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Effects of Nuclear Electromagnetic Pulse (EMP) on Synchronous Stability of the Electric Power System

R. W. Manweiler

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R. W. Manweiler

NOVEMBER 1975

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ABSTRACT

The effects of a nuclear electromagnetic pulse (EMP) on the synchronous stability of the electric power transmission and distribution systems are evaluated. The various modes of coupling of EMP to the power system are briefly discussed, with particular emphasis on those perturbations affecting the synchronous stability of the transmission system. A brief review of the fundamental concepts of the stability problem is given, with a discussion of the general characteristics of transient analysis. A model is developed to represent single sets as well as repetitive sets of multiple faults on the distribution systems, as might be produced by EMP. The results of many numerical stability calculations are presented to illustrate the transmission system's response from different types of perturbations. The important parameters of both multiple and repetitive faults are studied, including the dependence of the response on the size of the perturbed area, the fault density, and the effective impedance between the fault location and the transmission system. Both major load reduction and the effect of the opening of tie lines at the time of perturbation are also studied. We conclude that there is a high probability that EMP can induce perturbations on the distribution networks causing a large portion of the transmission network in the perturbed area to lose synchronism. The result would be an immediate and massive power failure.

CHAPTER I

INTRODUCTION

A. PURPOSE OF THE STUDY

A high-altitude nuclear detonation causes currents to flow in the atmosphere. This current generates an electromagnetic pulse (EMP) which propagates to the earth's surface where it induces current and voltage surges on conductors. The purpose of this study is to determine the extent to which such EMP-produced surges will disturb the synchronous stability of the electric power system through the production of multiple and repetitive faults.

B. THE ELECTROMAGNETIC PULSE

The nuclear EMP field is generated by the action of the primary gamma rays produced by a high-altitude nuclear detonation. The production mechanism is illustrated in Fig. 1. For a high-altitude burst (approximately 50 km or more height of burst) the gamma rays produced will interact with the atmosphere between 20 and 40 km altitude, primarily by Compton scattering with electrons of air molecules. This scattering causes the electrons to move downward away from the point of burst in a trajectory which is bent by the earth's geomagnetic field $\vec{B}_g$ (shown into the page in Fig. 1). These accelerated electrons radiate the electromagnetic pulse from the atmospheric umbrella between 20 and 40 km which is within line of sight of the burst. The primary Compton electrons, composing the "primary electron currents" also scatter and produce secondary electrons which are accelerated in the opposite direction by an electric field produced by the charge separation. This secondary electron current flows in roughly the opposite direction as the primary electron current.

The EMP field can be calculated from Maxwell's equations using both the primary Compton and the secondary electron currents as the source

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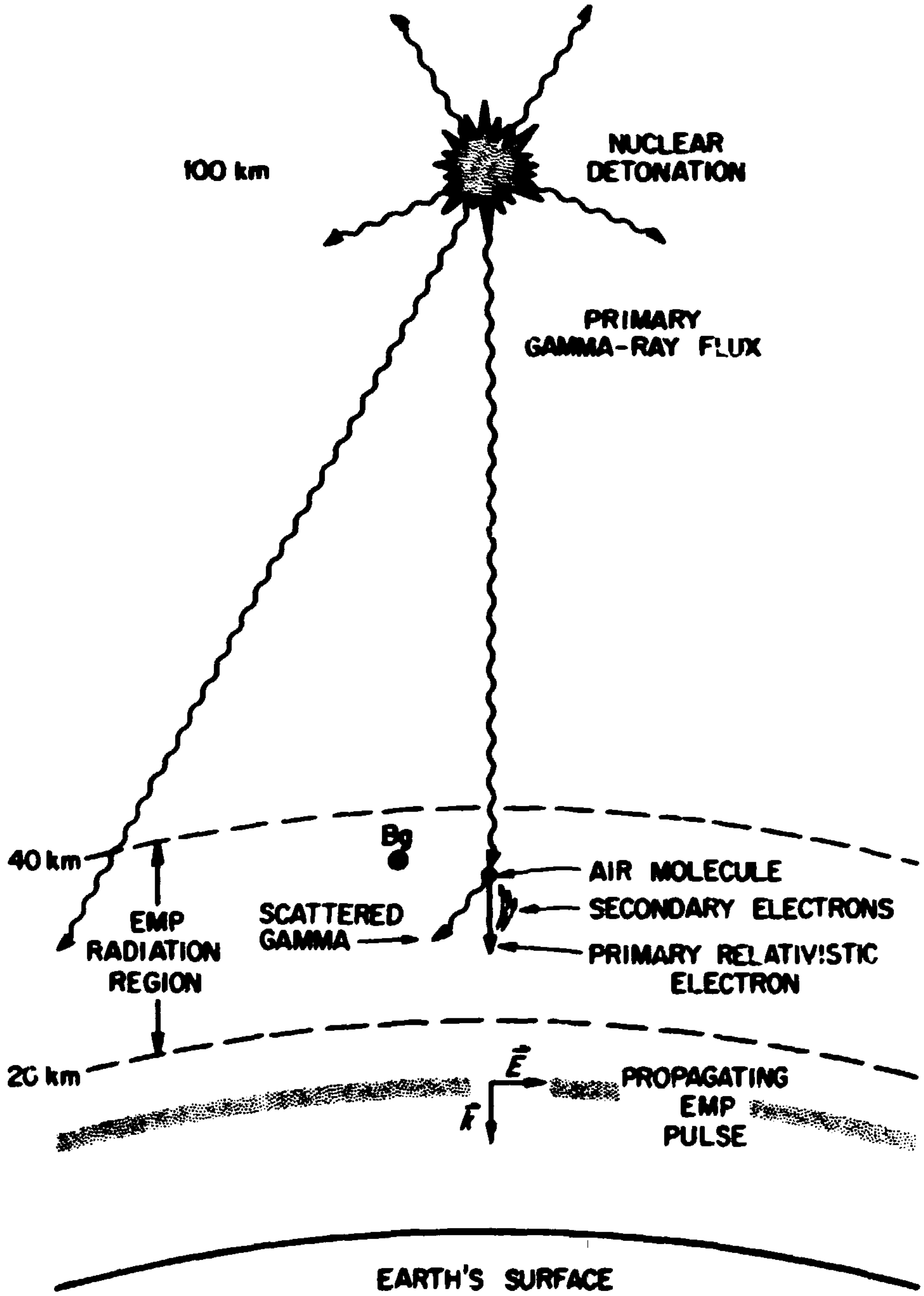

