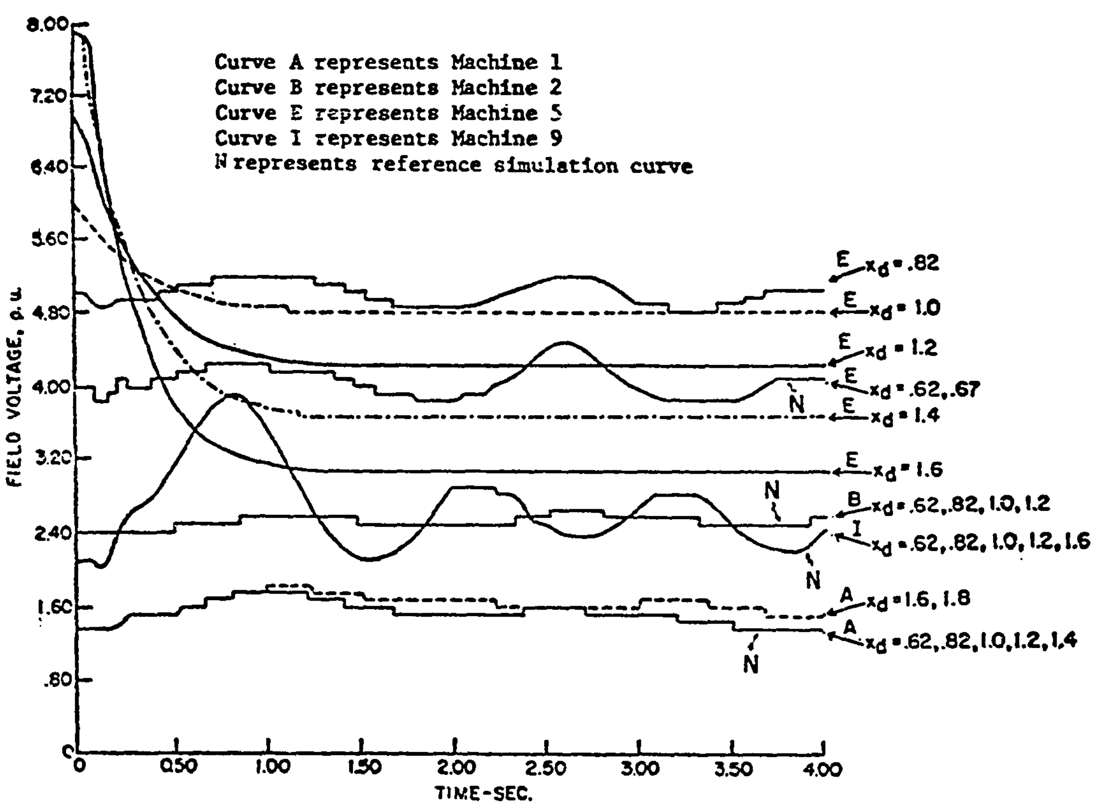


FIGURE 4-33
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING TERMINAL VOTLAGE AND x_d

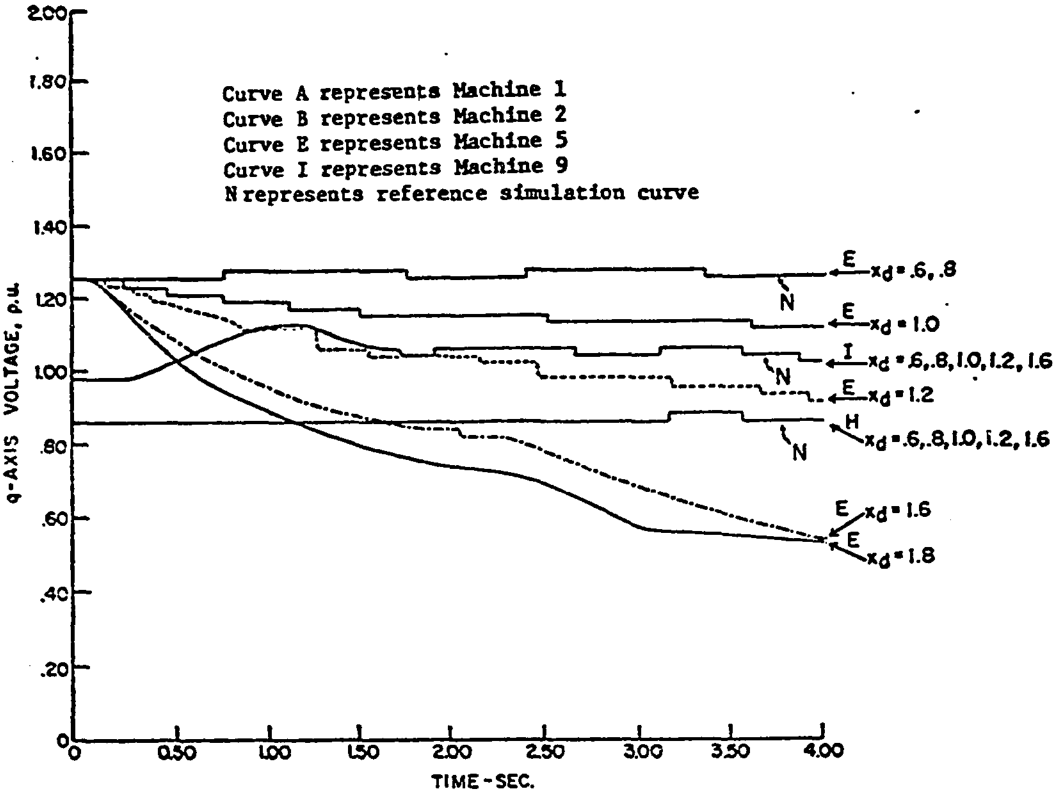


FIGURE 4-34

Q-AXIS TRANSIENT VOLTAGE e_q' UPON CHANGING TERMINAL VOLTAGE AND x_d

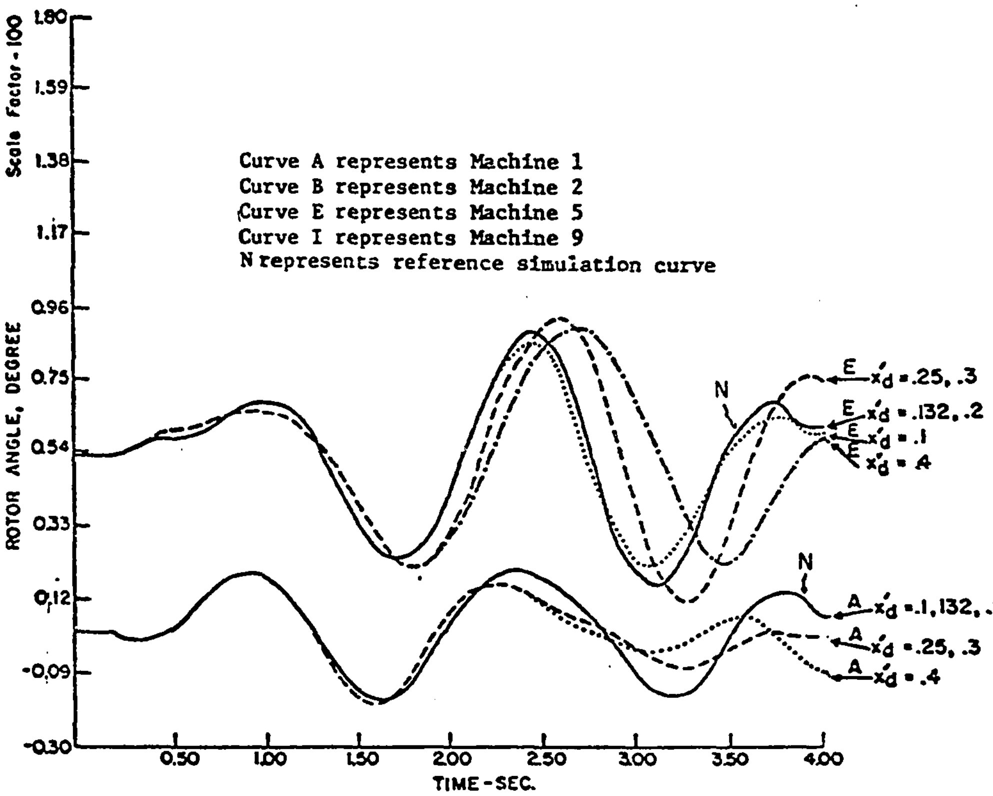


FIGURE 4-35

TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL VOLTAGE AND x_d'

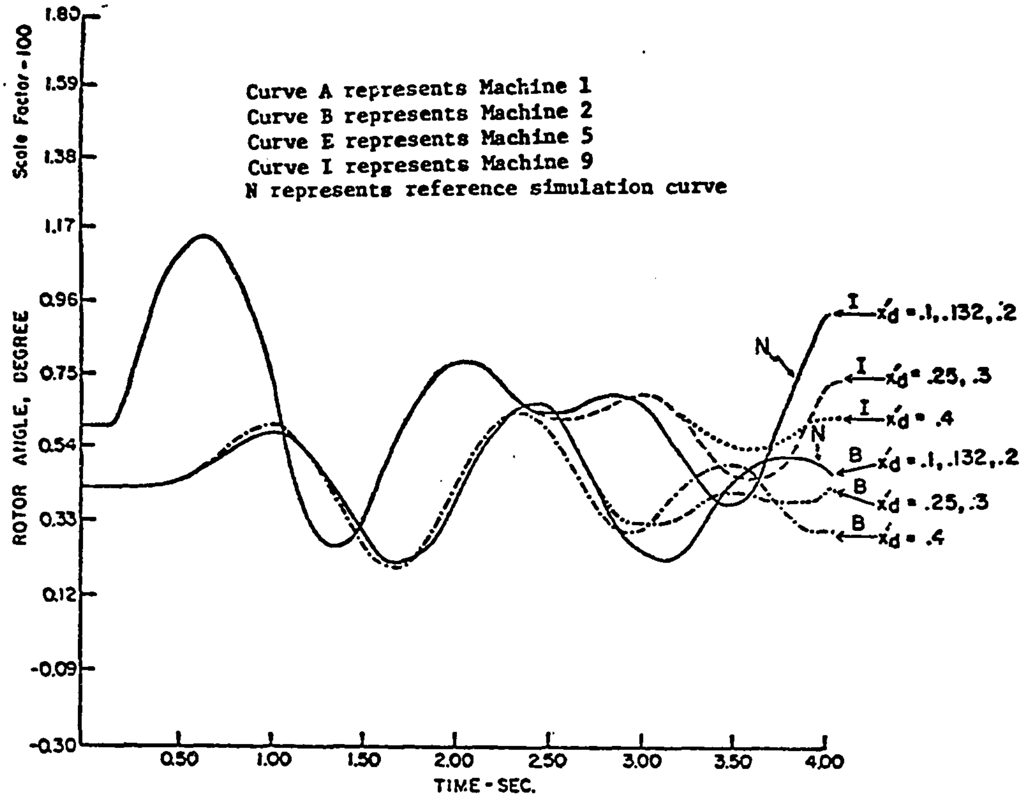


FIGURE 4-36
TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL VOTLAGE AND x'_d

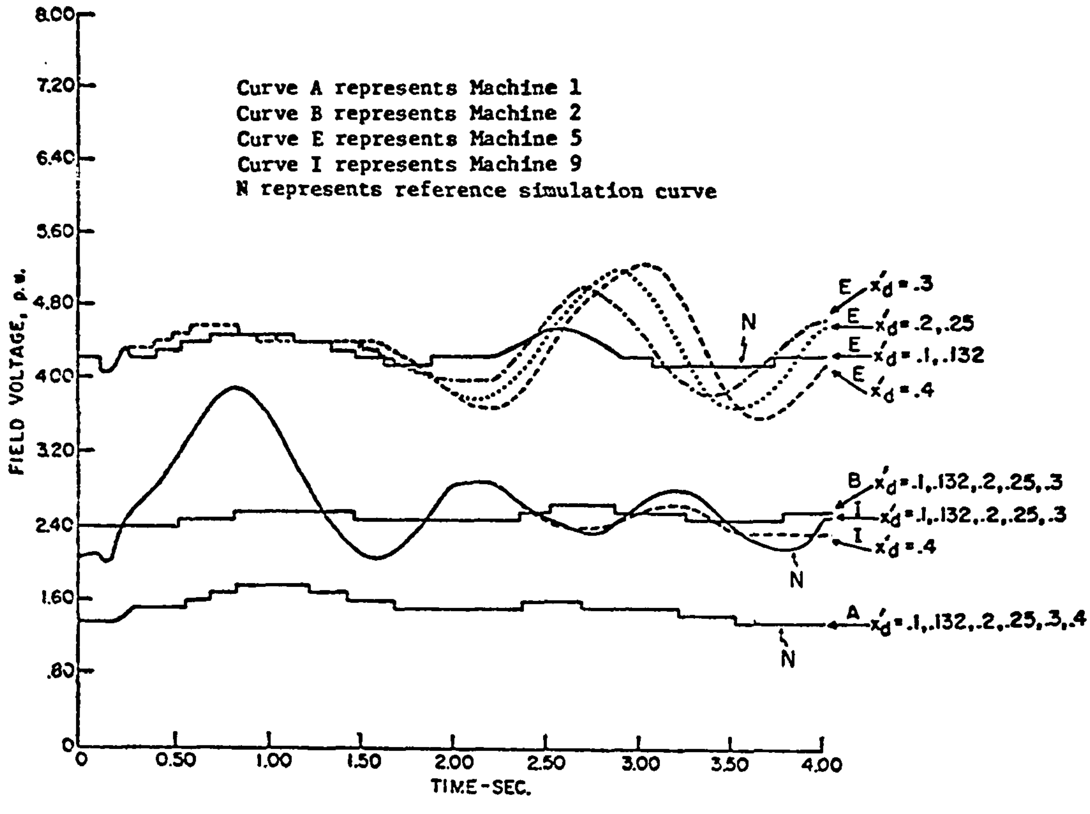


FIGURE 4-37
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING INITIAL TERMINAL VOLTAGE AND x'_d

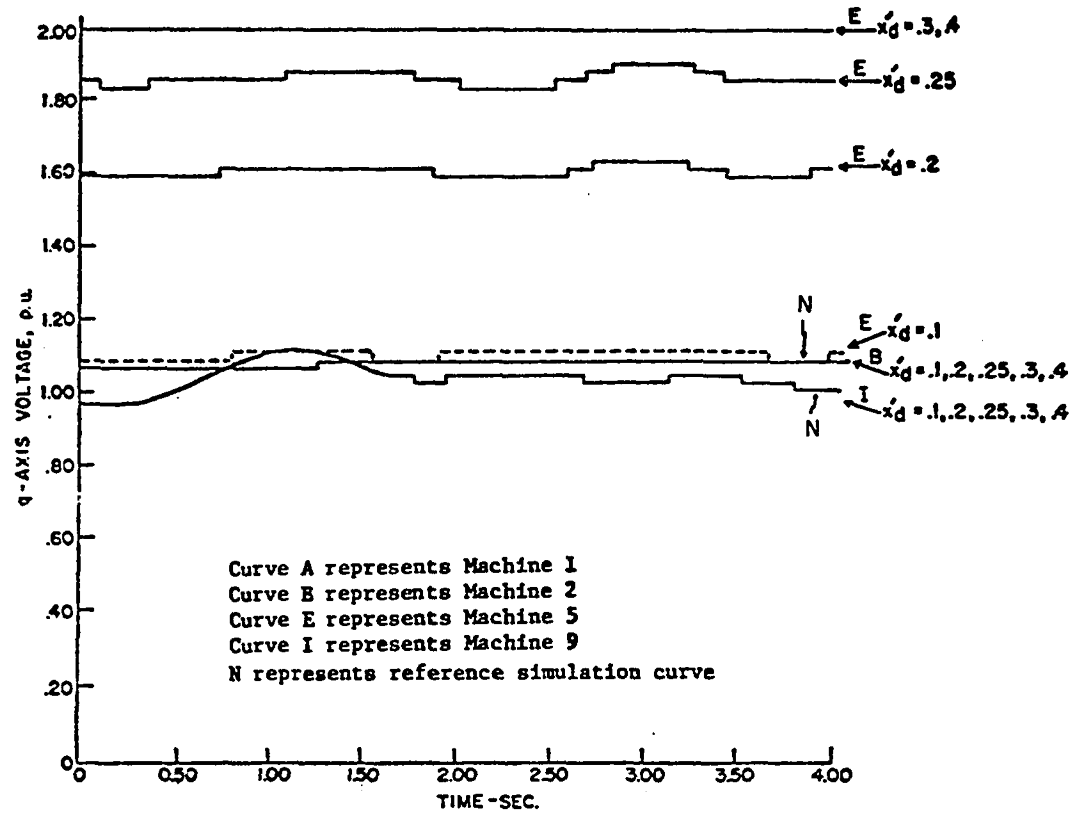


FIGURE 4-38

Q-AXIS TRANSIENT VOLTAGE e'_q UPON CHANGING INITIAL TERMINAL VOLTAGE AND x'_d

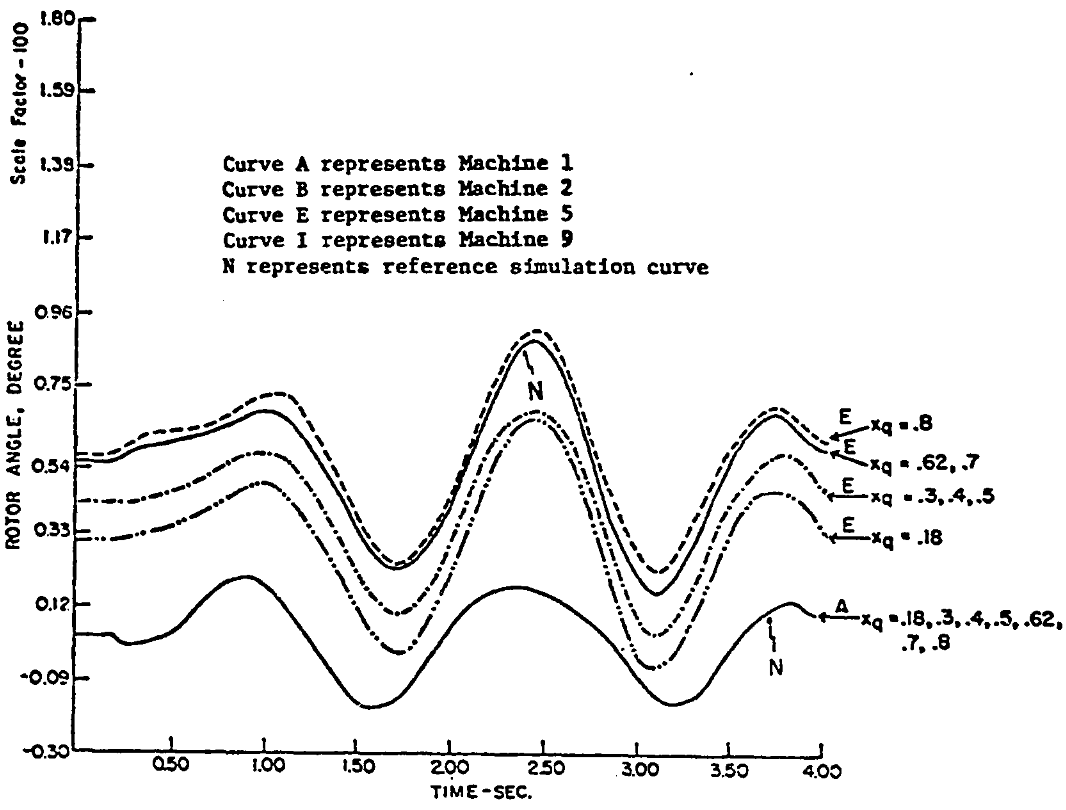


FIGURE 4-39

TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_q

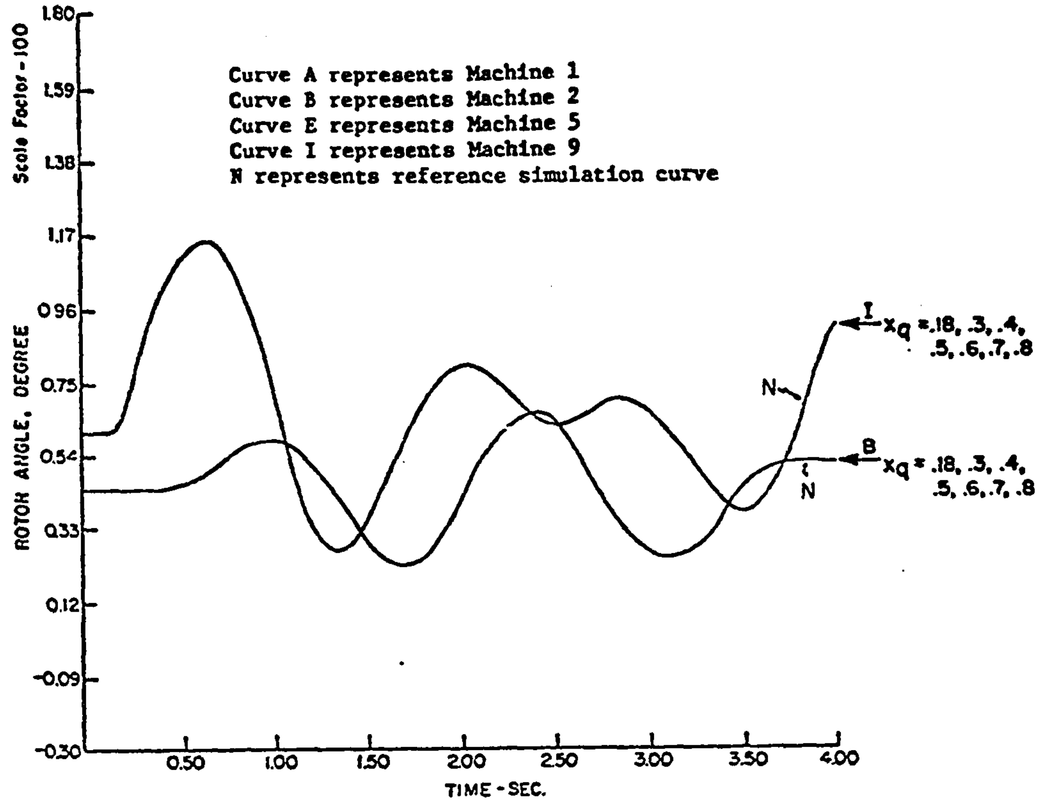


FIGURE 4-40
TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_q

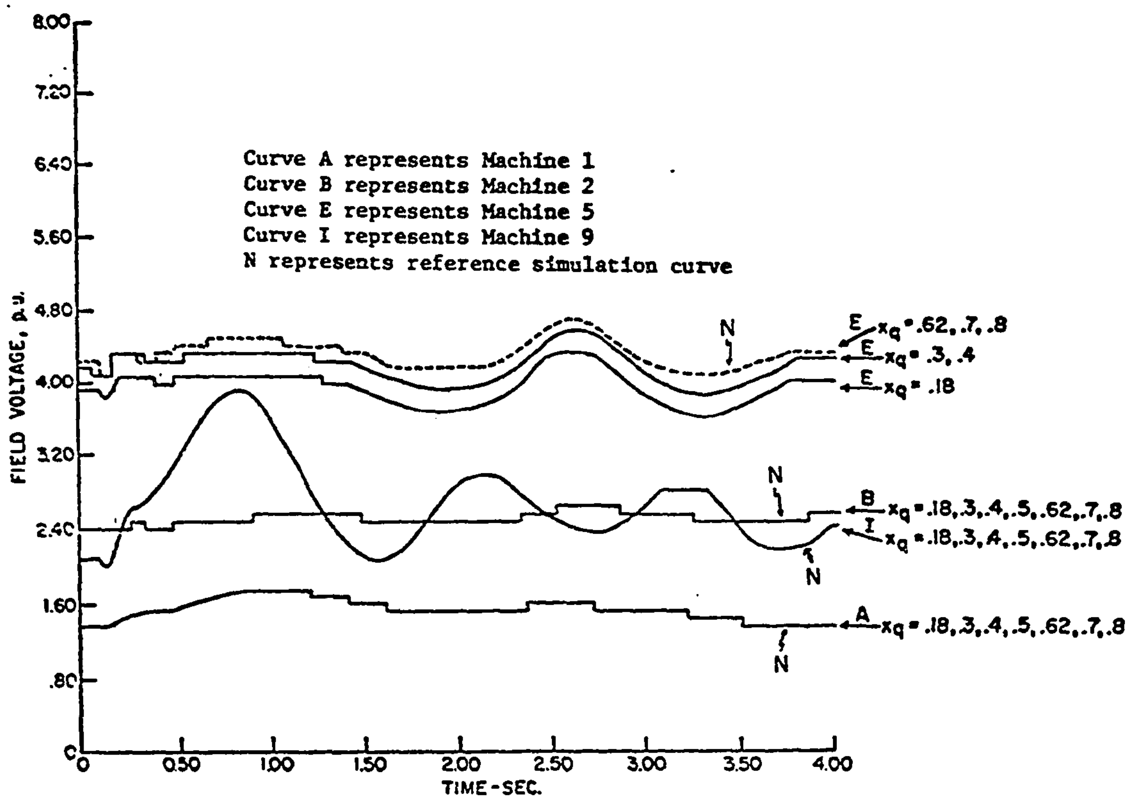


FIGURE 4-41
PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_q

Figures 4-43, 4-44 and 4-45 are plots of the machine's rotor angle, field current E_{fd} and the internal machine voltage for several values of the x'_q parameter. Looking at these figures it showed that they were ddentical with figures 4-16, 4-17, and 4-18 when changing only the x'_q parameter.

Therefore, the conclusion of this simulation was that there was not a major effect to the system under the pertubation initial condition of the terminal voltage of machine 5 by 1.092 per unit.

4-16 Summary

It is known that power systems are large and complex. Nonlinearity does exist in machine representation, load representation and line representation. Therefore, most of the stability studies in power systems are done by simulation. This consists of a step-by-step integration of the system's differential equations by using numerical techniques. This chapter presents a computer simulation of a synchronous machine's performance under variation of machine 5's data and the impact of this data on the system's stability. The simulation reflected the following parameters.