Fig. 1. The Generating Mechanism of the Electromagnetic Pulse Produced by a High-Altitude Nuclear Detonation.

currents. This generating mechanism has been described in detail some time ago by Karzas and Latter,[1] and others. A typical EMP pulse from a large yield detonation may have an electric field strength of 50 kilovolts/meter with a risetime (time to peak value) of 10 nanoseconds, and a time to half the peak value of 30 to 200 nanoseconds. Thus, such a pulse has a very large field strength and produces electrical transients with rapid risetime as compared to those typically occurring on power systems, e.g., lightning.

One distinctive feature of EMP is its extremely large geographical extent. For a high-altitude burst, the entire atmospheric umbrella defined above radiates so that the EMP field below this atmospheric umbrella does not decrease in intensity as r^{-1} from the burst location as in the case of fields radiated from a small volume. The EMP field occurs everywhere within line of sight of the burst, as Fig. 2 illustrates. Clearly EMP differs greatly from other perturbations of the power system in its large geographic extent, which has important effects on the system's stability, as will later be shown.

C. THE COUPLING OF EMP TO THE POWER SYSTEM

The coupling of EMP to the electric power system has been previously discussed by Nelson[2] and in more detail by Marable, et al.[3] The EMP field induces currents on exposed conductors. High voltage surges can be produced, particularly at points where lines change direction or branch and at locations where the impedance is discontinuous. Current and voltage surges of several kiloamps and of nearly a megavolt, respectively, can be produced on unshielded parts of the system, and only a few hundred meters of length of conductor are necessary for the induction of a significant pulse. Distribution, transmission, control, and communication lines are particularly good examples of conductors which will be affected, and all of the system in the exposed area will be simultaneously affected. (Actually the EMP wave front will travel at the speed of light c. But the important time scale for the power system is the