The x_d parameter has an adverse effect on the system's stability. It causes machine 5 to be unstable at the value of x_d equal to 1.8 per unit (machine 5 simulation), 1.6 per unit (machine model 4 simulation), 1.1 per unit (machine model 3 simulation), and 1.1 per unit (machine model 2 simulation). Also, it has an adverse effect on the performance of other machines of the system study. It damps out the rotor angle of machines 1, 2 and 9 starting at 2.5, 2.5 and 3.0 seconds, respectively. Noted that the breakpoint of x_d which causes machine 5 to be unstable

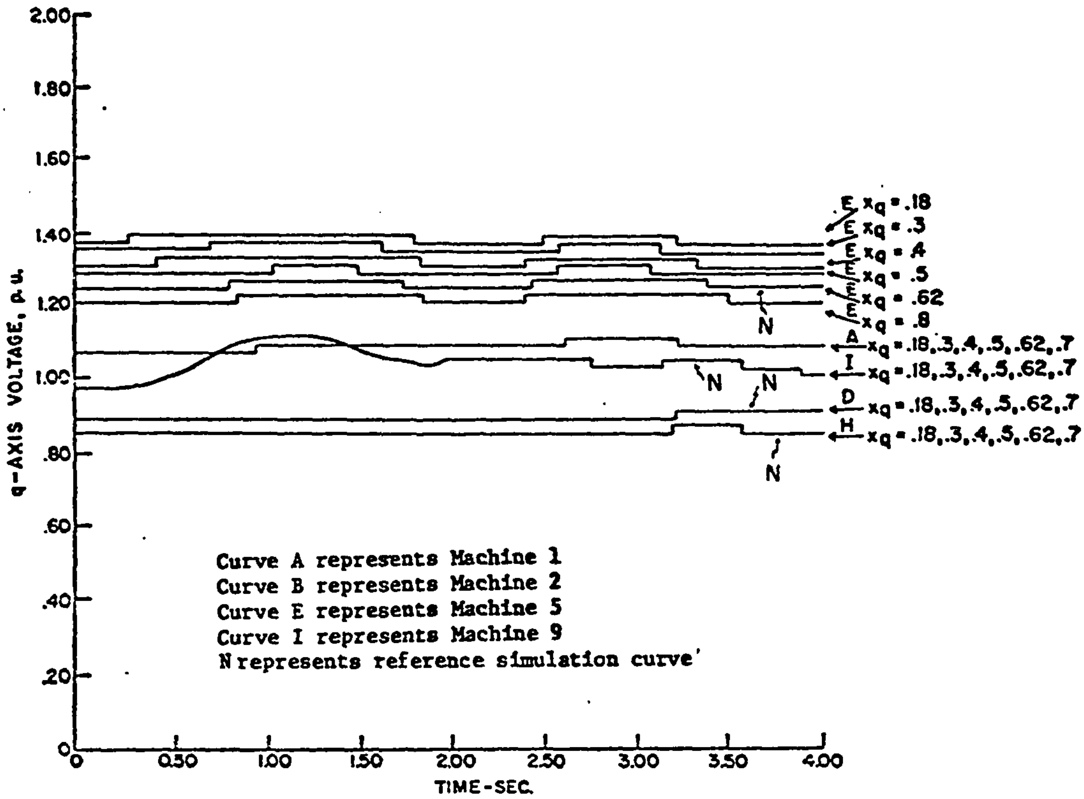


FIGURE 4-42
Q-AXIS TRANSIENT VOLTAGE e_q' UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_q

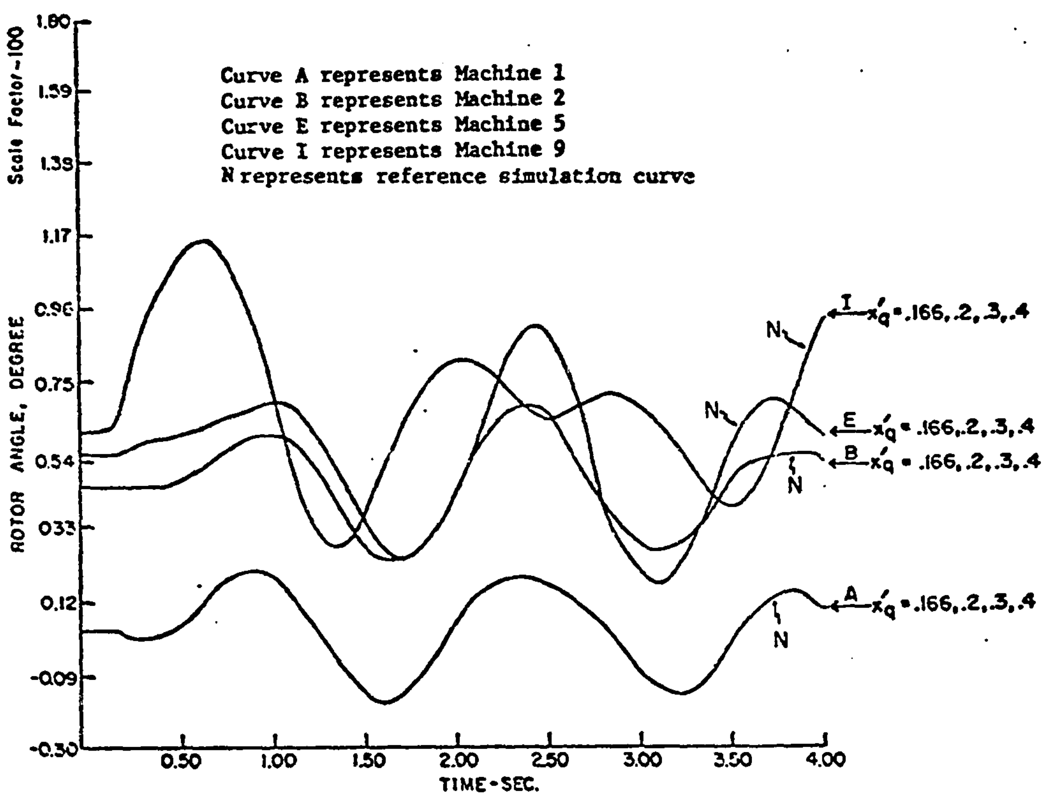


FIGURE 4-43
TRANSIENT ROTOR ANGLE UPON CHANGING INITIAL TERMINAL VOLTAGE AND x_q'

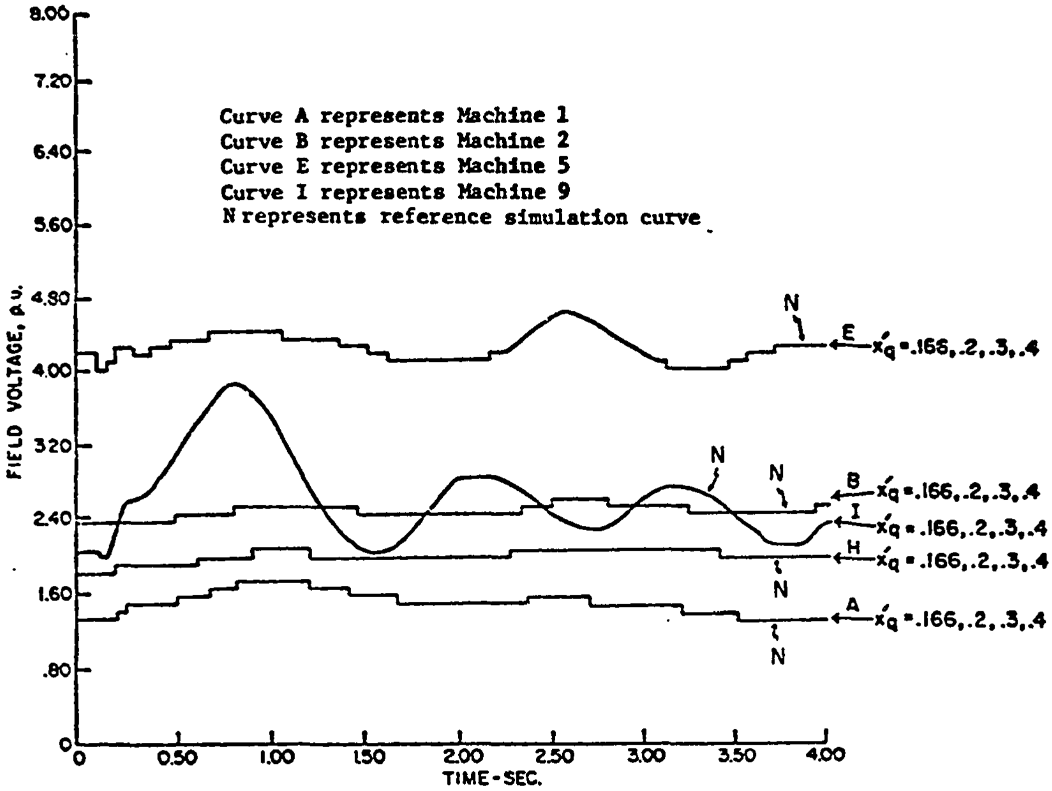


FIGURE 4-44

PER UNIT EXCITER OUTPUT E_{fd} UPON CHANGING INITIAL TERMINAL VOLTAGE AND x'_q

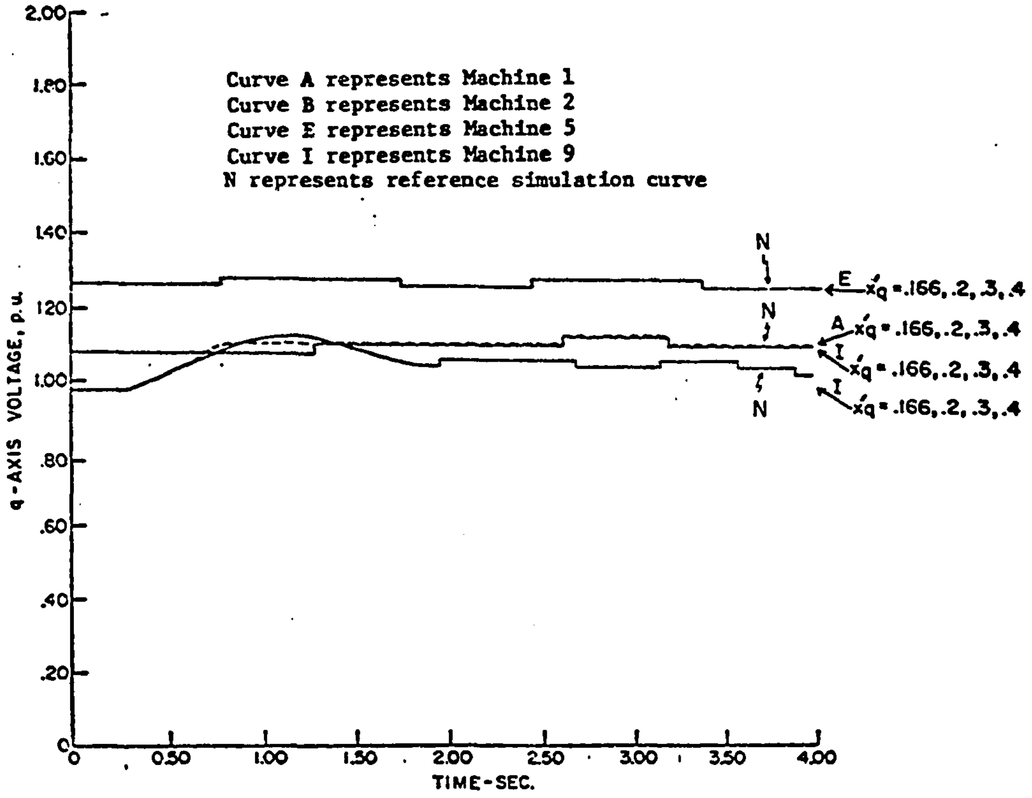


FIGURE 4-45

Q-AXIS TRANSIENT VOLTAGE e'_d UPON CHANGING INITIAL TERMINAL VOLTAGE AND x'_q

is the difference in the values from one machine model to the other. That is actually reflected in the structure level of machine modeling.

The x_d' parameter shows an adverse effect on the machine's performance under machine models 2, 3, 4 and 5. x_d' causes a change on the machine's performance which was a lesser degree than x_d, which is obvious.

The test on x_d'' shows no change in the performance of the machines for all levels of machine models.

The x_q parameters has become very important in the sense that it did change the machine 5's performance while it did not cause machines 1, 2 and 9's performance to be changed. Both x_q' and x_q'' cause the machine's performance not to be changed.

T_{do}' and T_{qo}' were not active parameters in the sense that no change of the machine's performance was noted.

The inertia of machine 5 has an adverse effect on the machine's performance under all of the machine models simulation. Thus, increasing the value of H causes the frequency of oscillation to increase, similarly the lower inertia value causes it to slow the frequency of oscillation of machine 5. The inertia of machines 1 and 2 act as a damping out of the rotor angle starting at 2.0 seconds by increasing its value.

The performance of the machines, by changing and holding x_d to 1.0 per unit and at the same time varying the x_q parameter, show an adverse effect on machine 5's performance.

Although the system is nonlinear, the reader should have some feeling of the variation structure of the machine's data. <u>If in fact</u>, we consider the whole system to be linear, this allows us to represent the system by dynamical equations:

$$\dot{x} = \{A\} \quad X + \{B\} \; U$$

$$Y = \{C\} \quad X$$

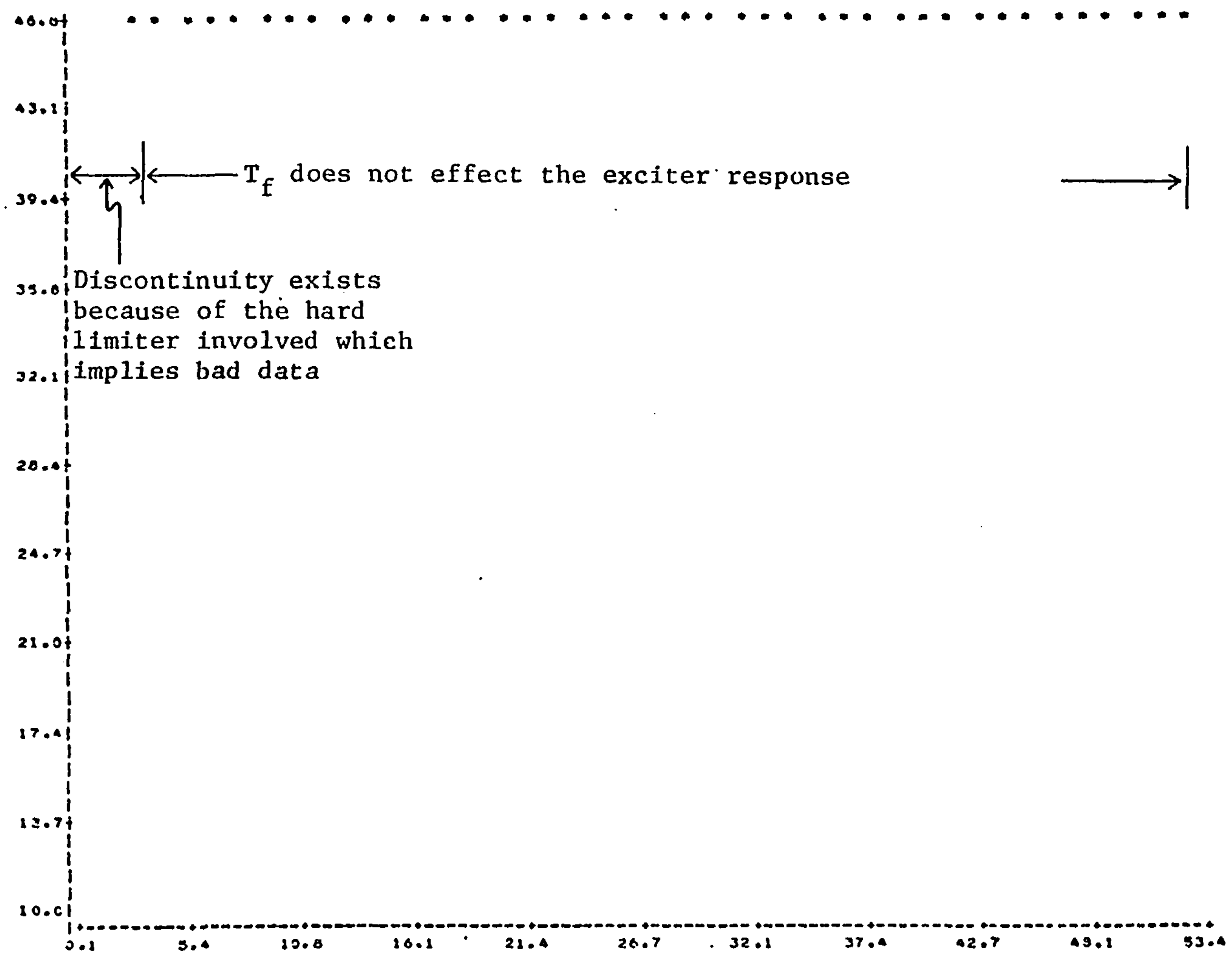
Where the machine and network parameters can be considered as elements of matrix {A}, the machine's controller elements are elements of matrix {B}, and the output of the system is an element of matrix {C}. Therefore, any change of the machine's data causes the mode of matrix {A} to be changed. Hence, the eigen values of the system change too. So these changes on the system's eigen values will reflect the change in the physical structure of the system. Physically, changing any value of the inductance leads to the change of the permeabilities, lengths, and cross-sectional areas of the associated magnetic circuit. Appendix H presents the definition of machine parameters as well as explains the physical interpretation of the machine data upon varying them.

CHAPTER V

SUMMARY AND CONCLUSION

This dissertation was conducted mainly to test four types of excitation systems (appendix B), two types of governor-turbine (appendix E), synchronous machine upon variation of their data, and the impact of machine data on overall system stability studies. The end-result is to study the sensitivity analysis of the machine's controller parameters and to observe their impact on the machine's controller response. This could help to characterize those parameters which do not contribute a major change on the exciter and governor turbine response for future work.

The curves in figures (5-1) and (5-2) reflect the behavior of exciter type I upon variation of the damping time constant T_f and the exciter time constant T_E, respectively. Figure (5-1) shows that the exciter response does not change upon varying the time constant T_f. This will lead to the conclusion that this parameter is not important to be represented in future digital simulation studies. Figure (5-2) shows that the exciter output holds a linear relationship with varying the exciter time constant T_E. The behavior of the exciter system is dominated by the slower response while the faster response has a lesser effect on the exciter response. Therefore, the conclusion can be stated that this parameter is essential to be represented in digital simulation studies.



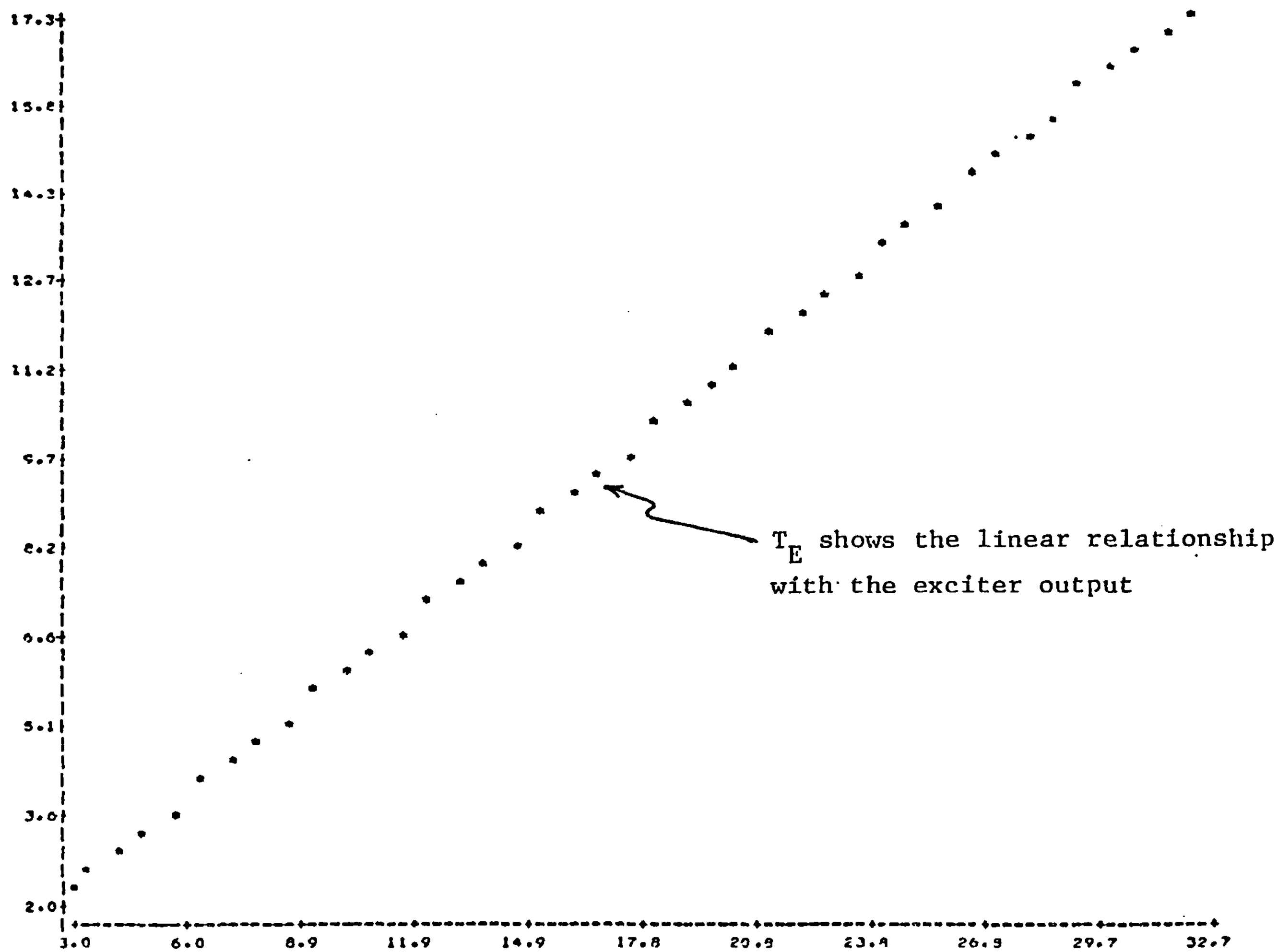
Y SCALE FACTOR USED IS 1.0E-02

X SCALE FACTOR USED IS 1.0E-01

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO 5.0

FIGURE 5-1



Y SCALE FACTOR USED IS 1.0E-01

X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO 5.00

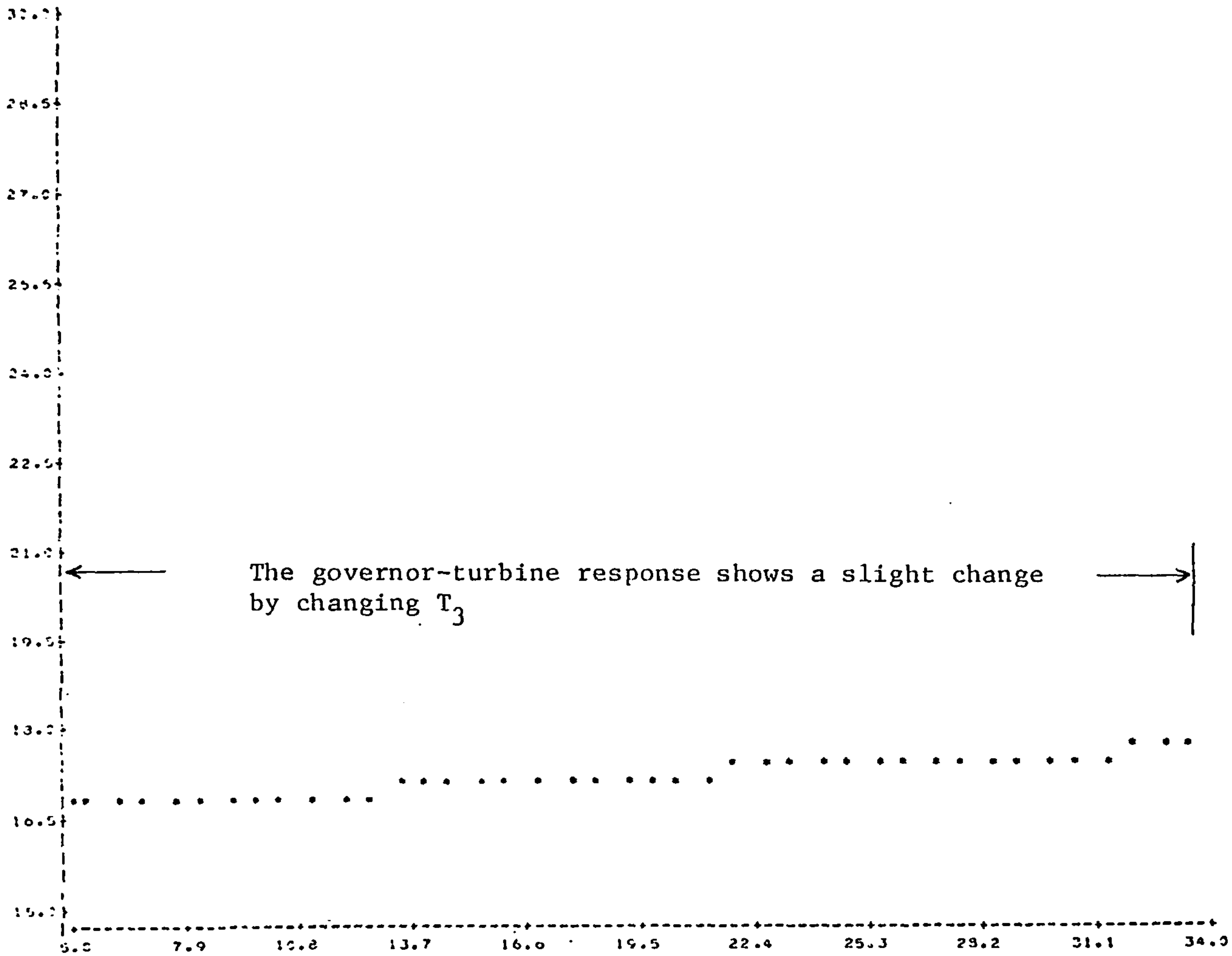
FIGURE 5-2

The curves in figures (5-3) and (5-4) reflect the behavior of the governor-turbine model, tandem compound double reheater IEEE type, upon variation of the servo motor time constant, T_3, and the reheater time constant, T_5, respectively. The governor-turbine response has a slight change with the variation of T_3. This will lead to the conclusion that this parameter has some sort of correlation with the governor-turbine response. Changing the data of the governor-turbine system may cause the structure of the governor-turbine to also change. Figure (5-4) shows that the governor-turbine response holds a linear relationship with varying the reheater time constant, T_5. The governor-turbine system output is dominated by the slower response.

The end-result is to study the impact of the machine data on overall system stability studies. Figures (5-5) and (5-6) are the machines' (machines one, two, five and nine) swing curves, upon varying the direct axis synchronous reactance x_d of machine five (figure 4-1). "N" represents the reference simulation curve of the study system data which is given in appendix G. Varying the x_d value reflected an adverse effect on the machines' quantities as shown in figures (5-5) and (5-6). This simulation could characterize those parameters which do not contribute a major change in the machine's performance for future simulation stability studies.

Therefore, this dissertation's conclusions will be presented in the following points:

A) The modification of a digital representation of synchronous machine modeling by C. C. Young, which includes a development of machine model III and ½.

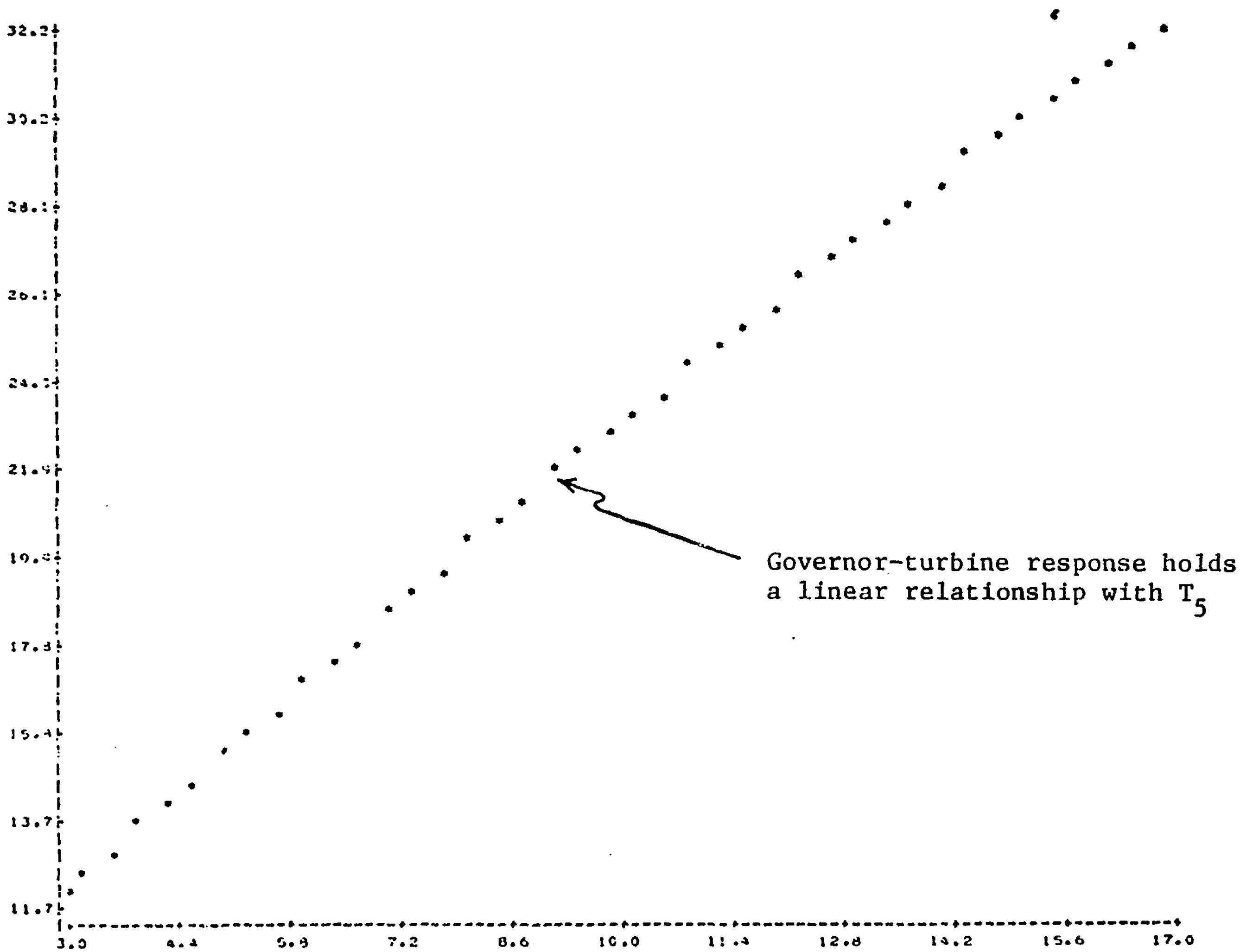


Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E-02

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T3 IS VARIED FROM 0.05 TO 0.2

FIGURE 5-3



Y SCALE FACTOR USED IS 1.0E-01 X SCALE FACTOR USED IS 1.0E 00

* IS SYSTEM TIME CONSTANT

SENSITIVITY ANALYSIS OF TANDEM COMPOUND GOVERNOR AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT OF THE SYSTEM WHEN TIME CONSTANT T5 IS VARIED FROM 3.0 TO 15.0

FIGURE 5-4

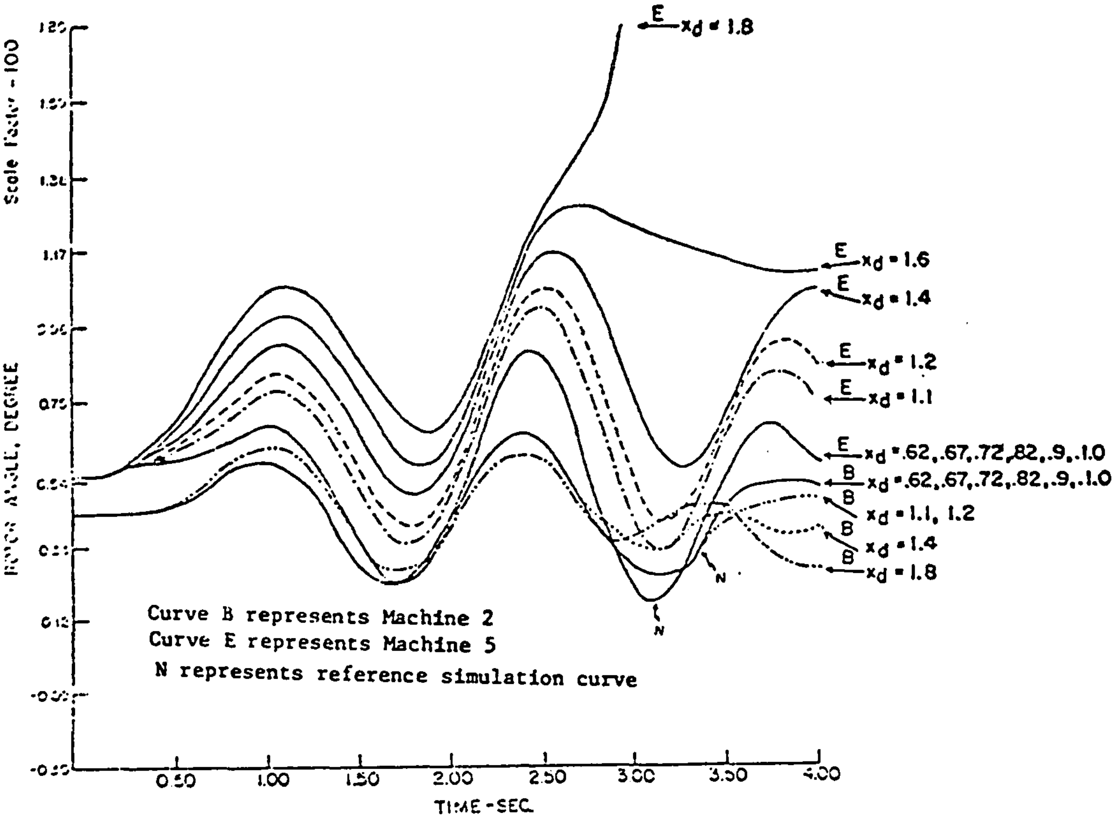


FIGURE 5-5

TRANSIENT ROTOR ANGLE UPON CHANGING x_d

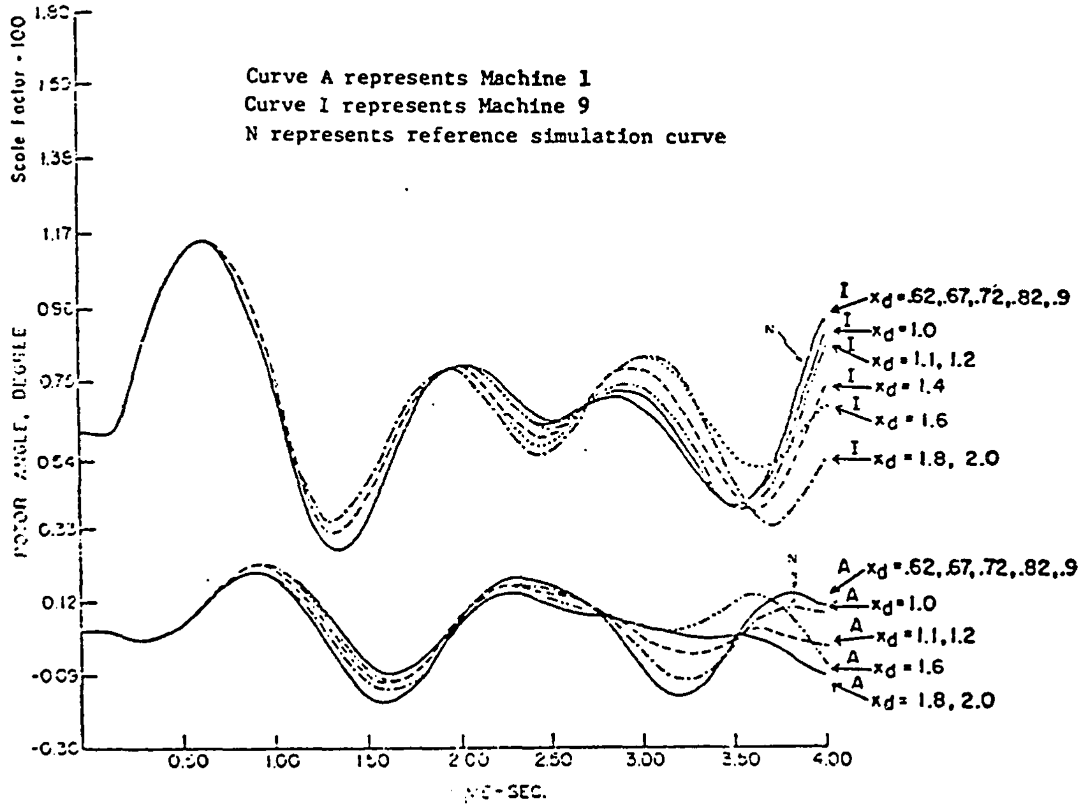


FIGURE 5-6

TRANSIENT ROTOR ANGLE UPON CHANING x_d

B) The study of data sensitivity analysis of the excitation system. Four types of excitation systems were tested to see their performance. A conclusion can be drawn that the exciter type I and type II parameters can be classified into three categories:

i) Essential parameters such as exciter time constant T_E and exciter gain K_E.

ii) Important parameters such as regulator gain K_A, feedback gain parameter K_f and regulator amplifier time constant T_A.

iii) Exciter parameters not as important such as regulator input filter time constant T_R and feedback time constant T_f.

Exciter type III parameters can be classified into the following three categories:

i) Essential parameters such as exciter time constant T_E and exciter gain parameter K_E.

ii) Important parameters such as regulator gain K_A and feedback gain parameter, K_f.

iii) Parameters not as important such as regulator amplifier time constant, T_A, regulator input filter time constant T_R, and feedback time constant, T_f.

In exciter type IV all of the parameters are essential. Some parameters of exciter types I, II and III were not as essential to the effect of the exciter's response. Thus, the degree of the exciter dynamic equations can be reduced for digital representation of the above models.

C) Study of data sensitivity analysis of governor-turbine system. Tandem compound double reheater model and a Philadelphia Electric Company (PECO) model were subject to a test of their performance. A conclusion can be drawn that the tandem compound double reheater model's parameters can be classified into three categories:

i) Essential parameters such as steam chest time constant T_4 and reheat time constant T_5.

ii) Important parameters such as speed governor time constant T_2, servo motor time constant T_3, and cross-over timve constant T_7.

iii) Parameters not as important such as second reheat time constant T_6, fraction parameter K_3, hard limiter and steady state speed regulator K_G.

Also, a conclusion can be drawn that the Philadelphia Electric Company model's parameter can be classified into the following three categories:

i) Very important parameters such as time constant T_2 and time constant T_3.

ii) Important parameters such as time constant T_4.

iii) Parameters not as important such as time constant T_1, time constant T_5, and the hard limiter.

Some of the governor-turbine parameters are not essential to the effect of the behavior of the models. Therefore, the reduction of the dynamic equation's order is possible for the digital representation of the above two models.

D) Study of the impact of the machine data on overall stability studies' performance using synchronous machine models two, three, four and five simulation. A conclusion can be recognized that machine parameters have an adverse effect on the system stability and machine models four and five parameters can be classified into the three categories below:

i) Essential parameters such as direct axis synchronous reactance x_d, direct axis transient reactance x_d', quadrature axis synchronous reactance x_q and inertia constant H.

ii) Important parameters such as direct axis subtransient reactance x_d'', quadrature axis subtransient open-circuit time constant T_{qo}''.

iii) Parameters not as important such as quadrature axis transient reactance x_q', quadrature axis subtransient reactance x_q'', direct axis transient open-circuit time constant T_{do}', and quadrature axis transient open-circuit time constant T_{qo}'.

A conclusion can be drawn that the machine model's three parameters can be classified into the following three categories:

i) The essential parameters such as direct axis synchronous reactance x_d, direct axis synchronous transient reactance x_d', quadrature axis synchronous reactance x_q, and inertia constant H.

ii) Important parameters such as direct axis transient open-circuit time constant, T_{do}'.

iii) Parameters not as important such as quadrature axis synchronous transient reactance x_q', quadrature axis transient open-circuit time constant T_{qo}'.

And finally, a conclusion can be drawn that the machine model's parameters can be classified into two categories:

i) The essential parameters such as direct axis synchronous reactance x_d, direct axis synchronous transient reactance x_d', quadrature axis synchronous reactance x_q, and inertia constant H,

ii) And important parameters such as quadrature axis transient synchronous reactance x_q' and direct axis transient open-circuit time constant T_{do}'.

From this dissertation it can be concluded which parameters have an influential action on the system's stability. The conclusion of this study is that some of the machine's parameters do not influence the system model's performance for all the machine models. Therefore, the reduction of the dynamic equation's order is possible for the digital representation of the above four models.

APPENDIX A

DERIVATION OF MODEL III & ½ EQUATIONS

Park's model describing the dynamic characteristic of synchronous machine in a per unit form is given below. As stated, one winding of a damper will be represented in the d and q axis of synchronous machine referred to as X for d axis damping and g for q axis with the assumption mentioned earlier. The equation can then be written as:

Direct axis flux linkage

$$\lambda_f = -X_{af}\, i_d + X_{ff}\, i_f + X_{fx}\, i_x \tag{A-1}$$

$$\lambda_d = -X_d\, i_d + X_{af}\, i_f + X_{axd}\, i_x \tag{A-2}$$

$$\lambda_x = -X_{axd}\, i_d + X_{xx}\, i_x + X_{fx}\, i_f \tag{A-3}$$

Direct axis voltages

$$v_d = \frac{d\lambda d}{\omega_o dt} - \frac{\omega_r}{\omega_o}\lambda_q - R_a i_d \tag{A-4}$$

$$v_f = r_f i_f + \frac{d\lambda f}{\omega_o dt} \tag{A-5}$$

$$v_x = \frac{d\lambda x}{\omega_o dt} + R_x i_x \tag{A-6}$$

Quadrature axis linkage

$$\lambda_g = -X_{ag}\, i_q + X_{gg}\, i_g \tag{A-7}$$

$$\lambda_q = -X_q\, i_q + X_{aq} i_g \tag{A-8}$$

Quadrature axis voltage

$$v_q = \frac{d\lambda q}{\omega_o dt} + \frac{\omega_r}{\omega_o} \lambda_d - ri_q \tag{A-9}$$

$$v_g = R_g i_g + \frac{d\lambda g}{\omega_o dt} \tag{A-10}$$

Noted, equations (A-1), (A-2), (A-3), (A-7) and (A-8) are in five unknown currents. Equation (A-7) can be written as

$$i_g = \frac{1}{X_{gg}} (\lambda_g + X_{ag}\, i_q) \tag{A-11}$$

If field current, i_f, is eliminated from equations (A-1), (A-2) and (A-3) we will have:

$$i_d = -\frac{1}{X''_d} \lambda_d + \frac{1}{X''_d} \frac{X_{ax}}{X_{xx}} \lambda_x \tag{A-12}$$

Now taking i_g from (A-11) and put it in equation (A-8) which yields the following:

$$i_q = -\frac{1}{X''_q} \lambda_q + \frac{1}{X''_q} \frac{X_{ag}}{X_{gg}} \lambda_g \tag{A-13a}$$

where

$$X''_d = X_d - \frac{X^2_{af} X_{xx} + X^2_{ax} X_{ff} - 2X_{af} X_{fx} X_{ax}}{X_{ff} X_{xx} - X^2_{fx}} \tag{A-13b}$$

and

$$x''_q = X_q - \frac{X^2_{ag}}{X_{gg}} \tag{A-13c}$$

Further assumptions which must be made are:

1) Relationships must exist between the rotor and stator coil inductances in each axis.[59]

$$L_{ax} L_{fx} = L_{xx} L_{af}$$

or

$$X_{ax}\, X_{fx} = X_{xx}\, X_{af} \tag{A-14}$$

2) The time constants of the two rotor coils in each axis should be different by at least a factor of ten.[59] Hence, the following can be defined as:

$$X_q - X_q'' = \frac{X_{ag}^2}{X_{gg}} \tag{A-15}$$

$$X_d - X_d'' = X_{ax}^2/X_{xx} \tag{A-16}$$

$$X_d - X_d' = X_{af}^2/X_{ff} \tag{A-17}$$

$$X_d' - X_d'' = \frac{X_{ax}^2}{X_{xx}} - \frac{X_{af}^2}{X_{ff}} \tag{A-18}$$

Concordia had defined the so-called open circuit (that is, the armature is open circuited) rotor time constants as:

$$T_{qo}'' = \frac{X_{gg}}{R_g} \quad \text{Radians} \tag{A-19a}$$

$$T_{do}' = \frac{X_{ff}}{R_f} \quad \text{Radians} \tag{A-19b}$$

$$T_{do}'' = \left(\frac{X_{gg} - \frac{X_{fx}^2}{X_{ff}}}{R_x}\right) \quad \text{Radians}$$

or

$$T_{do}'' = \left(\frac{X_d' - X_d''}{X_d - X_d''}\right) \frac{X_{xx}}{R_x} \quad \text{Radians} \tag{A-19c}$$

Proof of these relations are:

$$\frac{\left(X_{gg} - \frac{X_{fx}^2}{X_{ff}}\right)}{R_x} = \left(\frac{X_d' - X_d''}{X_d - X_d''}\right) \frac{X_{xx}}{R_x} \quad \text{as follows:}$$

$$T_{do}'' = \left(\frac{X_d' - X_d''}{X_d - X_d''}\right) \frac{X_{xx}}{R_x}$$

$$T''_{do} = \left(\frac{\frac{X^2_{ax}}{X_{xx}} - \frac{X^2_{af}}{X_{ff}}}{X^2_{ax}/X_{ff}} \right) \frac{X_{xx}}{R_x}$$

$$= \frac{\frac{X^2_{ax}}{X_{xx}} - \frac{X^2_{ax}\ X^2_{fx}}{X^2_{xx}X_{ff}}}{X^2_{ax}/X_{ff}} \quad \frac{X_{xx}}{R_x}$$

$$= \frac{(X_{ff}X_{xx} - X^2_{fx})\ X_{ff}}{X^2_{xx}\ X_{ff}} \quad \frac{X_{xx}}{R_x}$$

$$= (\frac{X_{ff}X_{xx} - X^2_{fx}}{X_{xx}}) \frac{1}{R_x}$$

$$T''_{do} = (X_{ff} - \frac{X^2_{fx}}{X_{xx}}) \quad \frac{1}{R_x} \qquad \text{Radians}$$

which is equal to the above and

$$T''_{qo} = \frac{L_{gg}}{R_g} \text{ sec or } T''_{qo} = \frac{X_{gg}}{R_g} \qquad \text{Radians}$$

Next i_d, i_q, i_f, i_g and i_x will be found. Since we have five equations and five unknowns, the following can be implied to find the unknowns. Recall equation (A-7),

$$\lambda_g = -X_{ag}\ i_g + X_{gg}\ i_g$$

$$i_g = \frac{1}{X_{gg}}\ (\lambda_g + X_{ag}\ i_g) \tag{A-20}$$

Recall equation (A-8),

$$\lambda_q = X_{ag}\ i_g - X_q\ i_q$$

$$i_g = \frac{1}{X_{ag}}\ (\lambda_q + X_q\ i_q) \tag{A-21}$$

Equating equations (A-20) and (A-21) yields

$$\frac{1}{X_{gg}} \{\lambda_g + X_{ag}\, i_q\} = \frac{1}{X_{ag}} \{\lambda_q + X_q\, i_q\}$$

$$i_q \left(\frac{X_{ag}}{X_{gg}} - \frac{X_q}{X_{ag}}\right) = \frac{\lambda_q}{X_{ag}} - \frac{\lambda_g}{X_{gg}}$$

$$i_q \left(1 - \frac{X_{ag}^2}{X_q X_{gg}}\right) = -\frac{\lambda_q}{X_q} + \frac{X_{ag}\lambda_g}{\lambda_q X_{gg}}$$

$$i_q \left(X_q - \frac{X_{ag}^2}{X_{gg}}\right) = \frac{X_{ag}}{X_{gg}}\, \lambda_g - \lambda_q$$

Define

$$x_q'' = \left(X_q - \frac{X_{ag}^2}{X_{gg}}\right) \text{ and } (X_q - X_q'') = \frac{X_{ag}^2}{X_{gg}}$$

$$\therefore\ i_q = \frac{1}{X_q''} \left(-\lambda_q + \frac{X_{ag}}{X_{gg}}\, \lambda_g\right) \tag{A-22}$$

Equation (A-2) can be written as

$$i_x = \frac{1}{X_{ax}} \left(\lambda_d - X_{af} \cdot i_f + X_d\, i_d\right)$$

Substituting i_x in equation (A-1) yields

$$\lambda_f = -X_{af}\, i_d + X_{ff} \cdot i_f + \frac{X_{fx}}{X_{ax}} \{\lambda_d - X_{af}\, i_f + X_d i_d\}$$

$$\lambda_f = i_d \left(-X_{af} + \frac{X_d X_{fx}}{X_{ax}}\right) + i_f \left(X_{ff} - \frac{X_{fx} X_{af}}{X_{ax}}\right) + \lambda_d \left(\frac{X_{fx}}{X_{ax}}\right)$$

$$i_f (X_{ff} X_{ax} - X_{fx} X_{af}) = X_{ax}\lambda_f - X_{fx}\lambda_d + i_d (X_{af} X_{ax} - X_d X_{fx}) \tag{A-23}$$

i_x of equation (A-2) can be eliminated by substituting it into equation (A-3).

$$\lambda_x = -X_{ax}i_d + X_{fx}i_f + \frac{X_{xx}}{X_{ax}}(\lambda_d - X_{af}i_f + X_d i_d)$$

$$X_{ax}\lambda_x = i_d(-X_{ax}^2 + X_d X_{xx}) + i_f(X_{fx}X_{ax} - X_{xx}X_{af}) + X_{xx}\lambda_d \tag{A-24}$$

Eliminate i_f from equation (A-23) and (A-24)

$$X_{ax}\lambda_x = i_d(-X_{ax}^2 + X_d X_{xx}) + \left(\frac{X_{fx}X_{ax} - X_{xx}X_{af}}{X_{ff}X_{ax} - X_{fx}X_{af}}\right)\left|X_{ax}\lambda_f - X_{fx}\lambda_d\right.$$

$$\left. + i_d(X_{af}X_{ax} - X_d X_{fx})\right| + X_{xx}\lambda_d$$

$$i_d\left[X_d X_{xx} - X_{ax}^2 + \frac{X_{fx}X_{ax}^2X_{af} - X_{xx}X_{af}^2X_{ax}}{X_{ff}X_{ax} - X_{fx}X_{af}} + \frac{-X_d X_{fx}^2X_{ax} + X_d X_{fx}X_{xx}X_{af}}{(X_{ff}X_{ax} - X_{fx}X_{af}}\right] =$$

$$X_{ax}\lambda_x - \left(\frac{X_{fx}X_{ax} - X_{xx}X_{af}}{X_{ff}X_{ax} - X_{fx}X_{af}}\right)X_{ax}\lambda_f + \lambda_d\left(-X_{xx} + \frac{X_{fx}X_{fx} - X_{fx}X_{xx}X_{af}}{X_{ff}X_{ax} - X_{fx}X_{af}}\right)$$

$$i_d\,|(X_d X_{xx} - X_{ax}^2)(X_{ff}X_{ax} - X_{fx}X_{af}) + X_{fx}X_{ax}^2X_{af} - X_{xx}X_{af}^2X_{ax}$$

$$- X_d X_{fx}^2X_{ax} + X_d X_{fx}X_{xx}X_{af}| = (X_{ax}^2X_{ff} - X_{ax}X_{fx}X_{af})\,\lambda_x$$

$$- \lambda_f(X_{fx}X_{ax}^2 - X_{xx}X_{af}X_{ax}) + \lambda_d(-X_{xx}X_{ff}X_{ax} + X_{fx}X_{xx}X_{af} + X_{fx}^2X_{ax}$$

$$- X_{fx}X_{xx}X_{af})$$

$$i_d(X_d X_{xx}X_{ff}X_{ax} - X_{ax}^3X_{ff} + 2X_{fx}X_{ax}^2X_{af} - X_{xx}X_{af}^2X_{ax} - X_d X_{fx}^2X_{ax})$$

$$= \lambda_x(X_{ax}^2X_{ff} - X_{ax}X_{fx}X_{af}) + \lambda_d(X_{fx}^2X_{ax} - X_{xx}X_{ff}X_{ax}) - \lambda_f$$

$$(X_{fx}X_{ax}^2 - X_{xx}X_{af}X_{ax})$$

$$i_d\left|X_d - \frac{X_{xx}X_{af}^2 + X_{ax}^3X_{ff} - 2X_{fx}X_{ax}^2X_{af}}{(X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax})}\right| =$$

$$\lambda_x\frac{(X_{ax}^2X_{ff} - X_{ax}X_{fx}X_{af})}{(X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax})} + \lambda_d\left(\frac{X_{fx}^2X_{ax} - X_{xx}X_{ff}X_{ax}}{X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax}}\right)$$

$$- \lambda_f \frac{(X_{fx}X_{ax}^2 - X_{xx}X_{af}X_{ax})}{(X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax})}$$

Bearing in mind that $X_{xx}\,X_{af} = X_{ax}X_{fx}$. Define X_d'' as

$$X_d'' = (X_d - \frac{X_{xx}X_{af}^2 + X_{ax}^2X_{ff} - 2X_{fx}X_{af}X_{ax}}{(X_{xx}X_{ff} - X_{fx}^2)})$$

and

$$(X_d - X_d'') = \frac{X_{xx}X_{af}^2 + X_{ax}^2X_{ff} - 2X_{fx}X_{af}X_{ax}}{(X_{xx}X_{ff} - X_{fx}^2)}$$

$$i_dX_d'' = \lambda_x \{\frac{X_{ax}^2X_{ff} - X_{fx}X_{af}X_{ax}}{X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax}}\}$$

$$-\lambda_f\{\frac{X_{fx}X_{ax}^2 - X_{xx}X_{af}X_{ax}}{X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax}}\}$$

$$-\lambda_d(\frac{-X_{fx}^2X_{ax} + X_{xx}X_{ff}X_{ax}}{X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax}})$$

Therefore,

$$i_dX_d'' = \lambda_x (\frac{X_{ax}^2X_{ff} - X_{fx}X_{af}X_{ax}}{X_{xx}X_{ff}X_{ax} - X_{fx}^2X_{ax}}) - \lambda_d$$

or

$$i_dX_d'' = -\lambda_d + \lambda_x \frac{X_{af}}{X_{fx}} \tag{A-25}$$

To find i_f substitute it for i_d in equation (A-23).

$$i_fX_d'' \quad (X_{fx}X_{af} - X_{ax}X_{ff}) = \lambda_d \, (X_{fx}X_d'' + X_{af}X_{ax} - X_dX_{fx})$$

$$- X_d''X_{ax}\lambda_f + (\frac{X_{ax}}{X_{xx}}\lambda_x)\,(-\lambda_{af}X_{ax} + X_dX_{fx})$$

First term:

$$\lambda_d \; (X_{fx} \; X''_d + X_{af} X_{ax} - X_d X_{fx}) =$$

$$\lambda_d \; (-X_{fx} \; \frac{X^2_{ax}}{X_{xx}} + X_{af} \; X_{ax}) =$$

$$\lambda_d \; (\frac{-X^2_{af} \; X_{xx}}{X_{fx}} + X_{af} \; X_{ax}) = 0$$

Second term:

$$\frac{X''_d \; X_{ax} \; \lambda_f}{X''_d \; (X_{fx} X_{af} - X_{ax} \; X_{ff})} \; (\frac{X_{ax}}{X_{ax}} \frac{X_{xx}}{X_{xx}}) =$$

$$\frac{(X_d - X''_d) \; \lambda_f}{(X_{af} X_{fx} - X_{ax} \; X_{ff})} \; (\frac{X_{xx}}{X_{ax}}) =$$

$$\frac{(X_d - X''_d) \; X_{xx} \; \lambda_f}{(X^2_{af} \; X_{xx} - X^2_{ax} \; X_{ff})} =$$

$$\frac{(X_d - X''_d) \; X_{xx} \; \lambda_f}{X_{ff} (\frac{X^2_{af}}{X_{ff}} - \frac{X^2_{ax}}{X_{xx}}) \; X_{xx}} =$$

$$\frac{(X_d - X''_d) \; \lambda_f}{X_{ff} \; (X''_d - X'_d)}$$

Third term:

$$(\frac{X_{ax}}{X_{xx}} \lambda_x) \; \frac{(- X_{af} \; X_{ax} + X_d \; X_{fx})}{X''_d \; (X_{fx} X_{af} - X_{ax} \; X_{ff})} =$$

$$\frac{X_{ax}}{X_{xx}} \lambda_x \left| \frac{-X_{af} (\frac{X^2_{ax}}{X_{ax}}) \; \frac{X_{xx}}{X_{xx}} + X_d \; X_{fx}}{X''_d \; (X_{fx} \; X_{af} - X_{ax} \; X_{ff})} \right| =$$

$$\lambda_x \; \frac{X_{ax}}{X_{xx}} \left| \frac{-X_{af} (X_d - X''_d) \; \frac{X_{xx}}{X_{ax}} + X_d \; X_{fx}}{X''_d \; (X_{fx} \; X_{af} - X_{ax} \; X_{ff})} \right| =$$

$$\left(\frac{X_{ax}}{X_{xx}}\lambda_x\right)\left|\frac{-X_{af}X_{xx}X_d + X_d'' X_{af}X_{xx} + X_d X_{fx} X_{ax}}{X_{ax}X_d'' (X_{fx}X_{af} - X_{ax} X_{ff})}\right| =$$

$$\frac{X_{af}X_{xx} \left(\frac{X_{ax}}{X_{xx}}\lambda_x\right)}{X_{ax}(X_{fx}X_{af} - X_{ax}X_{ff})} =$$

$$\frac{X_{af} \left(\frac{X_{ax}}{X_{xx}}\lambda_x\right)}{X_{ff}\ (X_d'' - X_d)}$$