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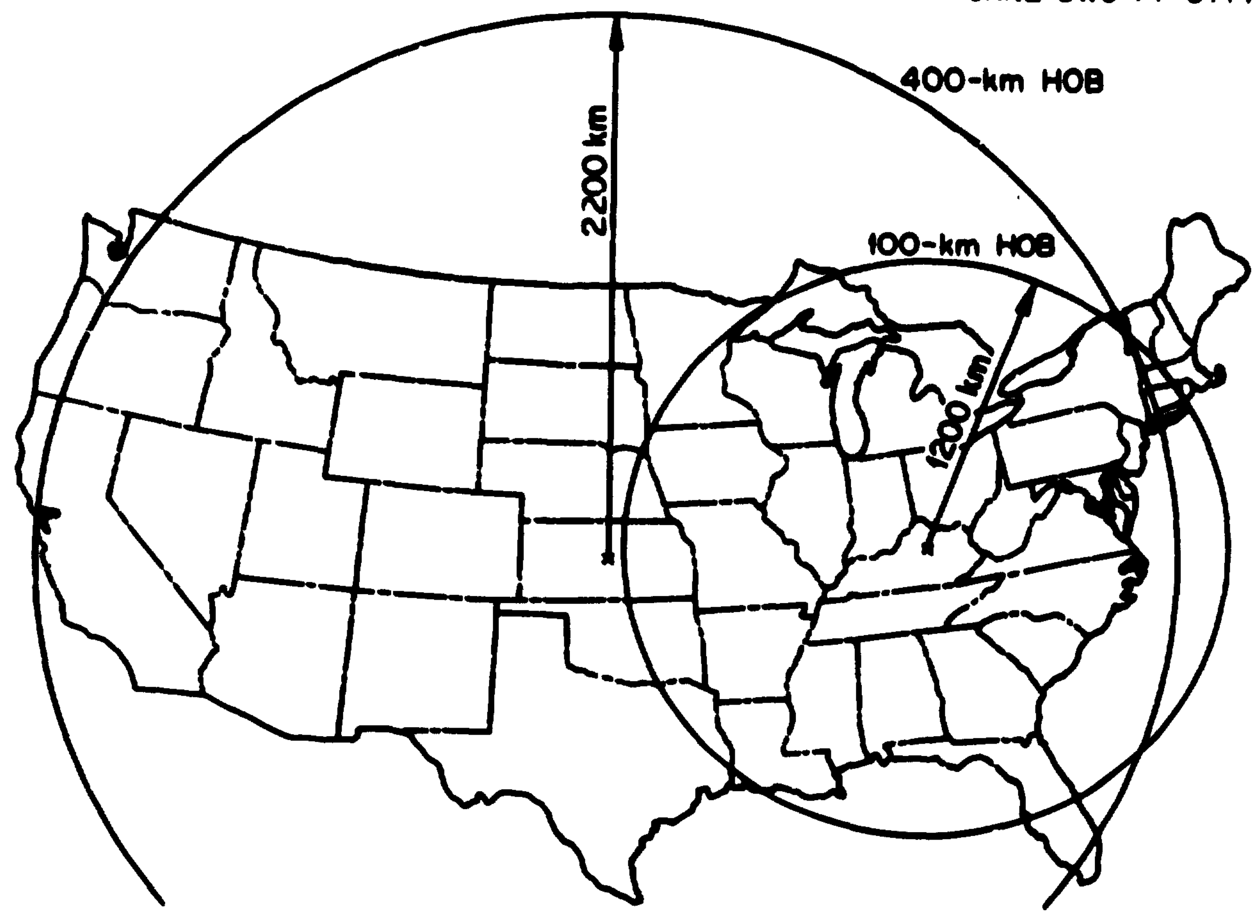

Fig. 2. Typical Area Coverage of EMP for Both a 100-Kilometer and a 400-Kilometer Height of Burst (HOB).

period of the synchronous system, i.e., one-sixtieth second. Thus, the time difference between arrival of the EMP pulse at different locations is of no significant consequence.)

Figure 3 shows a typical distribution system, and Fig. 4 shows a transmission system (the Tennessee Valley Authority Network) which supplies the connecting distribution systems at major substations. It is difficult to determine the precise effects of EMP surges on such complicated systems, but previous work[2,3] does provide us with reasonable expectations. In the next section we briefly discuss the effects of EMP which may perturb the power system sufficiently so that synchronism will be lost. A more detailed analysis of the coupling mechanisms is available in Refs. 2 and 3.

D. THE GENERAL NATURE OF EMP-INDUCED PERTURBATIONS

This study is primarily concerned with the effects of EMP on the transmission system, rather than on any single distribution system. However, the dynamical and electrical response of the transmission system cannot be separated from that of the distribution systems. EMP may perturb either system in such a manner as to cause part, or all, of the transmission system to lose synchronism. We use the term perturbation in the sense that a synchronous system at equilibrium is being initially "disturbed" by some event of finite or continuous duration which may then affect the synchronism of the system. Loss of synchronism entails one or more machines (generators) falling out of step with its connecting machines, necessitating the removal of the machine, or machines, from the electrical system. This study is concerned with determining the likelihood of major machine losses resulting in the transmission system's partitioning or complete collapse.

For convenience of analysis, we partition the system's response to a perturbation into two time intervals: the transient and the dynamic response. The first interval (the transient response) includes up to about the first one and one-half to two seconds and is the result of the