Therefore,

$$i_f = \frac{(X_d - X_d'')\ \lambda_f}{X_{af}\ (X_d' - X_d'')} - \frac{X_{af}X_{ax}\ (\lambda_x)}{X_{ff}X_{xx}\ (X_d' - X_d'')} \tag{A-26}$$

From equation (A-7) and (A-8)

$$\lambda_g = -X_{ag}i_q + X_{gg}\ i_g$$

$$\lambda_q = X_q\ i_q + X_{ag}\ i_g$$

Solving for i_g

$$X_q\lambda_g - X_{ag}\lambda_q = i_g\ (X_qX_{gg} - X_{ag}^2)$$

$$X_q\lambda_g - X_{ag}\lambda_q = X_{gg}i_g\ \left(X_q - \frac{X_{ag}^2}{X_{gg}}\right)$$

$$\frac{X_q\lambda_g}{X_{gg}} - \frac{X_{ag}^2\lambda_q}{X_{gg}X_{ag}} = i_g\ X_q''$$

$$\frac{X_{gg}X_qe_d''}{X_{gg}X_{ag}} - \frac{(X_q - X_q'')\lambda_q}{X_{ag}} = i_g\ X_q''$$

$$i_g = \frac{1}{X_{ag}X_q''}\left(e_d'' - \frac{(X_q - X_q'')}{1}\ \lambda_q\right) = i_g$$

$$i_g = \frac{1}{X_{ag}X_q''}\ (e_d'' - (X_q - X_q'')\ \lambda_q) \tag{A-27}$$

Equation (A-2) can be written as

$$i_x = \frac{1}{X_{ax}} (\lambda_d - X_{af}\, i_f + X_d\, i_d)$$

Switch the value of i_f from equation (A-25) to the above.

$$i_x = \frac{1}{X_{ax}} (\lambda_d - X_{af}\frac{(X_d - X''_d)}{(X'_d - X''_d)}\lambda_f + \frac{X^2_{af}}{X_{ff}}\frac{X_{ax}}{X_{xx}}\frac{\lambda_x}{(X'_d-X''_d)} + X_d i_d)$$

$$i_x = \frac{1}{X_{ax}} (\lambda_d - X_{af}\frac{(X_d-X''_d)}{(X'_d-X''_d)}\lambda_f + \frac{X_{ax}}{X_{xx}}\frac{(X_d-X'_d)\lambda_x}{(X'_d-X''_d)} + X_d i_d)$$

$$i_x = \left|\frac{\lambda_d}{X_{ax}} - \frac{X_{af}}{X_{ax}} \cdot e'_q \cdot \frac{X_{ff}}{X_{af}}\left(\frac{X_d-X''_d}{X'_d-X''_d}\right) + \frac{(X_d-X'_d)\lambda_x}{X_{xx}(X'_d-X''_d)} + \frac{X_d i_d}{X_{ax}}\right|$$

$$i_x = \frac{1}{X_{ax}}\left|\lambda_d - \frac{T'_{do}}{R_f}\left(\frac{X_d-X''_d}{X'_d-X''_d}\right) e'_q + \frac{(X_d-X'_d)}{(X'_d-X''_d)} e''_q + X_d i_d\right| \qquad \text{(A-28)}$$

We could also define the following as:[59]

$$e_{q_1} \propto i_f \rightarrow e_{q_1} = X_{af} i_f \text{ or } e_{q_1} = E_I \qquad \text{(A-29)}$$

$$e_{q_2} \propto i_x \rightarrow e_{q_2} = X_{ax} i_x \qquad \text{(A-30)}$$

$$e_d \propto -i_g \rightarrow e_d = X_{ag} i_g \qquad \text{(A-31)}$$

$$e''_q \propto \lambda_x \rightarrow e''_q = \frac{X_{ax}}{X_{xx}}\lambda_x \qquad \text{(A-32)}$$

$$e'_q \propto \lambda_f \rightarrow e'_q = \frac{X_{af}}{X_{ff}}\lambda_f \qquad \text{(A-33)}$$

$$e''_d \propto \lambda_g \rightarrow e''_d = \frac{X_{ag}}{X_{gg}}\lambda_g \qquad \text{(A-34)}$$

There is now a need to eliminate the flux linkages from the voltage representation. Refer back to equation (A-8) and switch λ_q in equation (A-4).

$$V_d = \frac{d\lambda_d}{\omega_o dt} - \frac{\omega_r}{\omega_o}(-X_q i_q + X_{ag} i_g) - R_a i_d$$

$$i_g = -e_d / X_{ag}$$

$$V_d = \frac{d\lambda_d}{\omega_o dt} - \frac{\omega_r}{\omega_o}(-X_q i_q - e_d) - R_a i_d \tag{A-35}$$

From equation (A-2)

$$\lambda_d = -X_d i_d + X_{af} i_f + X_{ax} i_x$$

and

$$i_x = e_{q_2} / X_{ax}$$

$$i_f = e_{q_1} / X_{af}$$

Now switch λ_d in equation (A-9).

$$V_q = \frac{d\lambda_q}{\omega_o dt} + \frac{\omega_r}{\omega_o}(-X_d i_d + e_{q_1} + e_{q_2}) - r i_q \tag{A-36}$$

Equation (A-24) can be written as a function of (i_d, e_{q_1}, e_{q_2}) after eliminating λ_f.

$$e_q' = \frac{X_{af}}{X_{ff}} \lambda_f$$

$$e_q' = \frac{X_{af}}{X_{ff}} \left| -X_{af} i_d + \frac{X_{ff}}{X_{af}} e_{q_1} + \frac{X_{fx}}{X_{ax}} e_{q_2} \right|$$

$$e_q' = \left| \frac{-X_{af}^2}{X_{ff}} i_d + e_{q_1} + \frac{X_{af} X_{fx}}{X_{ax} X_{ff}} e_{q_2} \right|$$

$$e_q' = -(X_d - X_d'') i_d + e_{q_1} + \frac{X_{af} X_{xx} X_{af}}{X_{ax}^2 X_{ff}} e_{q_2}$$

$$e'_q = -(X_d - X''_d)\ i_d + e_{q_1} + \frac{X_{af}^2}{X_{ax}^2}\ \frac{X_{xx}}{X_{ff}}\ e_{q_2}$$

$$e'_q = -(X_d - X''_d)\ i_d + e_{q_1} + \left(\frac{X_d - X'_d}{X_d - X''_d}\right) e_{q_2} \tag{A-37}$$

This is equation (2-14).

Equation (A-23) can be written as a function of (i_d, e_{q_1}, e_{q_2}) after eliminating λ_x.

$$e''_q = \frac{X_{ax}}{X_{xx}} [-X_{ax} i_d + X_{xx} i_x + X_{fx} i_f]$$

$$e''_q = \frac{X_{ax}}{X_{xx}} [-X_{ax} i_d + \frac{X_{xx}}{X_{ax}} e_{q_2} + \frac{X_{fx}}{X_{af}}\ e_{q_1}]$$

$$e''_q = \frac{-X_{ax}^2}{X_{xx}} i_d + e_{q_2} + \frac{X_{ax} X_{fx}}{X_{xx} X_{af}}\ e_{q_1}$$

$$e''_q = \frac{-X_{ax}^2}{X_{xx}}\ i_d + e_{q_2} + e_{q_1}$$

$$e''_q = -(X_d - X''_d)\ i_d + e_{q_2} + e_{q_1} \tag{A-38}$$

This is equation (2-13).

Equation (A-25) can be written as a function of (i_q, e_d) after eliminating λ_g.

$$e''_d = X_{ag}\ \lambda_g / X_{gg}$$

$$e''_d = \frac{X_{ag}}{X_{gg}}\ [-X_{ag}\ i_q + X_{gg}\ i_g]$$

$$i_g = -e_d / X_{ag}$$

$$e_d'' = \frac{X_{ag}}{X_{gg}} [-X_{ag}\ i_q + X_{gg}\ (-\frac{e_d}{X_{ag}})]$$

$$e_d'' = \frac{-X_{ag}^2 i_q}{X_{gg}}\ -e_d$$

or

$$e_d'' = -(X_q - X_q'')\ i_q - e_d \qquad \text{(A-39)}$$

This is equation (2-15).

THE FIELD FLUX LINKAGE RATE OF CHANGE

Apply Kirchoff's voltage law to the field circuit.

$$E_{fd}' = R_f\ i_f + \frac{d\lambda_f}{dt} \qquad \text{(A-40)}$$

E_{fd}' is an exciter armature e·m·f

$$e_{q_1} = X_{af}\ i_f \qquad \text{(A-41)}$$

Also

$$\frac{X_{ff}}{R_f} = T_{do}' \qquad \text{(A-42)}$$

Therefore,

$$\frac{X_{af}\lambda_f}{R_f} = \frac{X_{ff}}{R_f} \cdot \frac{X_{af}}{X_{ff}}\ \lambda_f = T_{do}'\ e_q'$$

Multiplying equation (A-40) by $\frac{X_{af}}{R_f}$ yields

$$\frac{X_{af}}{R_f}\ E_{fd}' = R_f\ \frac{X_{af}}{R_f}\ i_f + \frac{X_{af}}{R_f}\ \frac{d\lambda_f}{dt}$$

$$E_{fd} = X_{af}\ i_f + \frac{X_{ff}}{R_f} \cdot \frac{X_{af}}{X_{ff}}\ \frac{d\lambda_f}{dt} \qquad \text{(A-43)}$$

$$E_{fd} = \frac{X_{af}}{R_f} E'_{fd}$$

E_{fd} named the open-circuit armature voltage which would be produced by voltage E'_{fd} in a steady state. Equation (A-43) can be written as

$$E_{fd} = e_{q_1} + T'_{do} \frac{de'_q}{dt}$$

or

$$\frac{de'_q}{dt} = \frac{1}{T'_{do}} \{E_{fd} - e_{q_1}\} \tag{A-44}$$

This is equation (2-16).

The above equation represents the rate of change of the flux linkage of the e'_q component. The rate of change of e''_d and e''_q is defined by the following.

$$\frac{de''_q}{dt} = -\frac{e_{q2}}{T''_{do}} \left(\frac{X'_d - X''_d}{X_d - X''_d}\right) \tag{A-45}$$

This is equation (2-17).

$$\frac{de''_d}{dt} = -e_d/T''_{qo} \tag{A-46}$$

This is equation (2-18).

The mechanical motion equation is

$$\frac{d^2\delta}{dt} = \frac{180f}{H} (T_m - T_e - K \frac{d\delta}{dt}) \tag{A-47}$$

APPENDIX B
PHYSICAL AND SIMULATION MODEL OF EXCITATION SYSTEM

B-1 Rototrol Excitation System

Rototrols for excitation systems are available having single stage or two stage amplification. The principle of the operation of both types depends on the energy available in the control circuit and the total power output required. The Rototrol is similar in design to the d-c machine. The two stage Rototrol can be used as either a pilot exciter or a main exciter. Either the one or two stage of the amplification is supplied in the four-pole machine, hence, the Rototrol can be directly connected to the shaft of the generator. Figure (B-1) is the schematic design of the excitation system with the Rototrol pilot exciter and the single-field main exciter.

Variable voltage is supplied to the main exciter field by the Rototrol pilot exciter which is connected directly to the field. It is under the control of the voltage regulator automatic control unit or the manual control unit.

The manual control unit consists of a bridge circuit excited by the voltage drop across the main exciter field. By the way, the Rototrol control field is differentially connected in a the bridge circuit. Under a normal deviation of the main exciter shunt field voltage from its hand set value causes an unbalance in the bridge circuit and current flows in the Rototrol control field to correct the voltage. The manual control unit, therefore, regulates the main exciter shunt field voltage

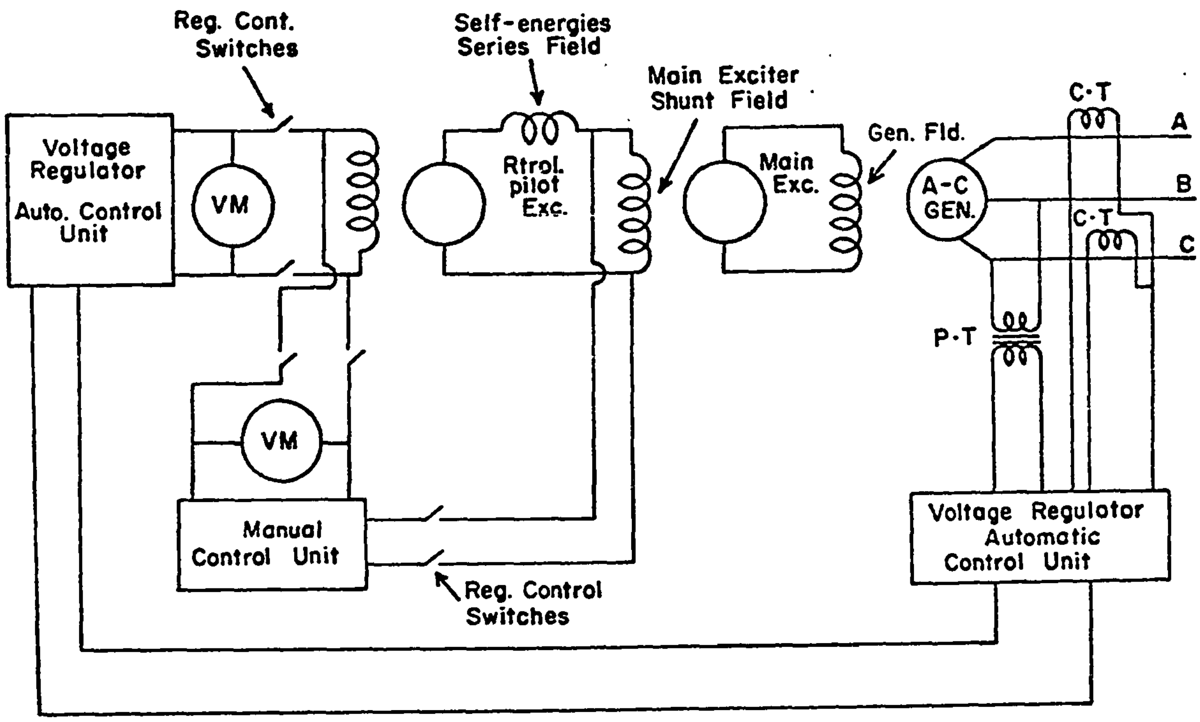


FIGURE B-1
SCHEMATIC DIAGRAM OF EXCITATION SYSTEM
WITH ROTOTROL PILOT EXCITER AND
SINGLE FIELD MAIN EXCITER

to maintain its constant at any value set by the operator without further attention on his part. The self-energized series field of the Rototrol provides all the excitation requirement of the pilot exciter when the a-c generator is operating with the regulated voltage output. The Rototrol pilot exciter supplies all the excitation requirements of the main exciter. In this respect, this scheme is identical with the exciter reheostatic system.[19,20,21]

B-2 Static Voltage Regulator for Exciter

Figure (B-2) is a schematic diagram showing the Rototrol pilot exciter, an exciter, and an a-c generator. A static type of circuit for

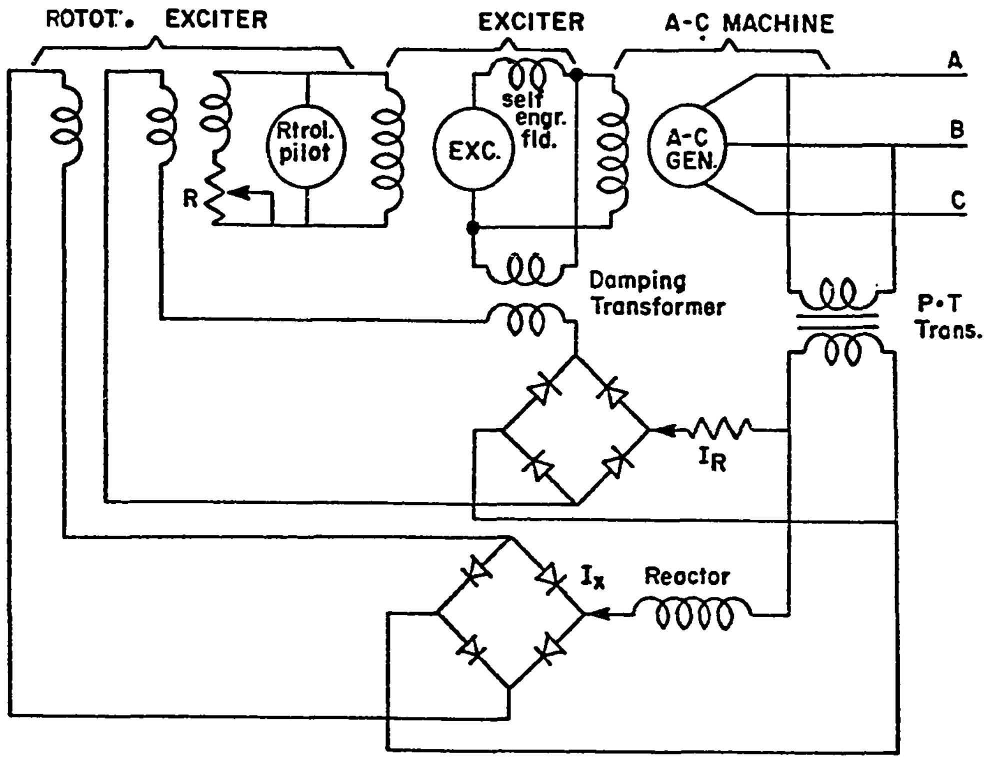


FIGURE B-2
SCHEMATIC DIAGRAM OF ROTOTROL PILOT
EXCITER REGULATOR SYSTEM

the purpose of regulating the a-c generator uses Rototrols for the amplification. As seen the resistor path I_R and a saturation reactor path I_X, with the current in each path rectified, is fed into the control fields of the Rototrol. The Rototrol control fields are connected to be equal and opposite magnetically when the a-c generator voltage is normal at the regulated value. Under this condition the Rototrol output voltage is maintained at the required value by its self energizing shunt and series fields.[18] If the alternating voltage does not have a normal deviation, the control fields adjust the Rototrol as needed to restore normal voltage.

B-3 Self-Excited Exciter and Direct-Acting Rheostatic Type of Voltage Regulator

Under a deviation that is not normal the a-c voltage will be adjusted by changing the resistance in the field exciter by the voltage regulator. The voltage sensitivity element of the regulator acts directly on the reheostat to vary its resistor.(3) The schematic diagram of the self-exciter and direct-acting rheostatic type of voltage regulator is shown in figure (B-3).

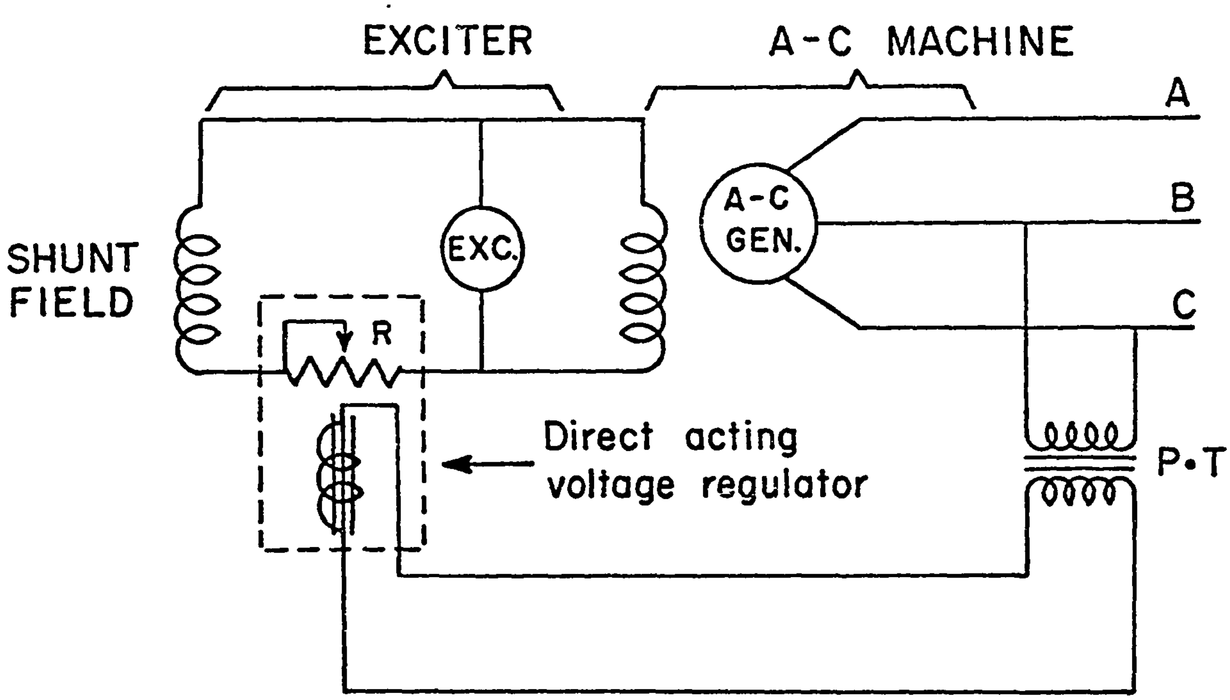


FIGURE B-3
SCHEMATIC DIAGRAM OF SELF-EXCITER EXCITER AND
DIRECT-ACTING RHEOSTATIC TYPE OF VOLTAGE REGULATOR

Other types of excitation systems such as a rotating amplifier d-c machine are designed as a power amplifier such as Amplidyne (General Electric), Regulex (Allis-Chalmers Manufacturing Co.), and Rototorl (Westinghouse Electric).

From the beginning of this appendix we have seen the physical layout of some of the kinds of excitation systems. Most of the above physical models of excitation systems have been simulated by mathematical models shown in figure (B-4, B-5, B-6, B-7, and B-10).

B-4 Mathematical Models of the Excitation Systems; Classified in Four Models by IEEE[8]

The type I model continuously acts as the regulator and the exciter. The excitation system designed in type I is shown in figure (B-4). The type I excitation system is representative of the majority of modern systems which are now in service. Continuously acting systems with rotating exciters are included. Example of these are Regulex, Amplidyne, Alterrex, Rototrol and TRA regulator.

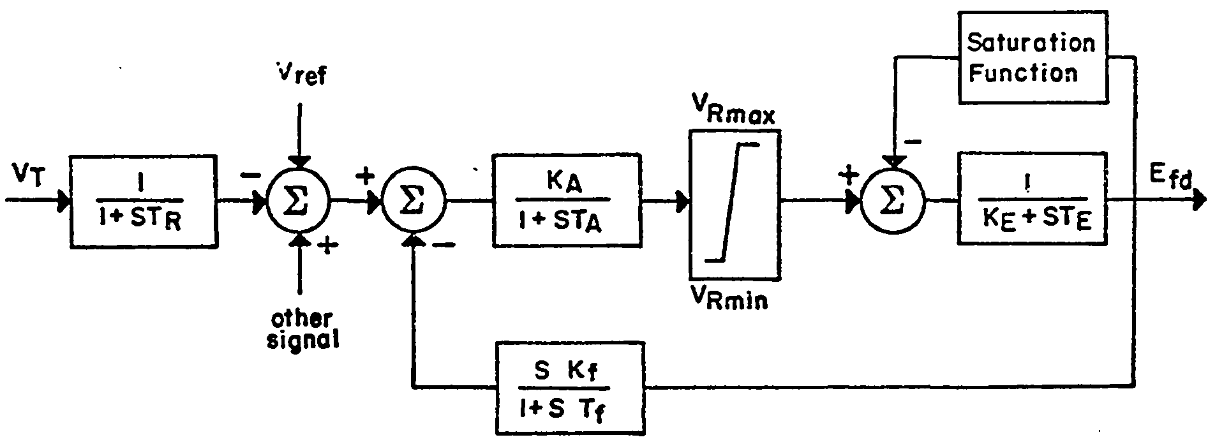


FIGURE B-4
TYPE I BLOCK DIAGRAM OF EXCITATION SYSTEM

Figure (B-4) shows the transfer function of each unit of the system which is a satisfactory representation for computer studies. Machine terminal V_T, is the input applied to the regulator input filtering. Its time constant T_R is usually very small. A comparative of the regulator reference with the output of the regulator filter output is illustrated.

The voltage error inputs to the regulator amplifier by the first summing point.

The second summing point combines the voltage error input with the excitation major damping loop signal. K_A and T_A are the gain and time constant of the regulator transfer function. The hard limiter is suggested to control the input to the exciter. An upper limit will prevent over heating of the field winding. The lower limit is used some times on generators to be sure that there is no loss of synchronism due to insufficient excitation. Therefore, a lower limit might be functioned as of the light load on the machine.[22]

The next summing point sees the saturation signal, $S_E = f(E_{fd})$, as well as the output from the hard limiter. This results in the input to the exciter. K_E and T_E are the gain and time constants of the exciter. Note that K_E is negative for a self excited shunt field. K_f and T_f are gain and time constant of the damping loop of the system.

B-5 Type II Excitation System-Rotating Rectifier System

The type II excitation system is similar to type I except that the major damping loop input is supplied from the regulator output as shown in figure (B-5).

B-6 Type III Excitation System--Static with Terminal Potential and Current Supplies

Excitation system, type III, is shown in figure (B-6). It represents the static systems which cannot be represented by previous types. This is because the generator terminal current is used with potential as the excitation source.

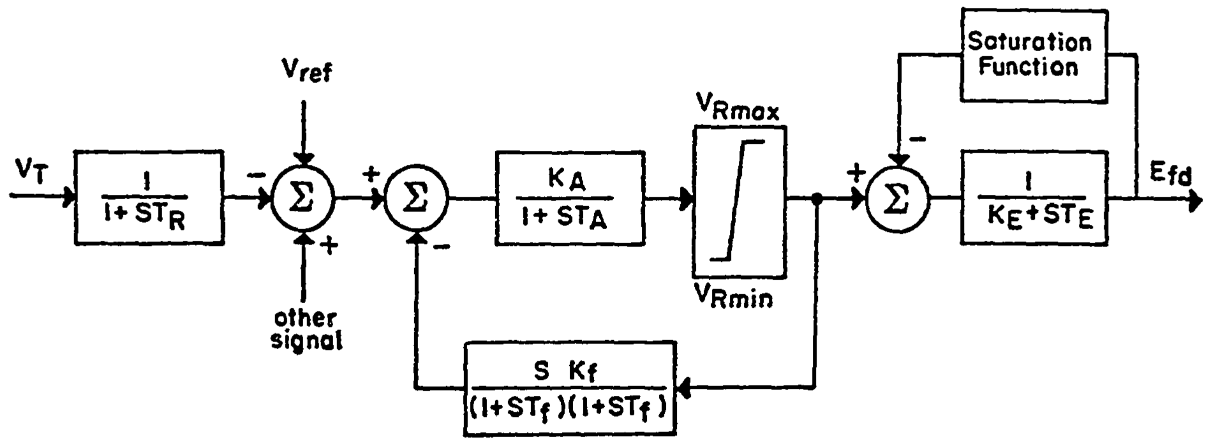


FIGURE B-5
TYPE II BLOCK DIAGRAM OF EXCITATION SYSTEM

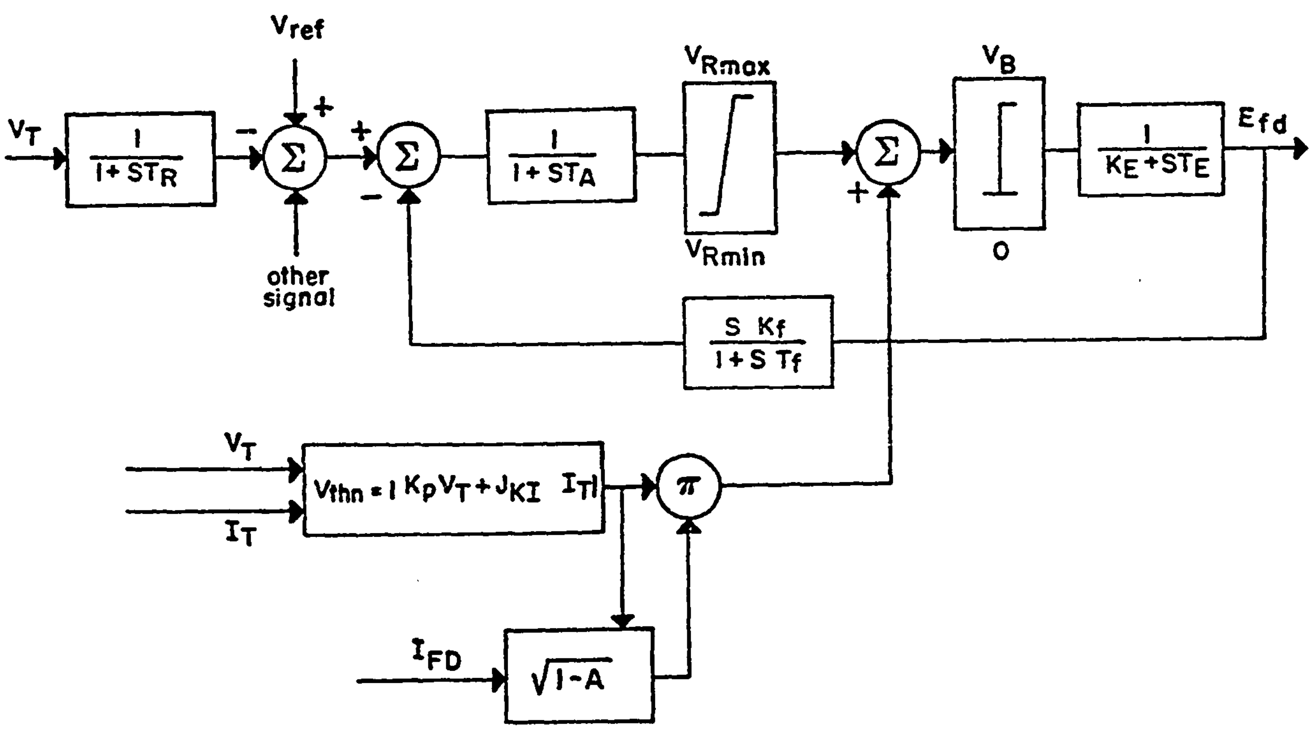


FIGURE B-6
TYPE III BLOCK DIAGRAM OF EXCITATION SYSTEM

An example of type III is the General Electric SCPT. The transfer function blocks are similar to type I except there is a signal added by the signal representing the self-excitation from the generator terminals. K_p and K_I are coefficient factors of the shunt excitation supply proportional to V_T and I_t. The multiplier accounts for the variation of self-excitation with change in the angular relation of field current I_{fd} and self-excitation voltage V_{thev}. The V_{Bmax} limiter causes the excitation system output to be zero if A > 1 which is when the field current exceeds the excitation output current,(8) where $A = (\frac{.78\ I_{fd}}{V_{Then}})$.