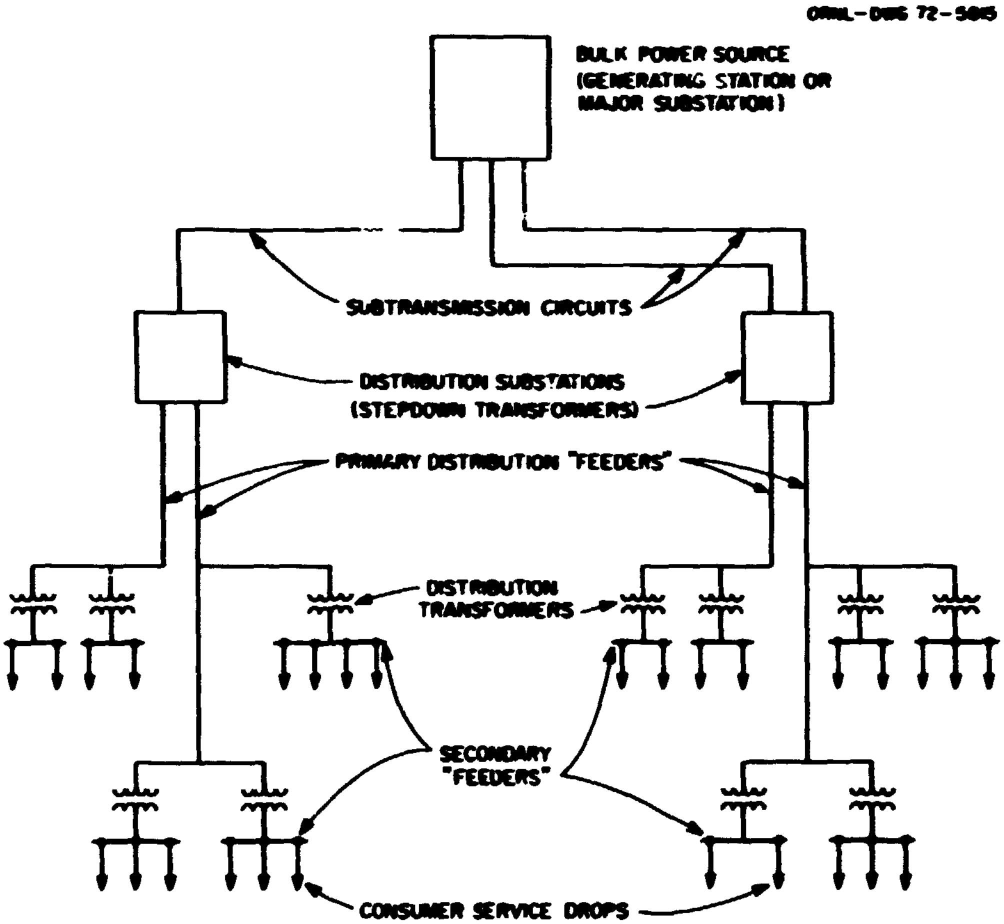

Fig. 3. A Typical Distribution System.

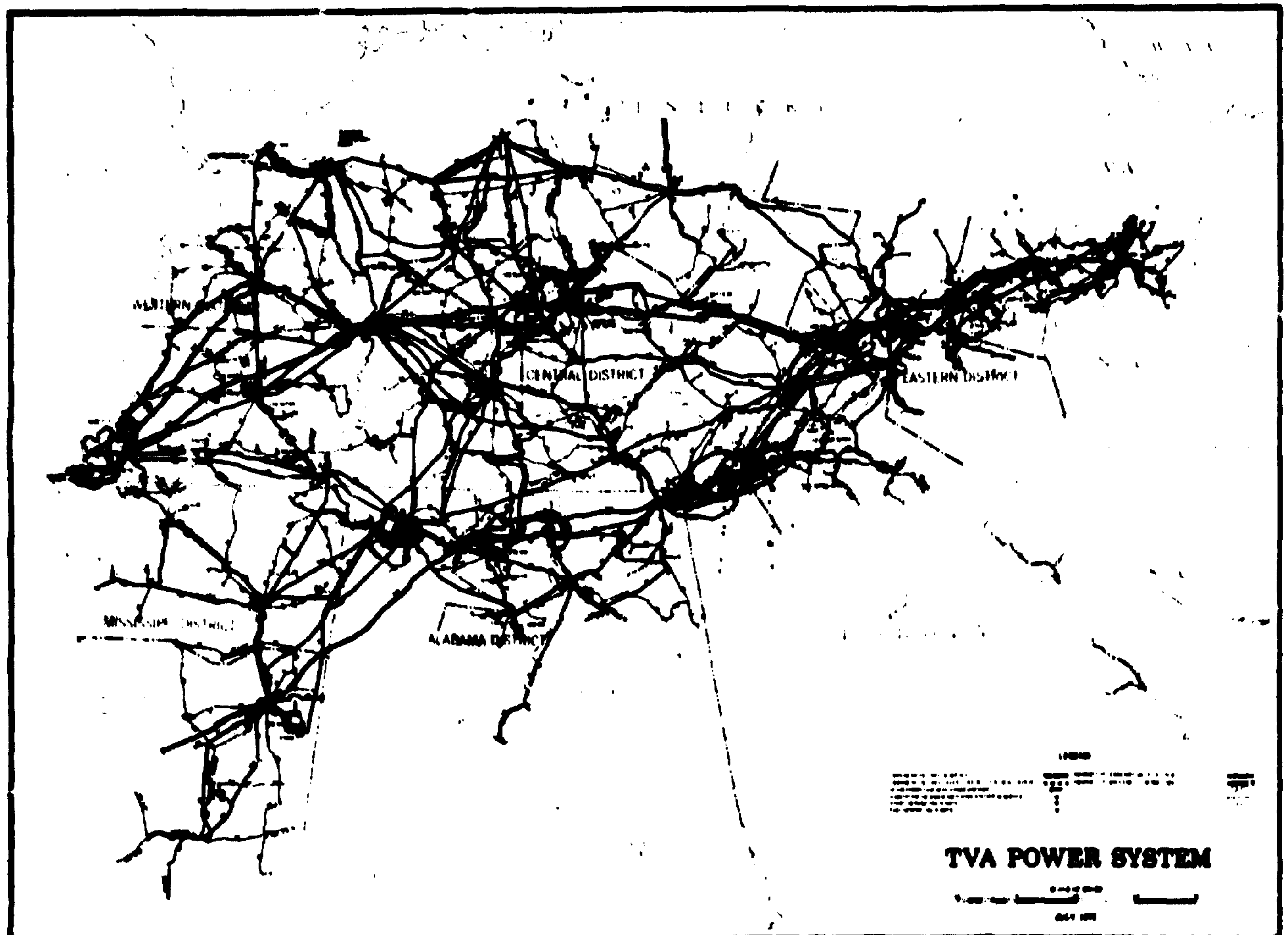

Fig. 4. The Tennessee Valley Authority (TVA) Power Transmission System.

immediate effects of the perturbation. The second interval (the dynamic response) starts at about 2 seconds and extends to the time when the system has reached a new equilibrium, i.e., it is the response determined by the later-time collective effects as well as by additional perturbations triggered after the first second or two following the initial perturbation. In the remainder of this subsection we discuss the major types of perturbations one may expect from EMP.

EMP-induced faults (short circuits between lines or from line to ground) pose a very serious perturbation for the entire electrical system. Because of the transmission lines' greater insulation, it is much less likely that EMP will cause faults on these higher voltage lines. But the typical distribution system is probably insufficiently insulated against EMP-induced surges, particularly at discontinuities in geometry, etc., as previously mentioned (Section C). It should be expected that induced electrical surges will initiate faults on the distribution lines, in which case the line voltage may maintain the faults until the line is opened (disconnected from the electrical system) and cleared in the normal manner. Such distribution system faults would pose no serious threat to the transmission system were it not for the fact that many distribution system faults may be induced simultaneously over a very large area (for example, see Fig. 2). The cumulative effects of the multiple fault perturbation on the distribution system will probably have a significant effect on the transmission system.

A second important type of EMP-produced perturbation is the possibility of repetitive EMP pulses produced from multiple detonations closely spaced in time. It is not the purpose of this paper to discuss possible nuclear scenarios. However, both single and multiple high-altitude detonations should be considered. Multiple bursts have two important effects. Firstly, there will be a cumulative effect of repetitive sets of faults, i.e., closely spaced groups of faults. Secondly, closely spaced repetitive surges may lock open many relays until they are manually reset. Since typical mechanical relays may interpret repetitive faults as being a "permanent fault," three or more bursts closely spaced could lock open many relays removing the consumer load normally fed by the lines, and thus reduce the transmission network's load. A substantial load reduction could cause the system to accelerate so rapidly that generation could not be reduced sufficiently before loss of synchronism, or before tripping of overspeed relays on generators. The effects of repetitive faults with or without substantial load reduction will be discussed in Chapter IV.

A third type of EMP-induced perturbation may be the malfunction of insufficiently protected transmission line relays causing either the unnecessary opening of lines, or the destruction of relay circuits. Solid state relays commonly used in very high voltage transmission lines may be particularly sensitive to EMP-produced transients. However, electromechanical relays typically used on distribution systems and lower voltage transmission lines should not be seriously vulnerable to this type of malfunction. In this study, we have assumed that the transmission system circuitry will <u>not</u> be affected by the transients. Otherwise, there is little hope of the system remaining in operation. The possible malfunctioning or damage of solid state relays should be carefully examined.

A fourth type of perturbation which may occur is generator tripping. When a generator is tripped, it is removed from the line and shut down. One must distinguish between two basic categories of generator tripping. First, generators may be falsely tripped at the time of the burst by electrical surges induced in the generator control system. If a sizable portion of the generation capacity is falsely tripped, the entire system could collapse. However, in this study we have <u>not</u> tripped generators to simulate such a false-tripping situation since it is not now known what effect EMP will have on generator control systems. Certainly if EMP causes serious problems of this nature, the effect on the stability will be severe. A second category of generator tripping to be considered is that which is necessitated some time after the initial EMP perturbation, i.e., after a few seconds or even after several minutes. Late-time generator tripping may be necessitated either if the generator governor systems are unable to react sufficiently rapidly to an increase in the system's average frequency, or if a machine falls out of step and loses synchronism. This second category of generator perturbations will affect the later time dynamic response rather than the earlier time transient response of the system. We discuss the dynamic response further at the end of this subsection.

An added difficulty in estimating the effects of generator tripping is the possibility of terminating too much generation in response to a legitimate need for a reduction. Such a situation could arise since normal generator regulation and control procedures may not respond properly to EMP-type perturbations in which the disturbed area is very large and is simultaneously affected. Operation and control procedures may need to be reviewed to determine whether they respond properly to EMP disturbances.

The various transmission networks are connected by tie lines, where the power flow between networks is controlled. A fifth type of perturbation would be direct interference with the tie line monitoring or control system. The normal power flow between networks could be interrupted if tie line control systems were affected by transient pulses, and the likelihood of such failure increases for computerized systems. Additionally, response of real-time tie line control may be quite crucial, since significant interactions between adjacent transmission networks should be expected, particularly if one network is subjected to the perturbation more severely than neighboring ones. In some circumstances it may be desirable to open tie lines, a possibility which will be further discussed in Chapter IV.