B-7 Type IV Excitation System--Non-Continuously Acting

The type IV block diagram is for rheostatic systems with contacts for fast response, such as the BJ-30 by Westinghouse and the GFA4 by General Electric. If the deviation in the generator terminal voltage from the desired value exceeds the range ± KV (typically .05 per unit), the output of the integrated is ignored and either V_{Rmax} V_{Rmin} is applied. Contacts to the exciter input reduces the generator voltage error quickly.

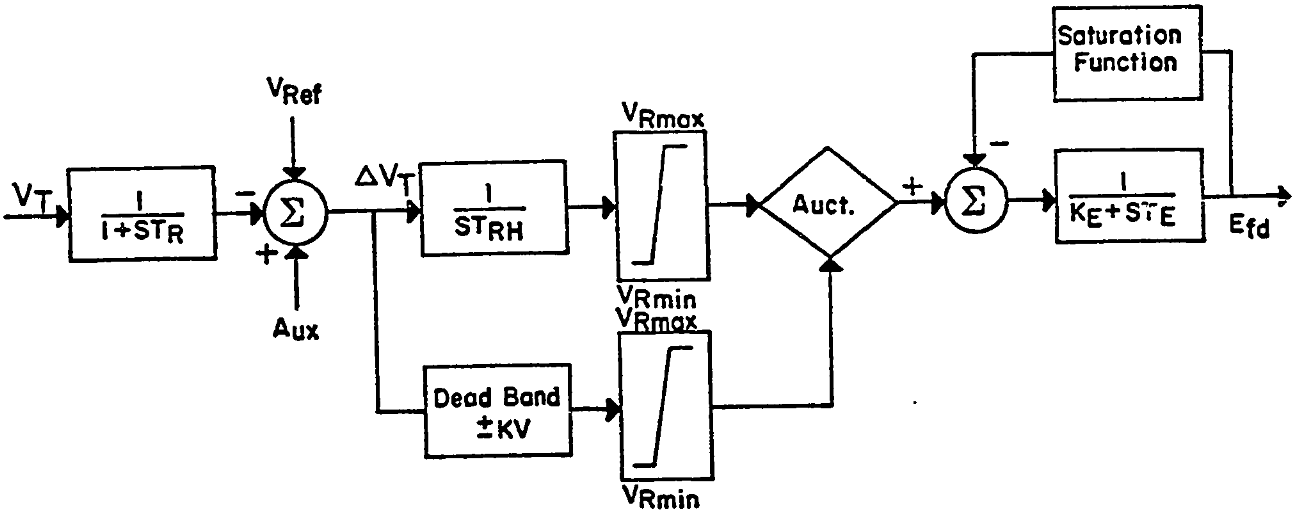


FIGURE B-7
TYPE IV BLOCK DIAGRAM OF EXCITATION SYSTEM--NON-CONTINUOUSLY ACTING

In block diagram, figure (B-7), the block marked by AUCT signifies an autioneering circuit which reflects the output of the integrator or the contact voltage V_{Rmax} or V_{Rmin}.[8, 10]

APPENDIX C
COMPUTER PROGRAM SIMULATION OUTPUT
LISTING OF TYPES OF EXCITATION SYSTEMS

```
****CONTINUOUS SYSTEM MODELING PROGRAM****

*** VERSION 1.3 ***

TITLE TYPE 1 EXCITATION SYSTEM
      FIXED ISET
      FIXED ICNT
      FIXED IRUN

INITIAL
PARAMETER TR=0.0,KA=40.,TA=.02,KE=1.0,KF=.03,TE=.73....
      TF=1.0,SE=.74,VRMAX=6.5,VRMIN=-6.5,VREF=1.0,ICNT=1,IRUN=1....
      AUX=0.0,EFDO=0.0
      ISET=0
      TI=TE/KE
      TRMAX=.09
      TRMIN=0.0
      TRDELT=(TRMAX-TRMIN)/40.0
      TEMIN=.01
      TEMAX=5.
      TEDELT=(TEMAX-TEMIN)/40.0
      KEMIN=.01
      KEMAX=5.
      KEDELT=(KEMAX-KEMIN)/40.0
      KAMAX=150.
      KAMIN=1.0
      KADELT=(KAMAX-KAMIN)/40.0
      TFMIN=0.01
      TFMAX=5.
      TFDELT=(TFMAX-TFMIN)/40.0
      TAMIN=0.0
      TAMAX=.4
      TADELT=(TAMAX-TAMIN)/40.0
      KFMAX=.3
      KFMIN=.003
      KFDELT=(KFMAX-KFMIN)/40.0
      NOSORT
      IF ( (0.5*KA) .LE. VRMAX ) GO TO 1
      KALIM=VRMAX
      GO TO 3
    1 IF ( (0.5*KA) .GE. VRMIN ) GO TO 2
      KALIM=VRMIN
      GO TO 3
    2 KALIM=0.5*KA
    3 CONTINUE
      EFDSS=(1.0/KE*KALIM)/(1.0+SE/KE)
      EFD1TC=(1.0-EXP(-1.0))*EFDSS
SORT

DYNAMIC
      VT=1.0-0.5*STEP(0.0)
PROCEDURE V1=HOFS(TR,VT)
      IF (TR) 10,20,10
   10 VINT=REALPL(1.0,TR,VT)
      GO TO 30
   20 VINT=VT
   30 V1=VINT
ENDPRO
      V2=VREF+AUX-V1
      V3=V2-V7
PROCEDURE V4=HOFS(TA,V3,KA)
      IF (TA) 40,41,40
   40 V4PRI=REALPL(0.0,TA,V3)
      GO TO 42
   41 V4PRI=V3
   42 V4=KA*V4PRI
ENDPRO
      V5=LIMIT(VRMIN,VRMAX,V4)
      V8=SE*EFD
      V6=V5-V8
      EFDPRI=REALPL(EFDO,TI,V6)
      EFD=1.0/KE*EFDPRI
      ZDOT=(EFD-Z)/TF
```

```
      Z=INTGRL(0.0,ZDOT)
      VT=KF*ZDOT
     NOSORT
      IF ( KEEP .NE. 1 ) GO TO 100
      IF(ISET-1) 300,100,100
  300 IF (EFD-EFDITC) 100,200,200
  200 TC=TIME
      ISET=1
  100 CONTINUE
SORT

TERMINAL
      TIMER DELT=0.001, FINTIM=5.0
      METHOD RKSFX
      GO TO (1000,1010,1020,1030,1035,1040,1050),IRUN
 1000 WRITE (3,51) TR,TC
      GO TO 1060
 1010 WRITE (3,51) TA,TC
      GO TO 1060
 1020 WRITE (3,51) TF,TC
      GO TO 1060
 1030 WRITE (3,51) KA,TC
      GO TO 1060
 1035 WRITE (3,51) KF,TC
      GO TO 1060
 1040 WRITE (3,51) TE,TC
      GO TO 1060
 1050 WRITE (3,51) KE,TC
 1060 ISET=0
      IF (ICNT-41) 500,510,510
  500 ICNT=ICNT+1
      GO TO (2000,2010,2020,2030,2035,2040,2050),IRUN
 2000 TR=TR+TRDELT
      GO TO 2060
 2010 TA=TA+TADELT
      GO TO 2060
 2020 TF=TF+TFDELT
      GO TO 2060
 2030 KA=KA+KADELT
      GO TO 2060
 2035 KF=KF+KFDELT
      GO TO 2060
 2040 TE=TE+TEDELT
      GO TO 2060
 2050 KE=KE+KEDELT
 2060 CALL RERUN
  510 CONTINUE
   51 FORMAT (2(E20.8))
      END
      PARAMETER TR=0.03,TA=0.06,IRUN=2,ICNT=1
      END
      PARAMETER TA=0.13,TF=0.35,IRUN=3,ICNT=1
      END
      PARAMETER TF=.01,KA=1.0 ,IRUN=4,ICNT=1
      END
      PARAMETER KA=50.1 ,TE=0.01,IRUN=5,ICNT=1
      END
      PARAMETER  KF=.25,TE=.25 ,IRUN=6,ICNT=1
      TIMER DELT=0.001, FINTIM=20.0
      END
      PARAMETER TE=0.5,KE=-.08 ,IRUN=7,ICNT=1
      TIMER DELT=0.001, FINTIM=25.
      END
      STOP

OUTPUT VARIABLE SEQUENCE
ISET   TI     TRMIN  TRMAX  TRDELT TCMIN  TCMAX  TEDELT KEMIN  KEMAX
KEDELT KAMIN  KAMAX  KADELT TFMIN  TFMAX  TFDELT TAMIN  TAMAX  TADELT
KFMIN  KFMAX  KFDELT ZZ0001 KALIM  KALIM  KALIM  EFDSS  EFDITC VT
ZZ0004 VINT   VI     EFD    ZDOT   V7     V2     V3     ZZ0007 VAPRI
V4     V9     V5     V6     ZZ0009 EFDPRI Z      ZZ0012 TC     ISET
ZZ0013 ISET   ICNT   TR     TA     TF     KA     KF     TE     KE

 OUTPUTS    INPUTS    PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
 64(500)    92(1400)  17(400)   4+   0=  4(300)  100(600)     21

ENDJOB
```

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0001            DIMENSION TR(43),TA(43),TF(43),KA(43),TE(41),KE(41),TC1(43),
               1 TC2(43), TC3(43),TC4(43),TC5(41),TC6(41),KF(43),TC7(43)
0002            INTEGER LABL(5)/'SYST','EM T','IME ','CONS','TANT'/
0003            READ (3,50) (TR(I),TC1(I),I=1,41)
0004            READ (3,50) (TA(I),TC2(I),I=1,41)
0005            READ (3,50) (TF(I),TC3(I),I=1,41)
0006            READ (3,50) (KA(I),TC4(I),I=1,41)
0007            READ (3,50) (TE(I),TC5(I),I=1,41)
0008            READ (3,50) (KE(I),TC6(I),I=1,41)
0009            READ (3,50) (KF(I),TC7(I),I=1,41)
0010            DO 10 I=42,43
0011         10 READ(5,51) TR(I),TA(I),TF(I),KA(I),KF(I)
0012            DO 20 I=42,43
0013         20 READ(5,51) TC1(I),TC2(I),TC3(I),TC4(I),TC7(I)
0014            WRITE (6,500)
0015        500 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/43X,'AS TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08',
               2 //47X,'RUN',8X,'TR',5X,'SYSTEM TIME CONSTANT')
0016            WRITE (6,52) (I,TR(I),TC1(I),I=1,41)
0017            WRITE (6,510)
0018        510 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/43X,'AS TIME CONSTANT TA IS VARIED FROM 0.0 TO .40 ',
               2 //47X,'RUN',8X,'TA',5X,'SYSTEM TIME CONSTANT')
0019            WRITE (6,52) (I,TA(I),TC2(I),I=1,41)
0020            WRITE (6,520)
0021        520 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/43X,'AS TIME CONSTANT TF IS VARIED FROM .01 TO 5.00',
               2 //47X,'RUN',8X,'TF',5X,'SYSTEM TIME CONSTANT')
0022            WRITE (6,52) (I,TF(I),TC3(I),I=1,41)
0023            WRITE (6,530)
0024        530 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/49X,'AS GAIN KA IS VARIED FROM 1.00 TO 150.0',
               2 //47X,'RUN',8X,'KA',5X,'SYSTEM TIME CONSTANT')
0025            WRITE (6,52) (I,KA(I),TC4(I),I=1,41)
0026            WRITE (6,535)
0027        535 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/48X,'AS GAIN KF IS VARIED FROM .003 TO .3  ',
               2 //47X,'RUN',8X,'KF',5X,'SYSTEM TIME CONSTANT')
0028            WRITE (6,52) (I,KF(I),TC7(I),I=1,41)
0029            WRITE (6,540)
0030        540 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/43X,'AS TIME CONSTANT TE IS VARIED FROM .01 TO 5.00',
               2 //47X,'RUN',8X,'TE',5X,'SYSTEM TIME CONSTANT')
0031            WRITE (6,52) (I,TE(I),TC5(I),I=1,41)
0032            WRITE (6,550)
0033        550 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION',
               1 ' SYSTEM',/49X,'AS GAIN KE IS VARIED FROM .01 TO 15.0',
               2 //47X,'RUN',8X,'KE',5X,'SYSTEM TIME CONSTANT')
0034            WRITE (6,52) (I,KE(I),TC6(I),I=1,41)
0035            CALL PRPLOT(TR,TC1,43,1,43,1,LABL)
0036            WRITE(6,1001)
0037       1001 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
```

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              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO ',
              3 '0.08')
0038          CALL PRPLOT(TA,TC2,43,1,43,1,LABL)
0039          WRITE(6,1002)
0040     1002 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM 0.0 TO ',
              3 ' .40')
0041          CALL PRPLOT(TF,TC3,43,1,43,1,LABL)
0042          WRITE(6,1003)
0043     1003 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO ',
              3 '5.0 ')
0044          CALL PRPLOT(KA,TC4,43,1,43,1,LABL)
0045          WRITE(6,1004)
0046     1004 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.00 TO 150.0')
0047          CALL PRPLOT(KF,TC7,43,1,43,1,LABL)
0048          WRITE(6,1007)
0049     1007 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN GAIN KF IS VARIED FROM .003 TO  .3 ')
0050          CALL PRPLOT(TE,TC5,41,1,41,1,LABL)
0051          WRITE(6,1005)
0052     1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO ',
              3 '5.00')
0053          CALL PRPLOT(KE,TC6,41,1,41,1,LABL)
0054          WRITE(6,1006)
0055     1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 1 EXCITATION ',
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
              2 /1X,'OF THE SYSTEM WHEN GAIN KE IS VARIED FROM .01 TO 15.0')
0056       50 FORMAT (2(F20.8))
0057       51 FORMAT(6(F10.2))
0058       52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0059          STOP
0060          END
```

```
        ****CONTINUOUS SYSTEM MODELING PROGRAM****

                  *** VERSION 1.3 ***

TITLE TYPE 2 EXCITATION SYSTEM. ROTATING RECTIFIER SYSTEM
TITLE WITH STATIC VOLTAGE REGULATOR
      FIXED ISET
      FIXED ICNT
      FIXED IRUN

INITIAL
PARAMETER TR=0.0.KA=40..TA=.02.KE=1.0.KF=.03.TE=.73....
      TF=1.0.SE=.74.VRMAX=6.5.VRMIN=-6.5.VREF=1.0.ICNT=1.IRUN=1....
      AUX=0.0.EFDC=0
      ISET=0
      TF1=TF
      TF2=TF
      T1=TE/KE
      KEFD=1.0/KE
      TRMAX=.08
      TRMIN=0.0
      TRDELT=(TRMAX-TRMIN)/40.0
      TEMIN=.1
      TEMAX=3.5
      TEDELT=(TEMAX-TEMIN)/40.0
      KEMAX=3.5
      KEMIN=.1
      KEDELT=(KEMAX-KEMIN)/40.0
      KAMAX=100.0
      KAMIN=1.0
      KADELT=(KAMAX-KAMIN)/40.0
      TFMIN=0.01
      TFMAX=10.0
      TFDELT=(TFMAX-TFMIN)/40.0
      TAMIN=0.0
      TAMAX=1.0
      TADELT=(TAMAX-TAMIN)/40.0
NOSORT
      IF ( (0.5*KA) .LE. VRMAX ) GO TO 1
      KALIM=VRMAX
      GO TO 3
    1 IF ( (0.5*KA) .GE. VRMIN ) GO TO 2
      KALIM=VRMIN
      GO TO 3
    2 KALIM=0.5*KA
    3 CONTINUE
      EFDSS=(1.0/KE*KALIM)/(1.0+SE/KE)
      EFD1TC=(1.0-EXP(-1.0))*EFDSS
SORT

DYNAMIC
      VT=1.0-0.5*STEP(0.0)
PROCEDURE V1=MOFS(TR.VT)
      IF (TR) 10.20.10
   10 VINT=REALPL(1.0.TR.VT)
      GO TO 30
   20 VINT=VT
   30 V1=VINT
ENDPRO
      V2=VREF+AUX-V1
      V3=V2-V7
PROCEDURE V4=MOFS(TA.V3.KA)
      IF (TA) 40.41.40
   40 V4PRI=REALPL(0.0.TA.V3)
      GO TO 42
   41 V4PRI=V3
   42 [illegible]
```

```
   42 V4=KA*V4PRI
ENDPRO
      V5=LIMIT(VRMIN,VRMAX,V4)
      V8=SE*EFD
      V6=V5-VR
      EFDPRI=REALPL(EFDO,T1,V6)
      EFD=1.0/KE*EFDPRI
      V9=REALPL(0.0,TF2,V5)
      ZDOT=(V9-Z)/TF1
      Z=INTGRL(0.0,ZDOT)
      V7=KF*ZDOT
    NOSORT
      IF ( KEEP .NE. 1 ) GO TO 100
      IF(ISET-1) 300,100,300
  300 IF (EFD-EFDITC) 100,200,200
  200 TC=TIME
      ISET=1
  100 CONTINUE
SORT

TERMINAL
      TIMER DELT=0.001, FINTIM=1.0
      METHOD RKSFX
      GO TO (1000,1010,1020,1030,1040,1050),IRUN
 1000 WRITE (3,51) TR,TC
      GO TO 1060
 1010 WRITE (3,51) TA,TC
      GO TO 1060
 1020 WRITE (3,51) TF,TC
      GO TO 1060
 1030 WRITE (3,51) KA,TC
      GO TO 1060
 1040 WRITE (3,51) TE,TC
      GO TO 1060
 1050 WRITE (3,51) KE,TC
 1060 ISET=0
      IF (ICNT-41) 500,510,510
  500 ICNT=ICNT+1
      GO TO (2000,2010,2020,2030,2040,2050),IRUN
 2000 TR=TR+TRDELT
      GO TO 2060
 2010 TA=TA+TADELT
      GO TO 2060
 2020 TF=TF+TFDELT
      GO. TO 2060
 2030 KA=KA+KADELT
      GO TO 2060
 2040 TE=TE+TEDELT
      GO TO 2060
 2050 KE=KE+KEDELT
 2060 CALL RERUN
  510 CONTINUE
   51 FORMAT (2(E20.8))
      END
      PARAMETER TA=0.0,IRUN=2,ICNT=1,TR=0.0
      END
      PARAMETER TA=0.02,TF=.6 ,IRUN=3,ICNT=1
      END
      PARAMETER TF=1.0,KA=25. ,IRUN=4,ICNT=1
      END
      PARAMETER KA=100.0,TE=.4  ,IRUN=5,ICNT=1
      TIMER DELT=0.001, FINTIM=2.0
      END
      PARAMETER TE=.8 ,IRUN=6,ICNT=1
      END
      STOP
```

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0001            DIMENSION TR(43).TA(43).TF(43).KA(43).TE(41).KE(41).TC1(43).
              1 TC2(43). TC3(43).TC4(43).TC5(41).TC6(41)
0002            INTEGER LABL(5)/'SYST'.'EM T'.'IME '.'CONS'.'TANT'/
0003            READ (3.50) (TR(I).TC1(I).I=1.41)
0004            READ (3.50) (TA(I).TC2(I).I=1.41)
0005            READ (3.50) (TF(I).TC3(I).I=1.41)
0006            READ (3.50) (KA(I).TC4(I).I=1.41)
0007            READ (3.50) (TE(I).TC5(I).I=1.41)
0008            READ (3.50) (KE(I).TC6(I).I=1.41)
0009            DO 10 I=42.43
0010         10 READ(5.51) TR(I).TA(I).TF(I).KA(I)
0011            DO 20 I=42.43
0012         20 READ(5.51) TC1(I).TC2(I).TC3(I).TC4(I)
0013            WRITE (6.500)
0014        500 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./43X.'AS TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08'.
              2 //47X.'RUN'.8X.'TR'.5X.'SYSTEM TIME CONSTANT')
0015            WRITE (6.52) (I.TR(I).TC1(I).I=1.41)
0016            WRITE (6.510)
0017        510 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./43X.'AS TIME CONSTANT TA IS VARIED FROM 0.0 TO  .2 '.
              2 //47X.'RUN'.8X.'TA'.5X.'SYSTEM TIME CONSTANT')
0018            WRITE (6.52) (I.TA(I).TC2(I).I=1.41)
0019            WRITE (6.520)
0020        520 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./43X.'AS TIME CONSTANT TF IS VARIED FROM 0.01 TO 3.5'.
              2 //47X.'RUN'.8X.'TF'.5X.'SYSTEM TIME CONSTANT')
0021            WRITE (6.52) (I.TF(I).TC3(I).I=1.41)
0022            WRITE (6.530)
0023        530 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./48X.'AS GAIN KA IS VARIED FROM 1.00 TO 100.0'.
              2 //47X.'RUN'.8X.'KA'.5X.'SYSTEM TIME CONSTANT')
0024            WRITE (6.52) (I.KA(I).TC4(I).I=1.41)
0025            WRITE (6.540)
0026        540 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./43X.'AS TIME CONSTANT TE IS VARIED FROM .1 TO 6.0'.
              2 //47X.'RUN'.9X.'TE'.5X.'SYSTEM TIME CONSTANT')
0027            WRITE (6.52) (I.TE(I).TC5(I).I=1.41)
0028            WRITE (6.550)
0029        550 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION'.
              1 ' SYSTEM'./49X.'AS GAIN KE IS VARIED FROM .1 TO 5.0'.
              2 //47X.'RUN'.8X.'KE'.5X.'SYSTEM TIME CONSTANT')
0030            WRITE (6.52) (I.KE(I).TC6(I).I=1.41)
0031            CALL PRPLOT(TR.TC1.43.1.43.1.LABL)
0032            WRITE(6.1001)
0033       1001 FORMAT(1X./1X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION '.
              1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT'.
              2 /1X.'OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO '.
              3 '0.08')
0034            CALL PRPLOT(TA.TC2.43.1.43.1.LABL)
0035            WRITE(6.1002)
0036       1002 FORMAT(1X./1X.'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION '.
```

```
                1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM 0.0 TO ',
                3 '.2  ')
0037              CALL PPPLOT(TF,TC3,43,1,43,1,LABL)
0038              WRITE(6,1003)
0039         1003 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION ',
                1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO ',
                3 '3.5 ')
0040              CALL PPPLOT(KA,TC4,43,1,43,1,LABL)
0041              WRITE(6,1004)
0042         1004 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION ',
                1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                2 /1X,'OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.00 TO  100.')
0043              CALL PRPLOT(TE,TC5,41,1,41,1,LABL)
0044              WRITE(6,1005)
0045         1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION ',
                1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .1  TO ',
                3 '5.00')
0046              CALL PRPLOT(KE,TC6,41,1,41,1,LABL)
0047              WRITE(6,1006)
0048         1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 2 EXCITATION ',
                1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                2 /1X,'OF THE SYSTEM WHEN GAIN KE IS VARIED FROM  .1 TO 5.0')
0049           50 FORMAT (2(E20.8))
0050           51 FORMAT(6(F10.2))
0051           52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0052              STOP
0053              END
```

```
****CONTINUOUS SYSTEM MODELLING PROGRAM****

*** VERSION 1.3 ***

TITLE TYPE 3 EXCITATION SYSTEM
      FIXED ISET
      FIXED ICNT
      FIXED IRUN

INITIAL
PARAMETER TR=0.0,KA=40.,TA=.02,KE=1.0,KF=.03,TE=.73,...
      TF=1.0,SE=.74,VRMAX=6.5,VRMIN=-6.5,VREF=1.0,ICNT=1,IRUN=1,...
      AUX=0.0,EFD0=0.0,KP=1.,KI=1.0,VEMAX=6.5
      ISET=0
      T1=TE/KE
      TRMAX=.08
      TRMIN=0.0
      TRDELT=(TRMAX-TRMIN)/40.0
      TEMIN=.01
      TEMAX=5.
      TEDELT=(TEMAX-TEMIN)/40.0
      KEMAX=15.
      KEMIN=.01
      KEDELT=(KEMAX-KEMIN)/40.0
      KAMAX=150.
      KAMIN=1.0
      KADELT=(KAMAX-KAMIN)/40.(
      TFMIN=0.01
      TFMAX=5.
      TFDELT=(TFMAX-TFMIN)/40.0
      TAMIN=0.0
      TAMAX=.5
      TADELT=(TAMAX-TAMIN)/40.0
      KFMIN=0.01
      KFMAX=.3
      KFDELT=(KFMAX-KFMIN)/40.0
NOSORT
      IF ( (0.5*KA) .LE. VRMAX ) GO TO 1
      KALIM=VRMAX
      GO TO 3
    1 IF ( (0.5*KA) .GE. VRMIN ) GO TO 2
      KALIM=VRMIN
      GO TO 3
    2 KALIM=0.5*KA
    3 CONTINUE
      EFDSS=KALIM/KE
      EFDITC=(1.0-EXP(-1.0))*EFDSS
      SORT

DYNAMIC
      IFD=1.-.5*STEP(0.0)
      IT=1.0-.5*STEP(0.0)
      VT=1.0-0.5*STEP(0.0)
PROCEDURE V1=MCFS(TR,VT)
      IF (TR) 10,20,10
   10 VINT=REALPL(1.0,TR,VT)
      GO TO 30
   20 VINT=VT
   30 V1=VINT
ENDPRO
      V2=VREF+AUX-V1
      NOSORT
      VTHEN=CABS( CMPLX(KP*VT,KI*IT))
      A=(.78*IFD/VTHEN)**2
        VTHEN1=VTHEN*SQRT(1.-A)
      IF(A.GT.1.) VBMAX=0.0
      SORT
      V3=V2-V7
PROCEDURE V4=MOFS(TA,V3,KA)
      IF (TA) 40,41,40
   40 V4PRI=REALPL(0.0,TA,V3)
      GO TO 42
   41 V4PRI=V3
   42 V4=KA*V4PRI
ENDPRO
```

```
ENDPRO
      V5=LIMIT(VAMIN,VAMAX,V4)
      V6=V5+VTHCN1
      V8=LIMIT(0.0,VDMAX,V6)
      EFDPRI=REALPL(EFDO,TI,V8)
      EFD=1.0/KL*EFDPRI
      ZDOT=(EFD-Z)/TF
      Z=INTGRL(0.0,ZDOT)
      V7=KF*ZDOT
    NOSORT
      IF ( KEEP .NE. 1 ) GO TO 100
      IF(ISET-1) 300,100,300
  300 IF (EFD-EFDITC) 100,200,200
  200 TC=TIME
      ISET=1
  100 CONTINUE
SORT

TERMINAL
      TIMER DELT=0.001, FINTIM=3.0
      METHOD RKSFX
      GO TO (1000,1010,1020,1030,1035,1040,1050),IRUN
 1000 WRITE (3,51) TR,TC
      GO TO 1060
 1010 WRITE (3,51) TA,TC
      GO TO 1060
 1020 WRITE (3,51) TF,TC
      GO TO 1060
 1030 WRITE (3,51) KA,TC
      GO TO 1060
 1035 WRITE (3,51) KF,TC
      GO TO 1060
 1040 WRITE (3,51) TE,TC
      GO TO 1060
 1050 WRITE (3,51) KE,TC
 1060 ISET=0
      IF (ICNT-41) 500,510,510
  500 ICNT=ICNT+1
      GO TO (2000,2010,2020,2030,2035,2040,2050),IRUN
 2000 TR=TR+TRDELT
      GO TO 2060
 2010 TA=TA+TADELT
      GO TO 2060
 2020 TF=TF+TFDELT
      GO TO 2060
 2030 KA=KA+KADELT
      GO TO 2060
 2035 KF=KF+KFDELT
      GO TO 2060
 2040 TE=TE+TEDELT
      GO TO 2060
 2050 KE=KE+KEDELT
 2060 CALL RERUN
  510 CONTINUE
   51 FORMAT (2(E20.8))
      END
      PARAMETER TR=0.03,TA=0.06,IRUN=2,ICNT=1
      END
      PARAMETER TA=0.13,TF=.35 ,IRUN=3,ICNT=1
      END
      PARAMETER TF=.01,KA=1.0,IRUN=4,ICNT=1
      END
      PARAMETER KA=50.0,TE=0.01,IRUN=5,ICNT=1
      END
      PARAMETER KF=.25,TE=.25,IRUN=6,ICNT=1
      TIMER DELT=0.001, FINTIM=15.
      END
      PARAMETER TE=.5 ,KF= -.08,IRUN=7,ICNT=1
      TIMER DELT=0.001, FINTIM=15.
      END
      STOP
```

```
0001            DIMENSION TR(43).TA(43).TF(43).KA(43).TE(41).KE(41).TC1(43).
               1 TC2(43). TC3(43).TC4(43).TC5(41).TC6(41).KF(43).TC7(43)
0002            INTEGER LABL(5)/'SYST'.'EM T'.'IME '.'CONS'.'TANT'/
0003            READ (3.50) (TR(I).TC1(I).I=1.41)
0004            READ (3.50) (TA(I).TC2(I).I=1.41)
0005            READ (3.50) (TF(I).TC3(I).I=1.41)
0006            READ (3.50) (KA(I).TC4(I).I=1.41)
0007            READ (3.50) (TE(I).TC5(I).I=1.41)
0008            READ (3.50) (KE(I).TC6(I).I=1.41)
0009            READ (3.50) (KF(I).TC7(I).I=1.41)
0010            DO 10 I=42.43
0011         10 READ(5.51) TR(I).TA(I).TF(I).KA(I).KF(I)
0012            DO 20 I=42.43
0013         20 READ(5.51) TC1(I).TC2(I).TC3(I).TC4(I).TC7(I)
0014            WRITE (6.500)
0015        500 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./43X.'AS TIME CONSTANT TR IS VARIED FROM 0.0 TO 0.08'.
               2 //47X.'RUN'.8X.'TR'.5X.'SYSTEM TIME CONSTANT')
0016            WRITE (6.52) (I.TR(I).TC1(I).I=1.41)
0017            WRITE (6.510)
0018        510 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./43X.'AS TIME CONSTANT TA IS VARIED FROM 0.0  TO 3.0 '.
               2 //47X.'RUN'.8X.'TA'.5X.'SYSTEM TIME CONSTANT')
0019            WRITE (6.52) (I.TA(I).TC2(I).I=1.41)
0020            WRITE (6.520)
0021        520 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./43X.'AS TIME CONSTANT TF IS VARIED FROM 0.01 TO 5.0'.
               2 //47X.'RUN'.8X.'TF'.5X.'SYSTEM TIME CONSTANT')
0022            WRITE (6.52) (I.TF(I).TC3(I).I=1.41)
0023            WRITE (6.530)
0024        530 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./48X.'AS GAIN KA IS VARIED FROM 1.0  TO 150.'.
               2 //47X.'RUN'.8X.'KA'.5X.'SYSTEM TIME CONSTANT')
0025            WRITE (6.52) (I.KA(I).TC4(I).I=1.41)
0026            WRITE (6.535)
0027        535 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./48X.'AS GAIN KF IS VARIED FROM 0.01 TO 0.3 '.
               2 //47X.'RUN'.8X.'KF'.5X.'SYSTEM TIME CONSTANT')
0028            WRITE (6.52) (I.KF(I).TC7(I).I=1.41)
0029            WRITE (6.540)
0030        540 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./43X.'AS TIME CONSTANT TE IS VARIED FROM .01  TO 5.0'.
               2 //47X.'RUN'.8X.'TE'.5X.'SYSTEM TIME CONSTANT')
0031            WRITE (6.52) (I.TE(I).TC5(I).I=1.41)
0032            WRITE (6.550)
0033        550 FORMAT('1'.////41X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION'.
               1 ' SYSTEM'./49X.'AS GAIN KE IS VARIED FROM .01   TO 15.0'.
               2 //47X.'RUN'.8X.'KE'.5X.'SYSTEM TIME CONSTANT')
0034            WRITE (6.52) (I.KE(I).TC6(I).I=1.41)
0035            CALL PRPLOT(TR.TC1.43.1.43.1.LABL)
0036            WRITE(6.1001)
0037       1001 FORMAT(1X./1X.'SENSITIVITY ANALYSIS OF A TYPE 3 EXC3TATION '.
```

```
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TR IS VARIED FROM 0.0 TO ',
                  3 '0.08')
0038                CALL PRPLOT(TA,TC2,43,1,43,1,LABL)
0039                WRITE(6,1002)
0040           1002 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TA IS VARIED FROM .0  TO ',
                  3 ' .5 ')
0041                CALL PRPLOT(TF,TC3,43,1,43,1,LABL)
0042                WRITE(6,1003)
0043           1003 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TF IS VARIED FROM .01 TO ',
                  3 '5.0 ')
0044                CALL PRPLOT(KA,TC4,43,1,43,1,LABL)
0045                WRITE(6,1004)
0046           1004 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN GAIN KA IS VARIED FROM 1.0  TO 150.')
0047                CALL PRPLOT(KF,TC7,43,1,43,1,LABL)
0048                WRITE(6,1007)
0049           1007 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN GAIN KF IS VARIED FROM .01 TO .3 ')
0050                CALL PRPLOT(TE,TC5,41,1,41,1,LABL)
0051                WRITE(6,1005)
0052           1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO ',
                  3 '5.0 ')
0053                CALL PRPLOT(KE,TC6,41,1,41,1,LABL)
0054                WRITE(6,1006)
0055           1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 3 EXCITATION ',
                  1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
                  2 /1X,'OF THE SYSTEM WHEN GAIN KE IS VARIED FROM -0.1  TO 15.0 ')
0056             50 FORMAT (2(E20.8))
0057             51 FORMAT(6(F10.2))
0058             52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0059                STOP
0060                END
```

```
****CONTINUOUS SYSTEM MODELING PROGRAM****

*** VERSION 1.3 ***

TITLE TYPE 4 EXCITATION SYSTEM
      FIXED ISET
      FIXED ICNT
      FIXED IRUN

INITIAL
PARAMETER VRMAX=10.5,VRMIN=-10.5,SE=.85,KE=0.1,TE=0.01,...
      EFDO=0.0,VREF=1.0,ICNT=1,IRUN=1
      ISET=0
      VRH=(VRMAX-VRMIN)*.6
      KV=.05*VRMAX
      T1=TE/KE
      TEMIN=.01
      TEMAX=5.0
      TEDELT=(TEMAX-TEMIN)/40.0
      KEMIN=-.01
      KEMAX=2.0
      KEDELT=(KEMAX-KEMIN)/40.0
NOSORT
      IF(V1.LE.VRMAX) GO TO 1
      V1=.5*VRMAX
      GO TO 3
    1 IF(V1.GE.VRMIN) GO TO 2
      V1=VRMIN
      GO TO 3
    2 V1=.5*VRMAX
    3 CONTINUE
      EFDSS=(1.0/KE* V1   )/(1.0+SE/KE)
      EFD1TC=(1.0-EXP(-1.0))*EFDSS
SORT

DYNAMIC
      VT=1.0-0.5*STEP(0.0)
      V1=VREF-VT
      NOSORT
      IF(V1.GE.KV) VR=VRMAX
      IF(V1.LE.(-KV)) VR=VRMIN
      IF(ABS(V1).LT.KV) VR=VRH
      SORT
      V2=VR-V3
      V3=SE*EFD
      EFDPRI=REALPL(EFDO,T1,V2)
      EFD=1.0/KE*EFDPRI
    NOSORT
      IF ( KEEP .NE. 1 ) GO TO 100
      IF(ISET-1) 300,100,300
  300 IF (EFD-EFD1TC) 100,200,200
  200 TC=TIME
      ISET=1
  100 CONTINUE
SORT

TERMINAL
      TIMER DELT=0.001, FINTIM=11.0
      METHOD RKSFX
      GO TO (1040,1050),IRUN
 1040 WRITE (3,51) TE,TC
      GO TO 1060
 1050 WRITE (3,51) KE,TC
```

```
1090 ISET=0
     IF (ICNT-41) 500,510,510
 500 ICNT=ICNT+1
     GO TO (2040,2050),IRUN
2040 TE=TE+TEDELT
     GO TO 2090
2050 KE=KE+KEDELT
2090 CALL RERUN
 510 CONTINUE
  51 FORMAT (2(E20.8))
     END
     PARAMETER TE=0.5,KE=-0.08,IRUN=2,ICNT=1
     TIMER DELT=0.001, FINTIM=11.0
     END
     STOP

OUTPUT VARIABLE SEQUENCE
ISET    VFM     KV      T1       TEMIN  TEMAX  TEDELT KEMIN  KEMAX  KEDELT
ZZ0001  V1      V1      V1       EFDSS  EFD1TC VT     V1     VR     VP
VF      EFD     V3      V2       ZZ0003 EFDPRI ZZ0004 TC     ISET   ZZ0005
ISET    ICNT    TE      KE

PARAMETERS NOT INPUT OR OUTPUTS NOT AVAILABLE TO SORT SECTION***SET TO ZERO***
KEMIN   EFD0

 OUTPUTS   INPUTS    PARAMS   INTEGS + MEM BLKS  FORTRAN  DATA COS
 38(500)   55(1400)  13(400)    1+  0=  1(300)   51(600)      9

        ENDJOB
```

```
FORTRAN IV G LEVEL  21              MAIN              DATE = 77097        03/11/48              PAGE 0001

0001            DIMENSION TE(41),KE(41),TC1(41),TC2(41)
0002            INTEGER LABL(5)/'SYST','EM T','IME ','CONS','TANT'/
0003            READ (3,50) (TE(I),TC1(I),I=1,41)
0004            READ (3,50) (KE(I),TC2(I),I=1,41)
0005            WRITE (6,540)
0006        540 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 4 EXCITATION',
               1 ' SYSTEM',/43X,'AS TIME CONSTANT TE IS VARIED FROM .01 TC 5.0',
               2 //47X,'RUN',8X,'TE',5X,'SYSTEM TIME CONSTANT')
0007            WRITE (6,52) (I,TE(I),TC1(I),I=1,41)
0008            WRITE (6,550)
0009        550 FORMAT('1',////41X,'SENSITIVITY ANALYSIS OF A TYPE 4 EXCITATION',
               1 ' STSTEM',/49X,'AS GAIN KE IS VARIED FROM -.011  TO 2.00',
               2 //47X,'RUN',8X,'KE',5X,'SYSTEM TIME CONSTANT')
0010            WRITE (6,52) (I,KE(I),TC2(I),I=1,41)
0011            CALL PRPLOT(TE,TC1,41,1,41,1,LABL)
0012            WRITE(6,1005)
0013       1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 4 EXCITATION ',
               1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
               2 /1X,'OF THE SYSTEM WHEN TIME CONSTANT TE IS VARIED FROM .01 TO',
               3 ' 5.0')
0014            CALL PRPLOT(KE,TC2,41,1,41,1,LABL)
0015            WRITE(6,1006)
0016       1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A TYPE 4 EXCITATION ',
               1 'SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME CONSTANT',
               2 /1X,'OF THE SYSTEM WHEN GAIN KE IS VARIED FROM -.01 TO 2.0 ')
0017         50 FORMAT (2(E20.8))
0018         52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0019            STOP
0020            END
```

APPENDIX D
COMPUTER PROGRAM OF ROOT LOCUS AND FREQUENCY RESPONSE TECHNIQUE

```
    ROOT LOCUS PROGRAM
    PROBLEM IDENTIFICATION - RTLOC EXCTER TYPE I

********************************************

THE NUMERATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

   0.0          1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

   0.0

IMAGINARY PART

   0.0

*****************************

THE DENOMINATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

   1.1700E 02   1.6934E 02   5.3340E 01   1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

  -1.0000E 00  -2.3400E 00  -5.0000E 01

IMAGINARY PART

   0.0          0.0          0.0

*****************************

*********************************************************

YOU FORGOT YOUR OPTION CARD. ASSUME NOPT=0.

    MIN. GAIN =   1.00E 01          MAX. GAIN =    3.00E 03          K =  1.150 * ( K +   1.170E 00  )

STATIC SENSITIVITY =  8.54701925E-03 * GAIN                    GAIN =  1.1700006E 02  *  STATIC SENSITIVITY

*********************************************************

  1  K =    1.000E 01    S =   0.085 -0.8778       -2.677       -49.78
                                      0.0           0.0          0.0

  2  K =    1.285E 01    S =   0.110 -0.8507       -2.766       -49.72
                                      0.0           0.0          0.0

  3  K =    1.612E 01    S =   0.138 -0.8224       -2.865       -49.65
                                      0.0           0.0          0.0

  4  K =    1.988E 01    S =   0.170 -0.7929       -2.977       -49.57
```

FREQUENCY RESPONSE
PROBLEM IDENTIFICATION - FRESP EXCITER TYPE I

****

GAIN = 4.000000E 03

THE NUMERATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

1.0000E 00 1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

-1.0000E 00

IMAGINARY PART

0.0

****

THE DENOMINATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

1.7300E 02 3.7000E 02 7.8000E 01 1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

-5.2536E-01 -4.5133E 00 -7.2961E 01

IMAGINARY PART

0.0 0.0 0.0

****

WMIN = 9.9999964E-02 WMAX = 1.0000000E 02 NOMEG = 100 KNOW = 0 NODE = 0 NYQST = 1 ISIG = 0

****

RADIAN FREQ.	REAL PART	IMAGINARY PART	MAGNITUDE	PHASE (RAD)	PHASE (DEG)
9.999996E-02	2.267838E 01	-2.549512E 00	2.282123E 01	-1.119503E-01	-6.414283E 00
1.072267E-01	2.261465E 01	-2.720904E 00	2.277774E 01	-1.197404E-01	-6.860619E 00
1.149756E-01	2.254219E 01	-2.901063E 00	2.272820E 01	-1.280262E-01	-7.335361E 00
1.212846E-01	2.245992E 01	-3.092493E 00	2.267183E 01	-1.368291E-01	-7.839730E 00
1.321940E-01	2.236664E 01	-3.292806E 00	2.260777E 01	-1.461692E-01	-8.374879E 00
1.417474E-01	2.226123E 01	-3.502667E 00	2.253511E 01	-1.560643E-01	-8.941826E 00
1.519911E-01	2.214224E 01	-3.721799E 00	2.245245E 01	-1.665292E-01	-9.541421E 00
1.629751E-01	2.200832E 01	-3.949747E 00	2.235994E 01	-1.775757E-01	-1.017434E 01
1.747526E-01	2.185802E 01	-4.185842E 00	2.225520E 01	-1.892106E-01	-1.084097E 01
1.873817E-01	2.168994E 01	-4.429177E 00	2.213750E 01	-2.014353E-01	-1.154139E 01
2.009233E-01	2.150250E 01	-4.678585E 00	2.200560E 01	-2.142440E-01	-1.227528E 01
2.154436E-01	2.129440E 01	-4.932613E 00	2.185831E 01	-2.276236E-01	-1.304187E 01

```
    ROOT LOCUS PROGRAM
    PROBLEM IDENTIFICATION - RTLOC EXCIT.TYPE II

****************************************

THE NUMERATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

   0.0          1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

   0.0

IMAGINARY PART

   0.0

**************************

THE DENOMINATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

   5.0000E 01   1.0100E 02   5.2000E 01   1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

  -1.0000E 00  -1.0000E 00  -5.0000E 01

IMAGINARY PART

   0.0          0.0          0.0

**************************

**********************************************

YOU FORGOT YOUR OPTION CARD. ASSUME NOPT=0.

    MIN. GAIN =   2.00E 01          MAX. GAIN =   3.00E 03          K =  1.150 * ( K +   5.000E-01  )

STATIC SENSITIVITY =  2.0000018E-02 * GAIN                    GAIN =  5.0000046E 01  *  STATIC SENSITIVITY

**********************************************

  1  K =   2.000E 01   S =   0.400 -0.5349      -1.885      -49.56
                                   0.0          0.0         0.0

  2  K =   2.357E 01   S =   0.471 -0.5081      -1.988      -49.50
                                   0.0          0.0         0.0

  3  K =   2.769E 01   S =   0.554 -0.4813      -2.102      -49.42
                                   0.0          0.0         0.0

  4  K =   3.241E 01   S =   0.648 -0.4546      -2.230      -49.32
                                   0.0          0.0         0.0
```

FREQUENCY RESPONSE
PROBLEM IDENTIFICATION - FRESP EXCIT.TYPE II

****

GAIN = 4.000000E 03

THE NUMERATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

1.0000E 00   2.0000E 00   1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

-1.0000E 00   -1.0000E 00

IMAGINARY PART

0.0   0.0

****

THE DENOMINATOR IS GIVEN BY

THE POLYNOMIAL COEFFICIENTS - IN ASCENDING POWERS OF S

1.4700E 02   4.2340E 02   4.7236E 02   7.9440E 01   1.0000E 00

THE POLYNOMIAL ROOTS ARE

REAL PART

-5.3853E 00   -7.3053E 01   -5.0086E-01

IMAGINARY PART

0.0   0.0   3.5041E-01

****

WMIN = 9.9999964E-02   WMAX = 1.0000000E 02   NOMEG = 100   KNOW = 0   NODE = 0   NYQST = 1   ISIG = 0

****

RADIAN FREQ.	REAL PART	IMAGINARY PART	MAGNITUDE	PHASE (RAD)	PHASE (DEG)
9.999996E-02	2.711133E 01	-2.430054E 00	2.722002E 01	-8.939350E-02	-5.121871E 00
1.072267E-01	2.709442E 01	-2.610830E 00	2.721992E 01	-9.606379E-02	-5.504050E 00
1.149756E-01	2.707437E 01	-2.805742E 00	2.721936E 01	-1.032622E-01	-5.916492E 00
1.232846E-01	2.705049E 01	-3.015981E 00	2.721811E 01	-1.110359E-01	-6.361888E 00
1.321940E-01	2.702200E 01	-3.242031E 00	2.721590E 01	-1.194377E-01	-6.843277E 00
1.417474E-01	2.698784E 01	-3.487864E 00	2.721233E 01	-1.285257E-01	-7.363979E 00
1.519911E-01	2.694698E 01	-3.752472E 00	2.720699E 01	-1.383646E-01	-7.927706E 00
1.629751E-01	2.689748E 01	-4.038346E 00	2.719893E 01	-1.490253E-01	-8.538524E 00
1.747528E-01	2.683777E 01	-4.347213E 00	2.718756E 01	-1.605963E-01	-9.200918E 00
1.873817E-01	2.676541E 01	-4.680540E 00	2.717162E 01	-1.731329E-01	-9.919785E 00
2.009233E-01	2.667757E 01	-5.041003E 00	2.714966E 01	-1.867585E-01	-1.070046E 01
2.154435E-01	2.657069E 01	-5.429376E 00	2.711974E 01	-2.015422E-01	-1.154867E 01
2.310131E-01	2.644041E 01	-5.847403E 00	2.707948E 01	-2.176491E-01	-1.247030E 01

APPENDIX E
A PHYSICAL AND SIMULATION MODEL OF GOVERNOR-TURBINE

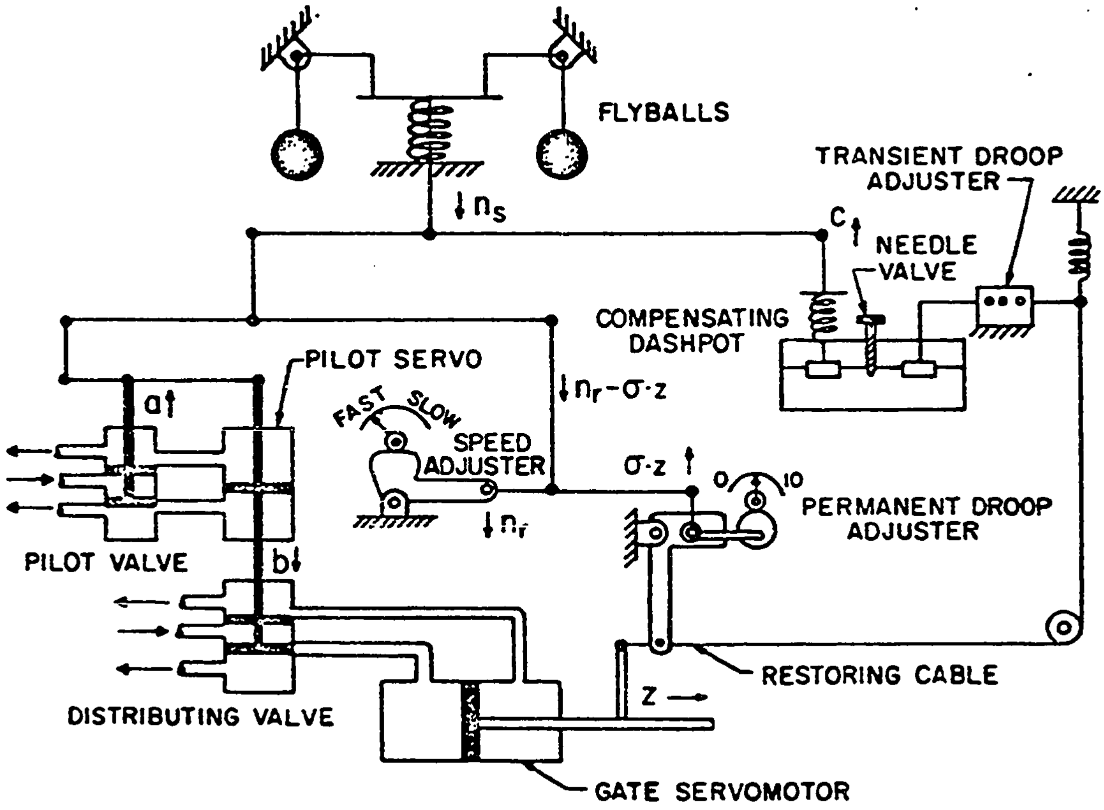


FIGURE E-1
MECHANICAL-HYDRAULIC HYDROGOVERNOR

"In steady state the shaft speed signal, n_s, is compared to the reference-speed setting nr, modified by the permanent speed droop times gate position $\sigma \cdot z$. Sometimes the permanent speed droop is obtained by using generator power output rather than gate position. An imbalance between actual speed and the modified reference speed appears as a change in the input "a" to the pilot servo. When gate position is changing, a transient droop signal C is developed to oppose fast changes in gate position. In mechanical-hydraulic governor illustrated, these signals are summed and transmitted through a system of floating levers from a mechanical motion to the operation of the pilot valve."(45, 46)

The mathematical representation for a speed-governoring hydro system is shown in figure (E-2). This model shows an initial power P_o. This initial power is combined with the increments power due to the speed deviation to obtain the total power, P_{GV}, which is subject to the time lag, T_3, imposed by the servomotor mechanism.

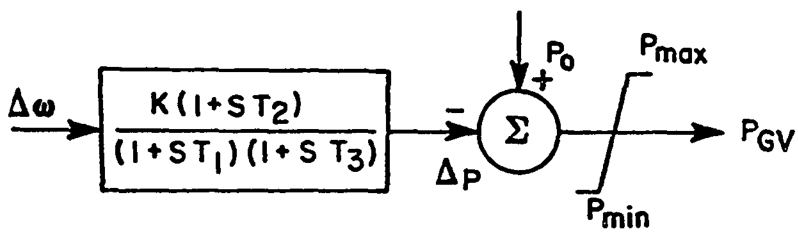


FIGURE E-2
MATHEMATICAL MODEL OF SPEED-GOVERNING HYDRO SYSTEM

The second speed-governing system for the steam turbine is shown in figure (E-3) and its mathematical representation is shown in figure (E-4).

Typically the mechanical hydraulic speed-governing system consists of a speed governor, a hydraulic servomotor, a speed relay and governor-controlled valves as seen in figure (E-3). The mathematical representation of speed-governing for steam turbine is shown in figure (E-4).(9)

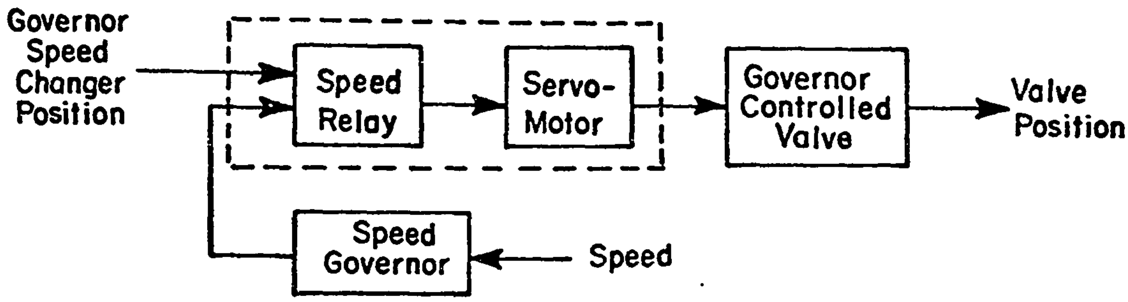


FIGURE E-3
SPEED GOVERNING SYSTEM FOR STEAM TURBINES

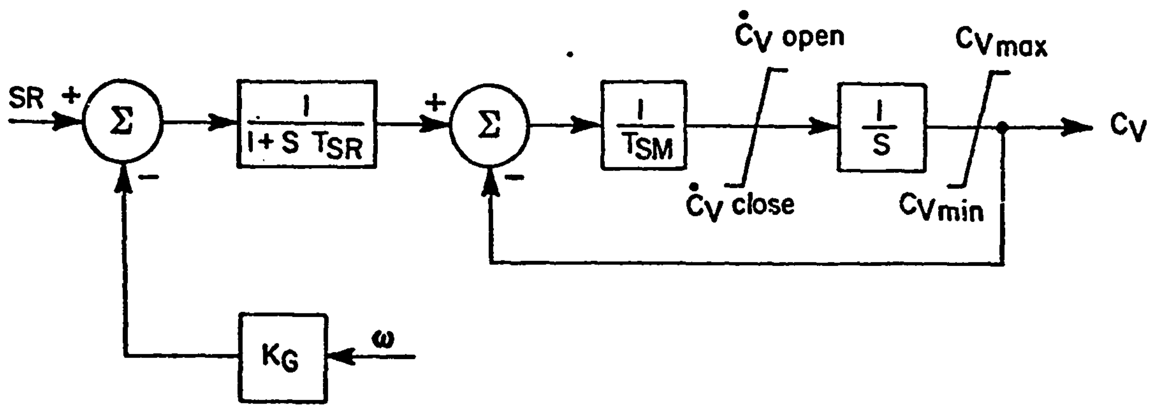


FIGURE E-4
MATHEMATICAL REPRESENTATION OF SPEED-GOVERNING
SYSTEM FOR STEAM TURBINE

STEAM TURBINE SYSTEM[9]

All compound steam turbine systems utilize governor-controlled valves at the high pressure or a very high, high pressure turbine. The steam chest and inlet piping to the first turbine cylinder and reheaters and crossover piping down stream all impose delays between the valve movement and change in the steam flow. The object in modeling the steam system for stability studies is to account for these delays. Flows into and out of any steam vessel are related by a simple time constant. The steam turbine configuration, as well as the mathematical representation, is shown in figure (E-5) and (E-6), respectively for only the tandem compound-double reheater. There are five major models of steam systems: nonreheat, tandem compound-single reheated, tandem compound-double reheat, cross compound-single reheat, and cross compound-double reheat. The time constants T_{CH}, T_{RH} and T_{CO} represent delays due to the steam chest and inlet piping, reheaters and crossover piping respectively. The fraction F_{VHP}, F_{HP}, F_{IP}, and F_{LP} represent portions of the total turbine power developed in the various cyclinders.

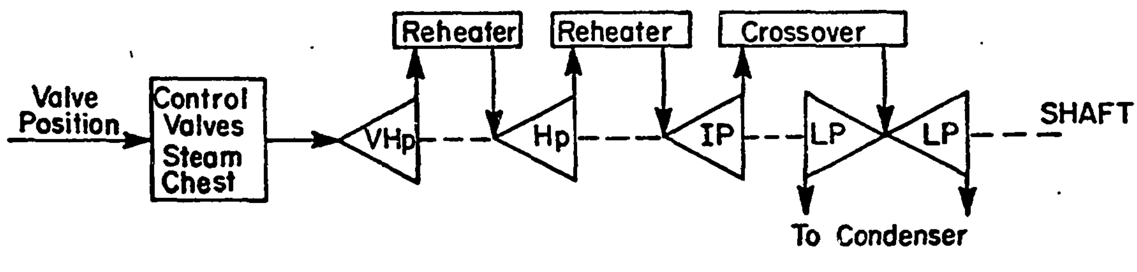


FIGURE E-5
STEAM SYSTEM CONFIGURATION--TANDEM
COMPOUND-DOUBLE REHEATER

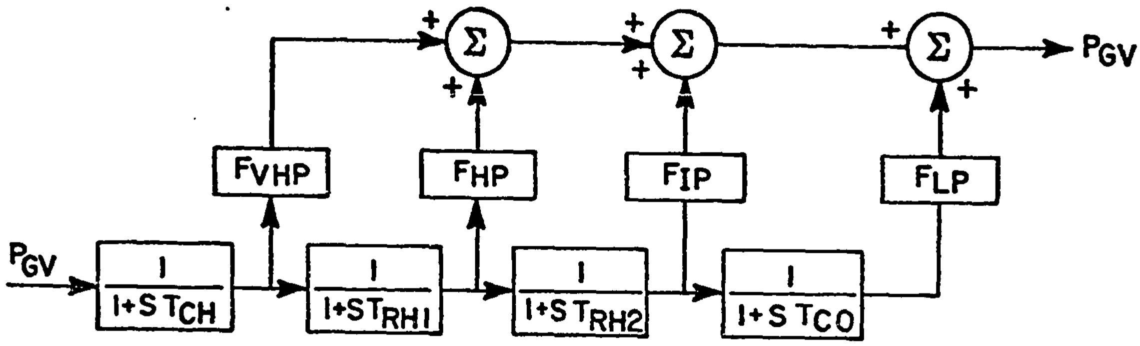


FIGURE E-6
MATHEMATICAL REPRESENTATION OF TANDEM
COMPOUND-DOUBLE REHEATER

Governor-Turbine, PECO Type

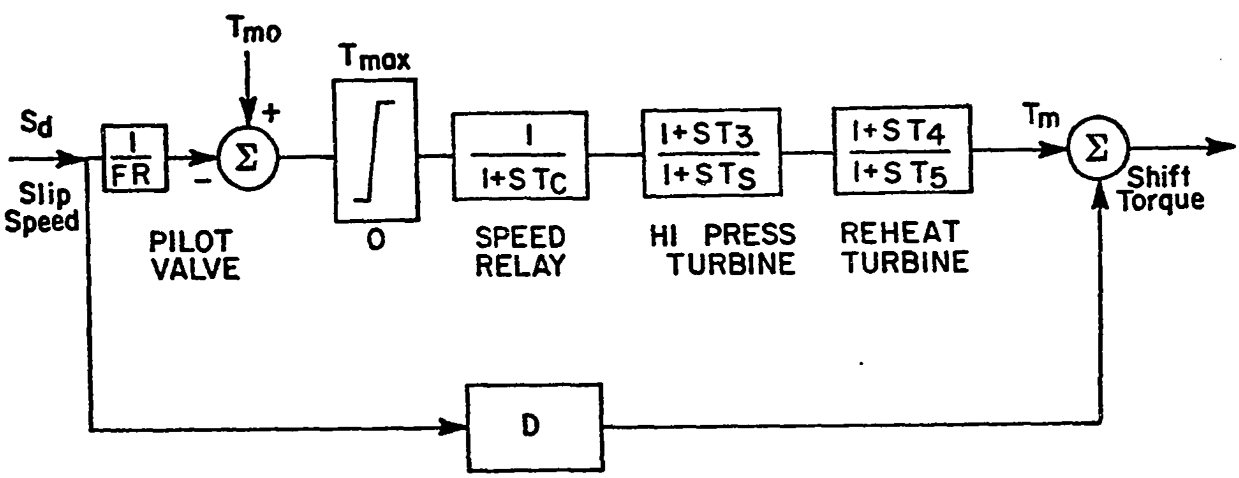


FIGURE E-7
GOVERNOR-TURBINE

In figure (E-7) R equals the steady state speed regulation; F equals the frequency; TC is the speed relay and steam bowl time constant; TS and T_3 are the servomotor and reheat time constant; T_4 and T_5 are the reheater time constants; T_{mo} is the initial steady state torque, zero slip torque and D is the damping factor.

APPENDIX F

COMPUTER PROGRAM SIMULATION OUTPUT
LISTING OF GOVERNOR-TURBINE SYSTEMS