A sixth perturbation which might result from EMP would be damage to or interference with computerized load flow centers and dispatch stations. Typical computer-controlled power systems are described by Ross and Green.[5] This is becoming a more serious threat because of the more extensive use of computers which, unless shielded, are particularly vulnerable to EMP effects and will likely malfunction. The possible effects from such perturbations are similar to tie line control problems.

As a consequence of collective effects of the various EMP-induced perturbations discussed above, there will certainly be late-time dynamic effects on the systems. However, one cannot precisely determine what specific dynamical effects will result from any given perturbation.

This study was therefore limited to the early-time transient response of the system. But we presently mention several possible dynamical effects which EMP could produce, for one must keep such possibilities in mind when assessing the total effect of EMP on the power system. If there is a major load loss, an increase in the system's average frequency in the dynamical time period might occur, which could tax generator control systems to an extreme. Another possible dynamical effect is transmission line overloading resulting in the opening of transmission lines and causing cascading failures similar to the Northeast power failure of 1965. The power surges in the transient period were monitored to detect overloading conditions. In this study we assume that transmission systems will remain in operation except for special cases of tie line openings. Certainly loss of major transmission lines will only magnify the perturbation. Consequently, it should also be expected that major blast damage to the transmission system would have a disastrous effect. However, much of the transmission system and the generation capacity is outside probable target areas and therefore may not be greatly affected by blast, particularly in a limited nuclear engagement. Again, one cannot at present easily calculate the dynamical response of the system, particularly to such complicated perturbations as will likely be induced by EMP.

CHAPTER II

THE STABILITY PROBLEM FOR THE SYNCHRONOUS POWER SYSTEM

In this chapter the general characteristics of stability are described, and two historical examples of perturbed transmission systems are presented in Section A. The stability equations are given and discussed in Section B.

A. GENERAL CHARACTERISTICS OF LOSS OF STABILITY

1. Historical Examples

Perhaps the most notable historical example of loss of stability of the transmission network is the Northeast Power Failure of 1965. Extensive studies[6] of that blackout of nearly all of the Northeastern states have been made. Since 1965, the transmission and generation systems have been considerably improved, yet the failure is a good illustration of cascading failures, i.e., failures in which one event triggers a succession of events eventually leading to the collapse of all or part of the power system. The sequence of events leading to the collapse of the Northeast power system was evidently initiated by a backup relay opening one of five 230-kilovolt circuits between the Beck Generating Station and Toronto-Hamilton, both in Canada. This event resulted in more than two dozen switches tripping within the next five seconds, and producing enormous power surges. Generators in western New York and at the Beck Station accelerated until synchronism was lost, necessitating their separation from the remainder of the system. After about 7 seconds from the opening of the first circuit, the transmission network had split into several separate areas. The frequency of parts of the system was very low, subnormal by as much as 10% for many minutes. Even isolated parts of the system which had reasonably balanced load and generation collapsed because of the initial effects of the perturbation. Swing curves of various generators (see Section B of this Chapter for an explanation) are presented in Volume III of Reference 6. It should be noted that this particular perturbation occurred on the transmission system, not on the distribution system, and therefore differs from the expected EMP-generated perturbations. The collective effect of the series of events resulted in the nearly complete collapse of a major segment of the transmission network.

We wish to consider a second example, much less spectacular than the Northeast power failure. In this second case, the power system did not collapse, primarily because of a strong transmission system. On January 19, 1964, sudden outage occurred on the TVA Paradise Steam Plant when generation of 1250 megawatts was abruptly lost. Immediately after the event, the adjacent tie lines supplied the TVA network with additional power. The tie line power flow before and after the loss of generation is shown in Fig. 5. A strong transmission system provided the generation-deficient TVA network (a "sink" of power after the event) with power from the adjacent networks (a large "source" of power), thus preventing loss of synchronism. The system in this case was stable to this particular perturbation.

Numerous power failures have occurred since 1965 and continue to occur frequently, usually on a state-wide basis. Most, if not all, have been cascading type of failures initiated by a single event usually associated with the transmission system. The type of initiating events range from storms to mechanical failure of equipment.

2. *Differences Between EMP and "Natural" Perturbations*

EMP-induced perturbations will differ substantially from "natural" perturbations, such as those mentioned briefly above. As explained in Chapter I, EMP will most likely induce multiple faults on the distribution systems--not on the transmission system, and the area covered by faults can be extensive. Repetitive sets of faults would possibly occur for multiple nuclear detonations. EMP effects may cause the transmission system's average frequency to increase substantially. Local

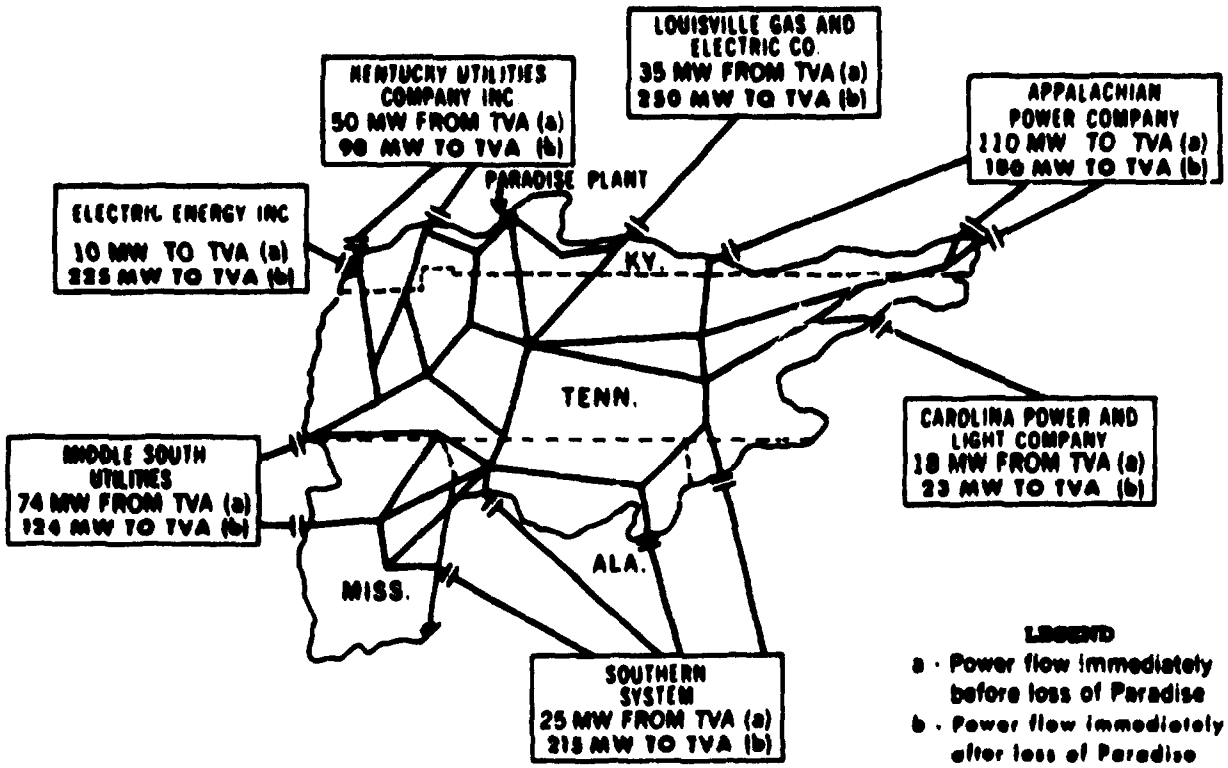

Fig. 5. The Interconnected Network Power Flow Immediately Before and After a Sudden Outage of a Major Generator.

increases in frequency do occur at times from "natural" perturbations, but not on the same scale as EMP. Additionally, EMP may perturb the transmission system in many different ways than natural perturbations. The experience which power companies have gained in determining the system response from natural perturbations may therefore not be directly applicable in determining the response in an EMP environment. We further compare the two historical examples given with the calculated EMP response in Chapter IV, Section D.

B. BASIC PHYSICS AND MATHEMATICS OF THE STABILITY PROBLEM

The purpose of this section is to introduce the reader to the general physical and mathematical concepts important in determining the response of the transmission system to a perturbation such as EMP. It should not be considered as a rigorous treatment. A reader interested in a more rigorous development of the stability problem should refer to standard texts.[7,8,9] Reference 7 gives a particularly good physical explanation. The modeling of the transmission system and the numerical method for solving the stability equations will be presented in Chapter III.

1. Basic Equations

The transmission system consists basically of: (a) generating devices, or machines; (b) the electrical circuitry which transmits the generated power to the various major substations of the distribution systems (which we refer to as the network in this chapter); and (c) the various control and monitoring equipment, with which we are not presently concerned.

Electrical transients on the network propagate at slightly less than the speed of light. However, the important time scale relevant to the synchronous behavior is in fact not determined by the time of travel of electrical pulses. Rather, there are two important response times (or frequencies) determining the system's transient response. One can relate the response time T to a corresponding frequency f by the definition

$$f = \frac{1}{T} \quad . \tag{2.1}$$

The equilibrium synchronous frequency f_o or its inverse period T_o (60 hertz and 16.7 milliseconds respectively in the U.S.A.) sets an important time scale. Frequency deviations from the equilibrium synchronous frequency f_o which we designate as Δf become important at a time Δt when $(\Delta f \cdot \Delta t)$ becomes a significant fraction of a complete cycle. Most of the mechanical relays on both the transmission and distribution networks operate on this time scale, from one to twenty T_o (approximately 15 to 350 milliseconds).