```
****CONTINUOUS SYSTEM MODELING PROGRAM****

*** VERSION 1.3 ***

TITLE SIMULATION OF GOVERNOR TURBINE SYSTEM.TANDEM COMPOUND-TWO REHEAT
      FIXED ISET
      FIXED IRUN
      FIXED ICNT

INITIAL
      PARAMETER T1=.07.T2=.125.T3=.125.T4=.25.T5=7.0.T6=8.5....
      T7=.4.KG=15. .K1=.22.K3=.22.K5=.3.K7=.26 .PMIN= -1..PMAX=1.0....
      AUX=2.0.INITP=6.0.T1MIN=0.0.T1MAX=.15.T2MAX=.3 .T2MIN=.01....
      T3MAX=.3.T3MIN=.01 .T4MAX=.6.T5MAX=15.0.T4MIN=.05....
      T5MIN=1.0.T6MAX=15..T6MIN=1.0.T7MAX=.99.T7MIN=.1....
      KGMAX=25..KGMIN=.4.K1MAX=.5.K1MIN=0.0.K3MIN=0.0.K3MAX=.8....
      K5MAX=.8. K5MIN=.01. K7MAX=.8.K7MIN=.05.  ICNT=1.IRUN=1
      ISET=0
      T1DELT=(T1MAX-T1MIN)/40.0
      T2DELT=(T2MAX-T2MIN)/40.0
      T3DELT=(T3MAX-T3MIN)/40.0
      T4DELT=(T4MAX-T4MIN)/40.0
      T5DELT-(T5MAX-T5MIN)/40.0
      T6DELT=(T6MAX-T6MIN)/40.0
      T7DELT=(T7MAX-T7MIN)/40.0
      KGDELT=(KGMAX-KGMIN)/40.0
      K3DELT=(K3MAX-K3MIN)/40.0
      PDELT=(1.5- .3)/40.0
      K1DELT=(K1MAX-K1MIN)/40.0
      K5DELT=(K5MAX-K5MIN)/40.0
      K7DELT=(K7MAX-K7MIN)/40.0
      NOSORT
      IF ( (-KG) .LE. PMAX ) GO TO 1
      KGLIM=PMAX
      GO TO 3
    1 IF ( (-KG) .GE. PMIN ) GO TO 2
      KGLIM=PMIN
      GO TO 3
    2 KGLIM=-KG
    3 CONTINUE
      PSS=KGLIM*(K1+K3+K5+K7)
      PTC=(1.0-EXP(-1.0))*PSS  *.42 -
SORT

DYNAMIC
      SPDERR=STEP(0.0)
      P1=SPDERR+AUX
      P2A=REALPL(0.0.T3.P1)
      P2B=LEDLAG(T1.T2.P2A)
      P2=KG*P2B
      P3=INITP-P2
      P4=LIMIT(PMIN.PMAX.P3)
      P5=REALPL(0.0.T4.P4)
      P6=REALPL(0.0.T5.P5)
      P7=REALPL(0.0.T6.P6)
      P8=REALPL(0.0.T7.P7)
      P5A=K1*P5
      P6A=K3*P6
      P6B=P6A+P5A
      P7A=K5*P7
      P7B=P7A+P6B
      P8A=P8*K7
```

```
   NOSORT
      IF ( KEEP .NE. 1 ) GO TO 100
      IF(ISET-1) 300.100.300
  300 IF (PTC-P) 100.200.200
  200 TC=TIME
      ISET=1
  100 CONTINUE
SORT

TERMINAL
      TIMER DELT=0.011. FINTIM=5.0  .OUTDEL=.1
      METHOD RKSFX
      GO TO (1000.1010.1020.1030.1040.1050.1060.1070.1085.1090).IRUN
 1000 WRITE (3.51) T1.TC
      GO TO 1080
 1010 WRITE (3.51) T2.TC
      GO TO 1080
 1020 WRITE (3.51) T3.TC
      GO TO 1080
 1030 WRITE (3.51) T4.TC
      GO TO 1080
 1040 WRITE (3.51) T5.TC
      GO TO 1080
 1050 WRITE(3.51)T6.TC
      GO TO 1080
 1060 WRITE(3.51) T7.TC
      GO TO 1080
 1070 WRITE (3.51) PMAX.TC
      GO TO 1080
 1085 WRITE (3.51) KG.TC
      GO TO 1080
 1090 WRITE(3.51) K3.TC
 1080 ISET=0
      IF(IRUN.EQ.10.AND.ICNT.GE.41) END FILE 3
      IF (ICNT-41) 500.510.510
  500 ICNT=ICNT+1
      GO TO (2000.2010.2020.2030.2040.2050.2060.2070.2085.2090).IRUN
 2000 T1=T1+T1DELT
      GO TO 2080
 2010 T2=T2+T2DELT
      GO TO 2080
 2020 T3=T3+T3DELT
      GO TO 2080
 2030 T4=T4+T4DELT
      GO TO 2080
 2040 T5=T5+T5DELT
      GO TO 2080
 2050 T6=T6+T6DELT
      GO TO 2080
 2060 T7=T7+T7DELT
      GO TO 2080
 2070 PMAX=PMAX+PDELT
      PMIN=PMIN-PDELT
      GO TO 2080
```

```
      GO TO 2080
 2095 KG=KG+KGDELT
      GO TO 2080
 2090 K3=K3+K3DELT
 2080 CALL RERUN
  510 CONTINUE
   51 FORMAT (2(E20.8))
      END
      PARAMETER T2=0.05,T1=0.10,IRUN=2,ICNT=1
      END
      PARAMETER T3=0.05,T2=0.125,IRUN=3,ICNT=1
      END
      PARAMETER T4=0.1,T3=0.125,IRUN=4,ICNT=1
      END
      PARAMETER T5=3.0,T4=0.35,IRUN=5,ICNT=1
      END
      PARAMETER  KG=.4,IRUN=6,ICNT=1  ,T6=1.0
      END
      PARAMETER T6=.8,T5=10.,IRUN=7,ICNT=1
      END
      PARAMETER KG=1.0,T7=.52,IRUN=8,ICNT=1
      END
      PARAMETER K3=0.1,KG=25.,IRUN=9,ICNT=1
      END
      PARAMETER T5=20. ,K3= .4,IRUN=10,ICNT=1
      END
      STOP

OUTPUT VARIABLE SEQUENCE
ISET    T1DELT T2DELT T3DELT T4DELT T5DELT T6DELT T7DELT KGDELT K3DELT
PDELT   K1DELT K5DELT K7DELT ZZ0001 KGLIM  KGLIM  KGLIM  PSS    PTC
SPDERR  P1     ZZ0004 P2A    ZZ0005 ZZ0006 P2B    P2     P3     P4
ZZ0011  P5     ZZ0014 P6     ZZ0017 P7     ZZ0020 P8     P5A    P6A
P6B     P7A    P7B    P8A    P      ZZ0021 TC     ISET   ZZ0022 ISET
ICNT    T1     T2     T3     T4     T5     T6     T7     PMAX   PMIN
KG      K3

 OUTPUTS    INPUTS    PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
 66(500)  121(1400)  45(400)    6+  0=  6(300)  104(600)      29

        ENDJOB
```

```
FORTRAN IV G LEVEL  21                    MAIN                DATE = 77309          00/29/45                PAGE 0001

0001              DIMENSION T1(43),T2(43),T3(43),T4(43),T5(43),KG(43),K3(43),
                 1 PMAX(43),TC1(43),TC2(43),TC3(43),TC4(43),TC5(43),TC6(43),
                 2 TC7(43),TC8(43) ,                T6(43),T7(43),TC9(43),TC10(43)
0002              INTEGER LABL(5)/'SYST','EM T','IME ','CONS','TANT'/
0003              READ (3,50) (T1(I),TC1(I),I=1,41)
0004              READ (3,50) (T2(I),TC2(I),I=1,41)
0005              READ (3,50) (T3(I),TC3(I),I=1,41)
0006              READ (3,50) (T4(I),TC4(I),I=1,41)
0007              READ (3,50) (T5(I),TC5(I),I=1,41)
0008              READ (3,50) (KG(I),TC6(I),I=1,41)
0009              READ (3,50) (K3(I),TC7(I),I=1,41)
0010              READ (3,50) (PMAX(I),TC8(I),I=1,41)
0011              READ (3,50) (T6(I),TC9(I),I=1,41)
0012              READ (3,50) (T7(I),TC10(I),I=1,41)
0013              DO 10 I=42,43
0014           10 READ(5,51) T1(I),T2(I),T3(I),T4(I),T5(I),KG(I),K3(I),PMAX(I) ,
                 1                T6(I),T7(I)
0015              DO 20 I=42,43
0016           20 READ(5,51) TC1(I),TC2(I),TC3(I),TC4(I),TC5(I),TC6(I),TC7(I),
                 1 TC8(I),TC9(I),TC10(I)
0017              WRITE (6,500)
0018          500 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/42X,'AS TIME CONSTANT T1 IS',
                 2 ' VARIED FROM 0.05 TO 0.15',
                 3 //47X,'RUN',8X,'T1',5X,'SYSTEM TIME CONSTANT')
0019              WRITE (6,52) (I,T1(I),TC1(I),I=1,41)
0020              WRITE(6,510)
0021          510 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/42X,'AS TIME CONSTANT T2 IS',
                 2 ' VARIED FROM 0.05 TO 0.2',
                 3 //47X,'RUN',8X,'T2',5X,'SYSTEM TIME CONSTANT')
0022              WRITE (6,52) (I,T2(I),TC2(I),I=1,41)
0023              WRITE(6,520)
0024          520 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/42X,'AS TIME CONSTANT T3 IS',
                 2 ' VARIED FROM 0.05 TO 0.2',
                 3 //47X,'RUN',8X,'T3',5X,'SYSTEM TIME CONSTANT')
0025              WRITE (6,52) (I,T3(I),TC3(I),I=1,41)
0026              WRITE(6,530)
0027          530 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/42X,'AS TIME CONSTANT T4 IS',
                 2 ' VARIED FROM 0.1 TO 0.6',
                 3 //47X,'RUN',8X,'T4',5X,'SYSTEM TIME CONSTANT')
0028              WRITE (6,52) (I,T4(I),TC4(I),I=1,41)
0029              WRITE(6,540)
0030          540 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TENDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/42X,'AS TIME CONSTANT T5 IS',
                 2 ' VARIED FROM 3.0 TO 10.0',
                 3 //47X,'RUN',8X,'T5',5X,'SYSTEM TIME CONSTANT')
0031              WRITE (6,52) (I,T5(I),TC5(I),I=1,41)
0032              WRITE(6,550)
0033          550 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
```

```
                 1 ' GOVERNOR AND STEAM SYSTEM',/48X,'AS TIME CONSTANT KG IS',
                 2 ' VARIED FROM 0.5 TO 3.7',
                 3 //47X,'RUN',8X,'KG',5X,'SYSTEM TIME CONSTANT')
0034               WRITE (6,52) (I,KG(I),TC6(I),I=1,41)
0035               WRITE(6,560)
0036           560 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/48X,'AS TIME CONSTANT K3 IS',
                 2 ' VARIED FROM 0.3 TO 0.7',
                 3 //47X,'RUN',8X,'K3',5X,'SYSTEM TIME CONSTANT')
0037               WRITE (6,52) (I,K3(I),TC7(I),I=1,41)
0038               WRITE(6,570)
0039           570 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/36X,'AS THE LIMITS OF THE HARD',
                 2 ' LIMITER ARE VARIED FROM 1.0 TO 2.0',
                 3 //47X,'RUN',7X,'PMAX',4X,'SYSTEM TIME CONSTANT')
0040               WRITE (6,52) (I,PMAX(I),TC8(I),I=1,41)
0041               WRITE(6,577)
0042           577 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF ATANDEM COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/48X,'AS TIME CONSTANT T6 IS',
                 2 ' VARIED FROM 0.5 TO 3.7',
                 3 //47X,'RUN',8X,'T6',5X,'SYSTEM TIME CONSTANT')
0043               WRITE (6,52) (I,T6(I),TC9 (I),I=1,41)
0044               WRITE(6,578)
0045           578 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND',
                 1 ' GOVERNOR AND STEAM SYSTEM',/48X,'AS TIME CONSTANT T7 IS',
                 2 ' VARIED FROM 0.5 TO 3.7',
                 3 //47X,'RUN',8X,'T7',5X,'SYSTEM TIME CONSTANT')
0046               WRITE (6,52) (I,T7(I),TC10(I),I=1,41)
0047               CALL PRPLOT(T1,TC1,43,1,43,1,LABEL)
0048               WRITE(6,1001)
0049          1001 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T1 IS VARIED',
                 3 ' FROM 0.05 TO 0.15')
0050               CALL PRPLOT(T2,TC2,43,1,43,1,LABEL)
0051               WRITE(6,1002)
0052          1002 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T2 IS VARIED',
                 3 ' FROM 0.05 TO 0.2')
0053               CALL PRPLOT(T3,TC3,43,1,43,1,LABEL)
0054               WRITE(6,1003)
0055          1003 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T3 IS VARIED',
                 3 ' FROM 0.05 TO 0.2')
0056               CALL PRPLOT(T4,TC4,43,1,43,1,LABEL)
0057               WRITE(6,1004)
0058          1004 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T4 IS VARIED',
                 3 ' FROM 0.1 TO 0.6')
```

```
0059              CALL PRPLOT(T5,TC5,43,1,43,1,LABL)
0060              WRITE(6,1005)
0061         1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T5 IS VARIED',
                 3 ' FROM 3.0 TO 10.0')
0062              CALL PRPLOT(KG,TC6,43,1,43,1,LABL)
0063              WRITE(6,1006)
0064         1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN GAIN KG IS VARIED',
                 3 ' FROM 0.5 TO 3.7')
0065              CALL PRPLOT(K3,TC7,43,1,43,1,LABL)
0066              WRITE(6,1007)
0067         1007 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN GAIN K3 IS VARIED',
                 3 ' FROM 0.3 TO 0.7')
0068              CALL PRPLOT(PMAX,TC8,43,1,43,1,LABL)
0069              WRITE(6,1008)
0070         1008 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN LIMITS OF THE HARD LIMITER',
                 3 ' ARE VARIED FROM PLUS OR MINUS 1.0 TO PLUS OR MINUS 2.0')
0071              CALL PRPLOT(T6,TC9,43,1,43,1,LABL)
0072              WRITE(6,1011)
0073         1011 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN GAIN T6 IS VARIED',
                 3 ' FROM 0.3 TO 0.7')
0074              CALL PRPLOT(T7,TC10,43,1,43,1,LABL)
0075              WRITE(6,1012)
0076         1012 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF TANDEM  COMPOUND GOVERNOR',
                 1 ' AND STEAM SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME',
                 2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T7 IS VARIED',
                 3 ' FROM 3.0 TO 10.0')
0077           50 FORMAT (2(E20.8))
0078           51 FORMAT(10(F5.2))
0079           52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0080              STOP
0081              END
```

```
                ****CONTINUOUS SYSTEM MODELING PROGRAM****

                        *** VERSION 1.3 ***

TITLE SIMULATUCN OF GOVERNOR AND TURBINE SYSTEM ''PECO'' MODEL .
      FIXED ISET
      FIXED IRUN
      FIXED ICNT

INITIAL
      PARAMETER TMO=9.0,TMAX=6.87,T1=3.0 ,T2=5.0,T3=.20,T4=.05....
      T5=5.,FR=.285,ICNT=1,TMIN= 3.,DAMP=.5,T1MAX=15.0,T1MIN=.05....
      T2MAX=15.0,T2MIN=.05,T3MAX=2.0,T3MIN=0.0,T4MAX=2.0,T4MIN=.05....
      T5MAX=15.0,T5MIN=.0,IRUN=1
      ISET=0
      T1DELT=(T1MAX-T1MIN)/40.0
      T2DELT=(T2MAX-T2MIN)/40.0
      T3DELT=(T3MAX-T3MIN)/40.0
      T4DELT=(T4MAX-T4MIN)/40.0
      T5DELT=(T5MAX-T5MIN)/40.0
      TDELT=(4.0-1.0)/40.
NOSORT
      SS=1./FR+.5
      IF((-SS).LE.TMAX) GO TO 1
      SSLIM=TMAX
      GO TO 3
    1 IF((-SS).GE.TMIN) GO TO 2
      SSLIM=TMIN
      GO TO 3
    2 SSLIM=-SS
    3 CONTINUE
       TSS=SSLIM
      TTC=(1.0-EXP(-1.0))*TSS
SORT

DYNAMIC
      SD=STEP(0.0)
      P1=SD/FR
      P2=TMO-P1
      P3=LIMIT(TMIN,TMAX,P2)
      P4=REALPL(0.0,T1,P3)
      P5=LEDLAG(T3,T2,P4)
      TM=LEDLAG(T4,T5,P5)
      P6=TM-DAMP*SD
```

```
        NOSORT
           IF( KEEP .NE. 1 ) GO TO 100
           IF(ISET-1) 300,100,300
       300 IF( TM-TTC) 100,200,200
       200 TC=TIME
           ISET=1
       100 CONTINUE
      SORT

      TERMINAL
           TIMER DELT=0.001, FINTIM=6.0,OUTDEL=.1
           METHOD RKSFX
           GO TO (1000,1010,1020,1030,1040,1050),IRUN
      1000 WRITE (3,51) T1,TC
           GO TO 1080
      1010 WRITE (3,51) T2,TC
           GO TO 1080
      1020 WRITE (3,51) T3,TC
           GO TO 1080
      1030 WRITE (3,51) T4,TC
           GO TO 1080
      1040 WRITE (3,51) T5,TC
           GO TO 1080
      1050 WRITE(3,51) TMAX,TC
      1080 ISET=0
           IF (ICNT-41) 500,510,510
       500 ICNT=ICNT+1
           GO TO (2000,2010,2020,2030,2040,2050),IRUN
      2000 T1=T1+T1DELT
           GO TO 2080
      2010 T2=T2+T2DELT
           GO TO 2080
      2020 T3=T3+T3DELT
           GO TO 2080
      2030 T4=T4+T4DELT
           GO TO 2080
      2040 T5=T5+T5DELT
           GO TO 2080
      2050 TMAX=TMAX+TDELT
           TMIN=TMIN-TDELT
      2080 CALL RERUN
       510 CONTINUE
        51 FORMAT (2(E20.8))
           END
           PARAMETER T2=0.05,T1=0.10,IRUN=2,ICNT=1
           END
           PARAMETER T3=0.05,T2=2.5  ,IRUN=3,ICNT=1
           END
           PARAMETER T4=0.1,T3=2.8  ,IRUN=4,ICNT=1
           END
           PARAMETER T5=3.0,T4=12.0,IRUN=5,ICNT=1
           END
           PARAMETER T5=15.0,IRUN=6,ICNT=1
           END
           STOP

OUTPUT VARIABLE SEQUENCE
ISET   T1DELT T2DELT T3DELT T4DELT T5DELT TDELT  SS     ZZ0001 SSLIM
SSLIM  SSLIM  TSS    TTC    SD     P1     P2     P3     ZZ0004 P4
ZZ0005 ZZ0006 P5     ZZ0009 ZZ0010 TM     P6     ZZ0013 TC     ISET
ZZ0014 ISET   ICNT   T1     T2     T3     T4     T5     TMAX   TMIN

 OUTPUTS    INPUTS    PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
 44(500)   75(1400)   25(400)    3+  0=  3(300)   69(600)      18

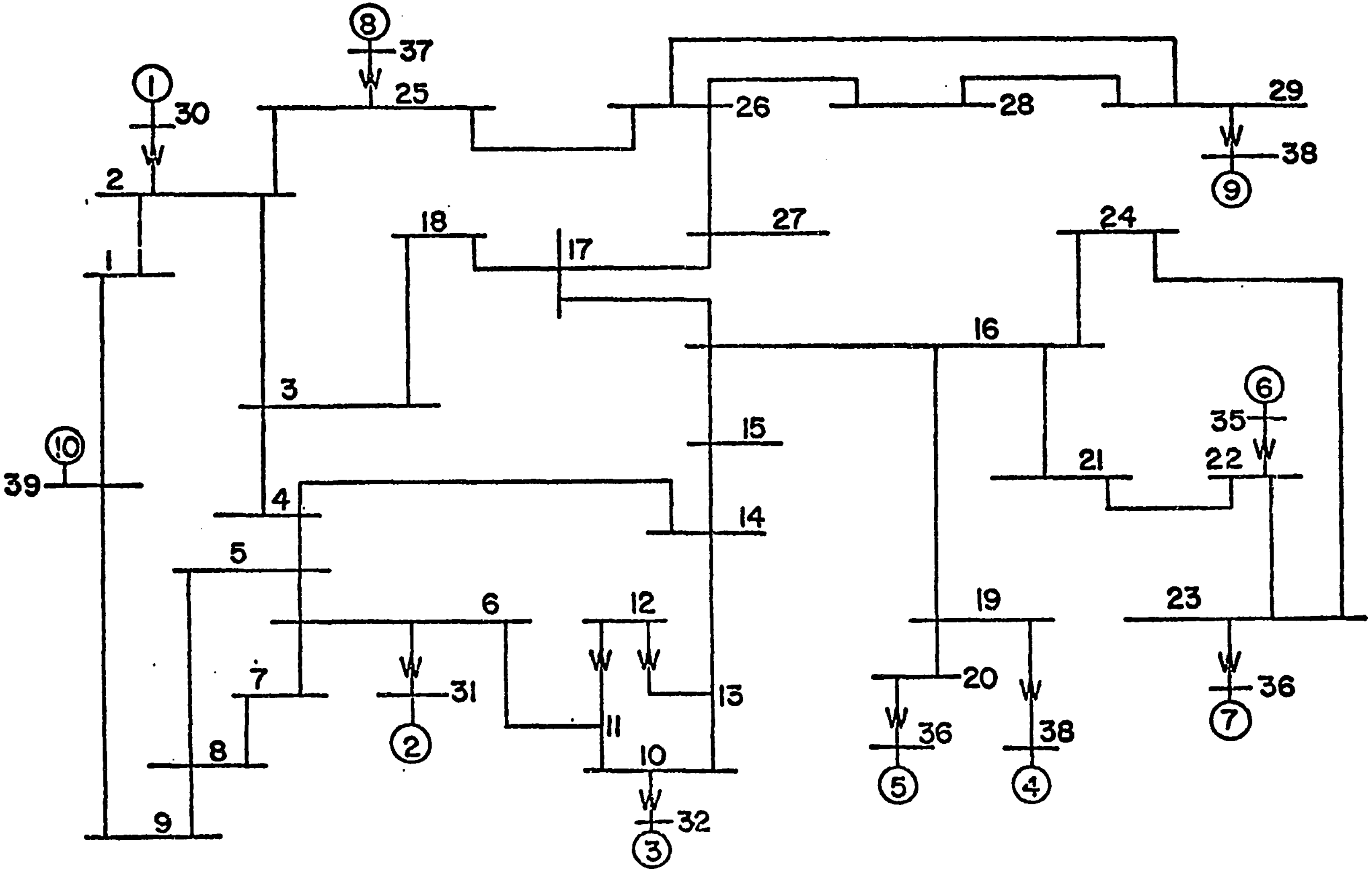

         ENDJOB
```

```
      DIMENSION T1(43),T2(43),T3(43),T4(43),T5(43),TMAX(43),
     1 TC6(43), TC1(43),TC2(43),TC3(43),TC4(43),TC5(43)
      INTEGER LABL(5)/'SYST','EM T','IME ','CONS','TANT'/
      READ (3,50) (T1(I),TC1(I),I=1,41)
      READ (3,50) (T2(I),TC2(I),I=1,41)
      READ (3,50) (T3(I),TC3(I),I=1,41)
      READ (3,50) (T4(I),TC4(I),I=1,41)
      READ (3,50) (T5(I),TC5(I),I=1,41)
      READ (3,50) (TMAX(I),TC6(I),I=1,41)
      DO 10 I=42,43
   10 READ(5,51) T1(I),T2(I),T3(I),T4(I),T5(I),TMAX(I)
      DO 20 I=42,43
   20 READ(5,51) TC1(I),TC2(I),TC3(I),TC4(I),TC5(I),TC6(I)
      WRITE (6,500)
  500 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECCO TYPE OF ',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS TIME CONSTANT T1 IS',
     2 ' VARIED FROM -.01 TO 1.05',
     3 //47X,'RUN',8X,'T1',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52) (I,T1(I),TC1(I),I=1,41)
      WRITE(6,510)
  510 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS TIME CONSTANT T2 IS',
     2 ' VARIED FROM 0.0  TO 2.0',
     3 //47X,'RUN',8X,'T2',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52) (I,T2(I),TC2(I),I=1,41)
      WRITE(6,520)
  520 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS TIME CONSTANT T3 IS',
     2 ' VARIED FROM -1.0 TO 1.0',
     3 //47X,'RUN',8X,'T3',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52) (I,T3(I),TC3(I),I=1,41)
      WRITE(6,530)
  530 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS TIME CONSTANT T4 IS',
     2 ' VARIED FROM -5. TO 15.',
     3 //47X,'RUN',8X,'T4',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52) (I,T4(I),TC4(I),I=1,41)
      WRITE(6,540)
  540 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS TIME CONSTANT T5 IS',
     2 ' VARIED FROM 0.0 TO 20.0',
     3 //47X,'RUN',8X,'T5',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52) (I,T5(I),TC5(I),I=1,41)
      WRITE(6,550)
  550 FORMAT('1',////33X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF ',
     1'GOVERNOR AND TURBINE SYSTEM',/42X,'AS LIMITER TMIN ANA TMAX',
     2 ' VARIED FROM 0.0 TO 20.0',
     3 //47X,'RUN',8X,'T5',5X,'SYSTEM TIME CONSTANT')
      WRITE (6,52)(I,TMAX(I),TC6(I),I=1,41)
      CALL PRPLOT(T1,TC1,43,1,43,1,LABL)
      WRITE(6,1001)
 1001 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR',
```

```
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T1 IS VARIED'.
              3 ' FROM -.01 TO 1.05')
0034            CALL PRPLOT(T2,TC2,43,1,43,1,LABL)
0035            WRITE(6,1002)
0036       1002 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR'.
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T2 IS VARIED'.
              3 ' FROM 0.00 TO 2.0')
0037            CALL PRPLOT(T3,TC3,43,1,43,1,LABL)
0038            WRITE(6,1003)
0039       1003 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR',
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T3 IS VARIED'.
              3 ' FROM -1.0 TO 1.0')
0040            CALL PRPLOT(T4,TC4,43,1,43,1,LABL)
0041            WRITE(6,1004)
0042       1004 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR'.
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T4 IS VARIED'.
              3 ' FROM -5. TO  15.0')
0043            CALL PRPLOT(T5,TC5,43,1,43,1,LABL)
0044            WRITE(6,1005)
0045       1005 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR'.
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN TIME CONSTANT T5 IS VARIED'.
              3 ' FROM 0.0 TO  20.')
0046            CALL PRPLOT(TMAX,TC6,43,1,43,1,LABL)
0047            WRITE(6,1006)
0048       1006 FORMAT(1X,/1X,'SENSITIVITY ANALYSIS OF A PECO TYPE OF GOVERNOR',
              1'AND TURBINE SYSTEM PLOTTING THE EFFECT ON THE APPROXIMATE TIME'.
              2 ' CONSTANT',/1X,'OF THE SYSTEM WHEN LIMITER TMIN AND TMAX'.
              3'VAIRED FROM 3.0 TO 10.')
0049         50 FORMAT (2(E20.8))
0050         51 FORMAT(6(F5.2))
0051         52 FORMAT (1X,45X,I3,F14.5,5X,F10.6)
0052            STOP
0053            END
```

APPENDIX G
SYSTEM STUDY'S DATA

STUDY SYSTEM



TEST SYSTEM BUS DATA

BUS	TYPE	VOLTS	ANGLE	LOAD MW	LOAD MVAR	GEN MW	GEN MVAR	SHUNT G	SHUNT B
1	0	1.0475	-9.370	.00	.00	.00	.00	.0000	.0000
2	0	1.0469	-6.800	.00	.00	.00	.00	.0000	.0000
3	0	1.0304	-9.650	322.00	2.40	.00	.00	.0000	.0000
4	0	1.0038	-10.470	500.00	184.00	.00	.00	.0000	.0000
5	0	1.0050	-9.310	.00	.00	.00	.00	.0000	.0000
6	0	1.0074	-8.620	.00	.00	.00	.00	.0000	.0000
7	0	.9967	-10.810	233.80	84.00	.00	.00	.0000	.0000
8	0	.9957	-11.320	522.00	176.60	.00	.00	.0000	.0000
9	0	1.0281	-11.120	.00	.00	.00	.00	.0000	.0000
10	0	1.0170	-6.210	.00	.00	.00	.00	.0000	.0000
11	0	1.0125	-7.030	.00	.00	.00	.00	.0000	.0000
12	0	1.0000	-7.040	8.50	88.00	.00	.00	.0000	.0000
13	0	1.0142	-6.920	.00	.00	.00	.00	.0000	.0000
14	0	1.0117	-8.580	.00	.00	.00	.00	.0000	.0000
15	0	1.0158	-8.970	320.00	153.00	.00	.00	.0000	.0000
16	0	1.0322	-7.550	329.40	32.30	.00	.00	.0000	.0000
17	0	1.0339	-8.550	.00	.00	.00	.00	.0000	.0000
18	0	1.0313	-9.400	158.00	30.00	.00	.00	.0000	.0000
19	0	1.0500	-2.920	.00	.00	.00	.00	.0000	.0000
20	0	.9909	-4.340	680.00	103.00	.00	.00	.0000	.0000
21	0	1.0321	-5.140	274.00	115.00	.00	.00	.0000	.0000
22	0	1.0500	-.690	.00	.00	.00	.00	.0000	.0000
23	0	1.0450	-.890	247.50	84.60	.00	.00	.0000	.0000
24	0	1.0377	-7.430	308.60	-92.20	.00	.00	.0000	.0000
25	0	1.0575	-5.430	224.00	47.20	.00	.00	.0000	.0000
26	0	1.0521	-6.680	139.00	17.00	.00	.00	.0000	.0000
27	0	1.0379	-8.700	281.00	75.50	.00	.00	.0000	.0000
28	0	1.0501	-3.170	206.00	27.60	.00	.00	.0000	.0000
29	0	1.0500	-.410	283.50	26.90	.00	.00	.0000	.0000
30	1	1.0475	-4.380	.00	.00	250.00	145.10	.0000	.0000
31	1	.9820	.000	9.20	4.60	563.30	205.50	.0000	.0000
32	1	.9831	1.790	.00	.00	650.00	205.70	.0000	.0000
33	1	.9972	2.290	.00	.00	632.00	109.10	.0000	.0000
34	1	1.0123	.850	.00	.00	508.00	167.00	.0000	.0000
35	1	1.0493	4.270	.00	.00	650.00	211.30	.0000	.0000
36	1	1.0635	6.960	.00	.00	560.00	100.50	.0000	.0000
37	1	1.0278	1.350	.00	.00	540.00	.70	.0000	.0000
38	1	1.0265	6.650	.00	.00	830.00	22.80	.0000	.0000
39	1	1.0300	-10.920	1104.00	250.00	1000.00	86.00	.0000	.0000

TEST SYSTEM LINE DATA
in p.u. on 100 MVA Base

BUS	BUS	RESISTANCE	REACTANCE	SUSCEPTANCE	TAP	PHASE
1	2	.00350	.04110	.69870	.0000	.00
1	39	.00100	.02500	.75000	.0000	.00
2	3	.00130	.01510	.25720	.0000	.00
2	25	.00700	.00860	.14600	.0000	.00
3	4	.00130	.02130	.22140	.0000	.00
3	18	.00110	.01330	.21380	.0000	.00
4	5	.00080	.01280	.13420	.0000	.00
4	14	.00080	.01290	.13820	.0000	.00
5	6	.00020	.00260	.04340	.0000	.00
5	8	.00080	.01120	.14760	.0000	.00
6	7	.00060	.00920	.11300	.0000	.00
6	11	.00070	.00820	.13890	.0000	.00
7	8	.00040	.00460	.07800	.0000	.00
8	9	.00230	.03630	.38040	.0000	.00
9	39	.00100	.02500	1.20000	.0000	.00
10	11	.00040	.00430	.07290	.0000	.00
10	13	.00040	.00430	.07290	.0000	.00
13	14	.00090	.01010	.17230	.0000	.00
14	15	.00180	.02170	.36600	.0000	.00
15	16	.00090	.00940	.17100	.0000	.00
16	17	.00070	.00890	.13420	.0000	.00
16	19	.00160	.01950	.30400	.0000	.00
16	21	.00080	.01350	.25480	.0000	.00
16	24	.00030	.00590	.06800	.0000	.00
17	18	.00070	.00820	.13190	.0000	.00
17	27	.00130	.01730	.32160	.0000	.00
21	22	.00080	.01400	.25650	.0000	.00
22	23	.00060	.00960	.18460	.0000	.00
23	24	.00220	.03500	.36100	.0000	.00
25	26	.00320	.03230	.51300	.0000	.00
26	27	.00140	.01470	.23960	.0000	.00
26	28	.00430	.04740	.78020	.0000	.00
26	29	.00570	.06250	1.02900	.0000	.00
28	29	.00140	.01510	.24900	.0000	.00
12	11	.00160	.04350	.00000	1.0060	.00
12	13	.00160	.04350	.00000	1.0060	.00
6	31	.00000	.02500	.00000	1.0700	.00
10	32	.00000	.02000	.00000	1.0700	.00
19	33	.00070	.01420	.00000	1.0700	.00
20	34	.00090	.01800	.00000	1.0090	.00
22	35	.00000	.01430	.00000	1.0250	.00
23	36	.00050	.02720	.00000	1.0000	.00
25	37	.00060	.02320	.00000	1.0250	.00
2	30	.00000	.01810	.00000	1.0250	.00
29	38	.00080	.01560	.00000	1.0250	.00
19	20	.00070	.01380	.00000	1.0600	.00

EXCITATION SYSTEM DATA

Unit	K_A	K_E	K_F	T_A	T_E	T_F	V_{RMAX}	V_{RMIN}	$S_{E.75Max}$	S_{EMAX}
1	5.0	-.0485	.04	.06	.25	1.0	1.0	-1.0	.08	.26
2	6.2	-.633	.057	.05	.405	.5	1.0	-1.0	.66	.88
3	5.0	-.0198	.08	.06	.50	1.0	1.0	-1.0	.13	.34
4	5.0	-.0525	.08	.06	.50	1.0	1.0	-1.0	.08	.314
5	40.0	1.0	.03	.02	.785	1.0	10.0	-10.0	.67	.91
6	5.0	-.0419	.0754	.02	.471	1.246	1.0	-1.0	.064	.251
7	40.0	1.0	.03	.02	.73	1.0	6.5	-6.5	.53	.74
8	5.0	-.047	.0845	.02	.528	1.26	1.0	-1.0	.072	.282
9	40.0	1.0	.03	.02	1.4	1.0	10.5	-10.5	.62	.85
10*	-	-	-	-	-	-	-	-	-	-

*Unit 10 has constant excitation.

TURBINE GOVERNOR SYSTEM DATA

Unit	$\frac{1}{fR}$	T_c	T_3	T_4	T_ℓ	T_5	T_{MAX}
1	3.5	.2	9.65	74.4	-1.93	.965	10.4
2	1.835	.45	0	.1	13.25	54.0	6.46
3	.725	3.0	0	5.0	0	5.0	7.25
4	1.99	.24	0	.18	2.02	10.0	6.52
5	2.56	.121	0	.154	4.5	9.64	6.00
6	2.18	3.0	0	5.0	0	5.0	6.87
7	1.95	.2	0	.18	3.75	7.5	5.8
8	1.79	3.0	0	3.0	0	4.0	5.64
9	2.76	.38	0	.1	1.68	6.0	8.65
10*	-	-	-	-	-	-	-

*Unit 10 has constant mechanical torque.

SYNCHRONOUS GENERATOR DATA - p.u. on 100 MVA Base

Unit	H	R	X_1	X_d	X'_d	X''_d	X'_q	X''_q	T''_{do}	T''_{qo}	$S_{1.0}$	$S_{1.2}$
1	42.0	.00014	.0125	.1	.031	.0155	-	.0480	.1020	.1020	.15	.425
2	30.3	.00027	.035	.295	.0697	.348	.17	.1190	.0656	.0656	.07	.391
3	35.8	.000386	.0304	.2495	.0531	.0265	.0876	.0613	.0570	.0570	.08	.283
4	28.6	.000222	.0295	.262	.0436	.0218	.166	.1162	.0590	.0590	.136	.591
5	26.0	.00014	.054	.67	.132	.0660	.166	.1162	.0540	.0540	.147	.6
6	34.8	.00615	.0224	.254	.05	.0250	.0814	.0569	.0730	.0730	.09	.291
7	26.4	.000268	.0322	.295	.049	.0245	.186	.130	.0566	.0566	.139	.529
8	24.3	.000686	.028	.290	.057	.0285	.0911	.0637	.0670	.0670	.083	.268
9	34.5	.0003	.0298	.2106	.057	.0285	.0587	.0411	.0479	.0479	.106	.447
10	500.00	.0001	.003	.02	.006	.0020	.008	.0056	.0700	.0700	.0	.0

APPENDIX H

REACTANCES OF SYNCHRONOUS MACHINES

The concepts of inductive reactance and of time constant for static circuits have been discussed by many authors. The following is a summarization of Kimbark's work (chapter XII) of the synchronous machine reactance.[3] The impedances of three-phase machines are classified base to the symmetrical components, into positive-sequence, negative sequence, and zero-sequence impedances. To determine one of these, the rotor circuits are closed but not excited and the rotor is turned forward at synchronous speed, current of the proper sequence is applied to the armature windings and the armature terminal voltage of the same phase sequence as the current is found. Of course the ratio of voltage to the current is the impedance. "Any one machine has only one zero-sequence reactance and one negative-sequence reactance"[3] but it has several different positive sequence reactances and that depends upon the angular position of the rotor and upon whether the positive-sequence armature currents are steady or are suddenly applied.

H-1 Direct-Axis Synchronous Reactance x_d

Applying positive-sequence armature currents in a polyphase armature winding will set up a rotating magnetic field in the air gap. This field consists of waves of m.m.f. and of flux. The space fundamentals which rotate forward at synchronous speed with respect to the armature, are stationary with respect to the field structure. Applying armature currents produce the same fundamental m.m.f. wave, regardless of the angular position of the rotor; but the fundamental flux wave varies greatly with the rotor position. If the rotor is so rotated that the direct axis stays in line with the crest of the rotating m.m.f. wave, a path of high permeance is offered (the paths are approximately as shown in figure H-1)[3,53] and the fundamental flux wave has its greatest possible magnitude for a given armature current. Therefore, the total flux linkage of each phase winding of the armature has the greatest possible value for a given current in the winding, and the armature inductance and inductive reactance are greater than what they would be for any other position of the rotor.

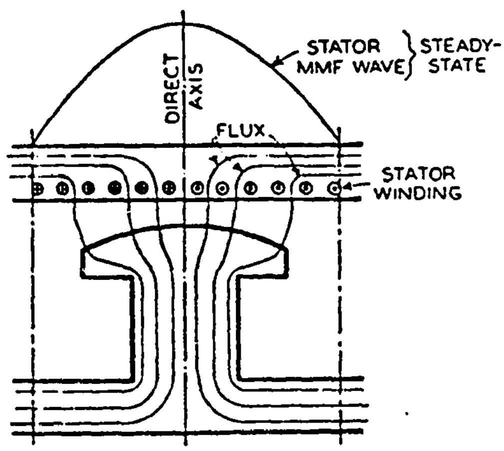


FIGURE H-1
DIRECT AXIS SYNCHRONOUS REACTANCE FLUX PATHS

The flux linkage of an armature phase per ampere of armature current under these conditions if the direct-axis synchronous inductance L_d, hence the direct-axis synchronous reactance is x_d. Other methods to measure x_d are available in the literature such as a slip test. Therefore, changing x_d physically causes permeance which is presented by the rotor iron to the stator m.m.f. wave to be changed also. The mathematical derivation of x_d was found in Appendix A.

H-2 Quadrature-Axis Synchronous x_q

It was mentioned previously that the magnitude of the space-fundamental wave of the air gap flux depends on the position of the rotor with respect to the space fundamental wave of m.m.f. and it is the greatest when the direct axis of the rotor coincides with the crest of the m.m.f. wave. On the other hand, the flux wave is smallest when the quadrature axis of the rotor coincides with the crest of the m.m.f. wave. The flux paths for these conditions are shown in figure H-2.[3,53] Under this condition the armature flux linkage per armature ampere is the quadrature axis synchronous inductance L_q and the quadrature-axis synchronous reactance is x_q. In round rotor machine x_d and x_q are equal.

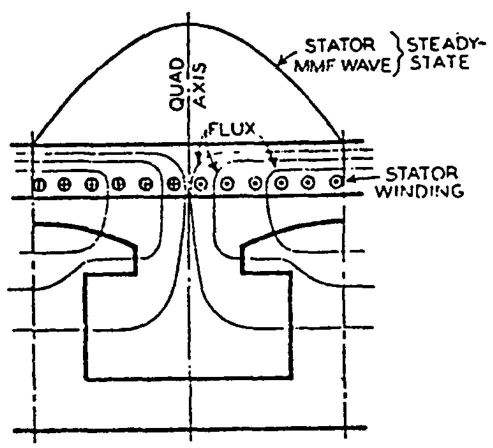


FIGURE H-2
QUADRATURE AXIS SYNCHRONOUS REACTANCE FLUX PATHS

The procedure for measuring x_q suggests it is similar to the first one used for measuring x_d. By applying positive-sequence currents to armature, the rotor would be driven forward at synchronous speed with the quadrature axis in line with the crest of the rotating m.m.f. wave. At the same time sustained positive sequence armature voltage would be measured, obviously, the ratio armature voltage to armature current would be x_q. A more feasible and easy to do measurement of x_q would be the slip test measurement which is explained thoroughly in reference 3. Definition for the synchronous reactance of both the d-axis and q-axis coils of the transformed machine have been defined. x_d is the self-inductance of the model's direct axis coil and x_q is the self-inductance of the quadrature axis coil of the model. One point that needs to be mentioned is that the effect of the fields or dampers are not represented in x_d or x_q.[53] The mathematical derivation of x_q were shown in Appendix A.

H-3 Direct Transient Reactance x'_d

"The conditions used in defining direct-axis synchronous reactance except that the positive-sequence armature currents are suddenly applied and the positive-sequence armature voltage is measured immediately after application of the current instead of after the voltage has reached its steady-state value. In both cases the rotor is rotated forward at synchronous speed, with its direct axis in line with crest of armature m.m.f. wave and with field winding closed but not excited."[3] "By the theorem of constant flux linkage, at the instant immediately after application of the armature currents the field linkage is still zero. Therefore, the only flux that can be established immediately is that which does not link the field winding but rather passes through low-permeance linkage paths, largely in air,"[3] as shown in figure H-3, "under these conditions the flux per ampere is small and is defined as direct-axis transient inductance L'_d."[3] The mathematical derivation of x'_d is in Appendix A.

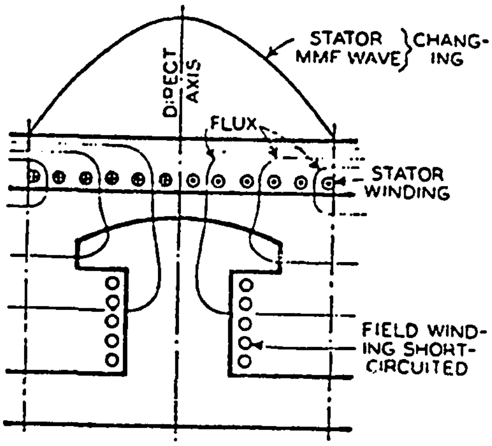


FIGURE H-3
DIRECT AXIS TRANSIENT REACTANCE FLUX PATHS

H-4 Direct-Axis Subtransient Reactance x_d''

It has been assumed in defining x_d' that there were no rotor circuits except the main field winding. However, there can be additional circuits on both axes. Salient pole machines have amortisseur windings as is shown in figures H-4 and H-5. A few salient-pole machines have field collars while in round rotor machines the solid steel rotor core furnishes significant paths for eddy currents.(3) Again, if positive-sequence armature currents are suddenly applied in such time phase that the crest of the rotating m.m.f. wave is in line with the direct axis of the rotor, transient currents are induced in additional direct-axis rotor circuits as well as in the main field winding. "These transient currents oppose the armature m.m.f. and initially they are strong enough to keep the flux linkage of every rotor circuit constant at zero value. The additional rotor circuits are situated nearer the air gap than the field winding is. Consequently, the flux set up by the armature current is initially forced into leakage paths of small cross-sectional area and lower permeance than

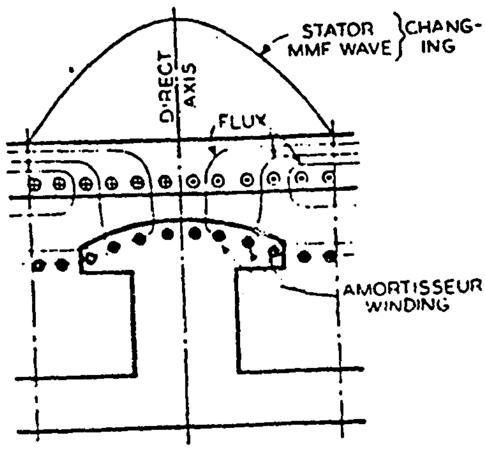


FIGURE H-4

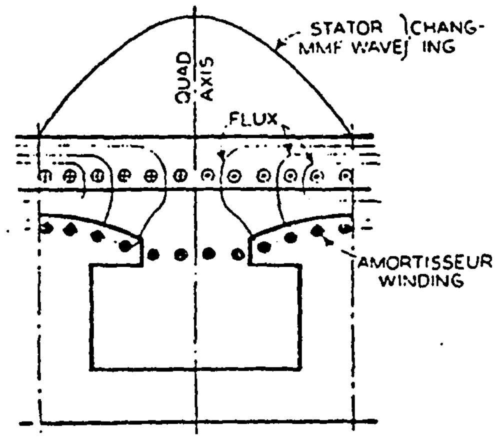


FIGURE H-5

would be the case if the only rotor circuit were the field winding."[3] (See figure H-4.) Under these conditions the armature flux linkage per armature ampere is the direct axis subtransient inductance L_d'' and direct-axis subtransient reactance is x_d''. Mathematical derivation of x_d'' is in Appendix A.

H-5 Quadrature-Axis Transient Reactance x_q' and Quadrature-Axis Subtransient Reactance x_q''

These quantities are defined in the same way as x_d' and x_d'' except that the suddenly applied positive-sequence armature current is in such time phase that the crest of the space-fundamental m.m.f. wave is in line with the quadrature axis of the rotor instead of the direct axis. The flux paths of figure H-6 are the same as those for a steady state flux (figure H-2).[3] Consequently, for salient-pole machine, x_q' is equal to x_q. "Because field current is inducted by a changing direct-axis flux though not by a changing quadrature axis flux x_d' is less than x_q'."[3] Amortisseur windings restrict the quadrature-axis flux initially to low-permeance

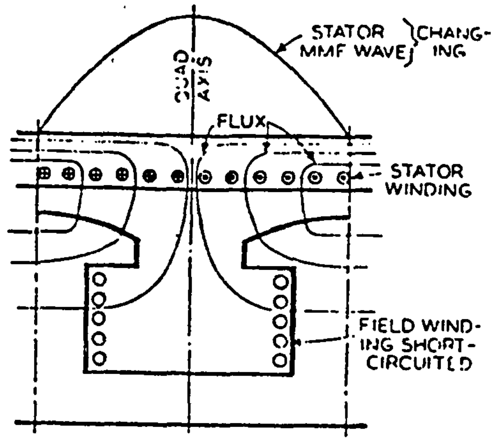


FIGURE H-6
QUADRATURE TRANSIENT REACTANCE FLUX PATHS

paths as shown in figure H-5. Mathematical derivation of x'_q and x''_q are in Appendix A.

H-6 Direct-Axis Transient Open-Circuit Time Constant T'_{do}

"If the armature is open-circuited and if there is no amortisseur winding, the field circuit is not affected by any other circuit. Under these conditoins the change of field current in response to suddent application, removal, or change of e.m.f. in the field circuit is governed by the field open circuit time constant, or direct-axis transient open-circuited time constant, which is given by an expression similar to that of any simple R-L circuit"[3]

$$T'_{do} = \frac{x_{ff}}{R_f} \quad \text{Radians}$$

H-7 Direct-Axis Subtransient Time Constant T''_{do} and T''_d

"In machine with amortisseurs, there are on the direct axis of the rotor two coupled circuits at rest with respect to one another but both in rotation with respect to the armature. The two coupled circuit have two time constants. The longer one is the transient time constant, the shorter one, the subtransient time constant. Both time constants are affected by the impedance of the armature circuit. If the armature circuit is open, the time constants have their open-circuit value T'_{do} and T''_{do}. If the armature is short-circuited, the time constants have their short-circuit values T'_d and T''_d."(3)

H-8 Quadrature-Axis Time Constants T'_{qo}, T'_q, T''_{qo}, and T''_q

"In a machine with a solid round rotor, the changing amplitude of the quadrature axis component of alternating armature current or voltage can be represented fairly well by the sum of two exponentials. The time constants of these exponentials are T'_{qo} and T''_{qo} when the armature circuit is open, T'_q and T''_q when the armature is short-circuited."(3) Some of the machine's time constants have been already defined in Appendix A.

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