A second important time scale determining the behavior of the system after being perturbed is the machine response time, or machine period, T_m. A single machine can be modeled as a rotating mass with a large moment of inertia I. The mass has an applied torque Γ_a delivering power to it (from steam plants, hydroplants, etc.), and has a back electrical torque Γ_e opposing Γ_a. Then at equilibrium

$$\Gamma_a - \Gamma_e \equiv \Gamma_d = 0 \quad , \tag{2.2}$$

and the mass rotates at frequency ω_o. However, if a perturbation is applied, the electrical torque Γ_e is changed resulting in a net torque on the mass and from Newton's law

$$\Gamma_d = I \frac{d^2}{dt^2} \theta(t) = I \frac{d^2}{dt^2} \delta(t), \tag{2.3}$$

where we have defined

$$\delta(t) = \theta(t) - \omega_o t + \delta_o \; . \tag{2.4}$$

The motivation for defining δ is the following. θ is just the absolute electrical phase angle which, in equilibrium, increases as $\omega_o t$. However the power delivered by machines depends upon their relative angles. Since the machines normally rotate together it is desirable to define a coordinate system rotating at frequency $\omega_o t$. Then $\delta(t)$ is the angle of departure from equilibrium, measured with respect to some rotating reference, with all initial angles given with respect to one particular machine at $t = 0$.

The mathematical difficulties arise from the complicated dependence of Γ_e on the machine angles. For n machines, there are n coupled nonlinear equations; for the i^{th} machine

$$I_i \ddot{\delta}_i = \Gamma_{a,i} - \Gamma_{e,i}(\delta_i, \delta_j, \ldots, \dot{\delta}_i, \dot{\delta}_j, \ldots) \qquad (2.5)$$

where the Γ's are the applied and electrical torques previously defined for the i^{th} machine. A dot means the derivative with respect to time. Clearly the electrical torque $\Gamma_{e,i}$ is a complicated function depending on all of the machine angles and their derivatives. Equation (2.5) can be expressed in terms of the applied and delivered power, P_a and P_e, respectively, by multiplying by ω and defining the inertia constant M,

$$M = I\omega \quad . \qquad (2.6)$$

The torque multiplied by the angular frequency is just the power transferred, and we have

$$M_i \ddot{\delta}_i = P_{a,i} - P_{e,i}(\delta_i, \delta_j, \ldots, \dot{\delta}_i, \dot{\delta}_j, \ldots) \qquad (2.7)$$

where the subscripts have the same meaning as in Eq. (2.5).

To get some feeling for the power P_e delivered, consider a simple example of a generator driving a motor as shown in Fig. 6. (Since there is only one motor, we can suppress the subscript i.) Then, for a purely inductive line X,

$$E_G = E_M + j|X|I \quad . \qquad (2.8)$$

The real power P delivered by the generator is just

$$P = \text{Re}(E_G^* \cdot I) = \left(\frac{|E_G|\,|E_M|}{|X|}\right) \sin \delta(t) \ , \qquad (2.9)$$

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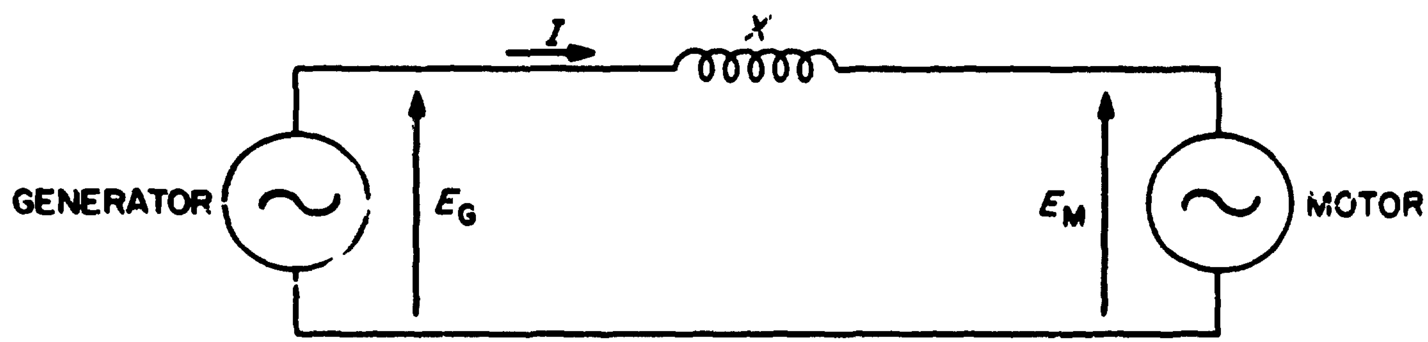

Fig. 6. A Schematic Diagram of a Simple Generator-Motor Problem.

where δ is the difference in phase between E_G and E_M. Clearly δ is the crucial angle since P depends upon the phase difference between E_G and E_M. In normal operation, E_G, E_M, and X are constants so that the power delivered by the generator is proportional to sin δ. Equation (2.7) becomes

$$M \ddot{\delta} = P_a - P_m \sin \delta \qquad (2.10)$$

where P_m is the maximum power transfer. It is easy to understand why Eq. (2.10) has stable solutions. Figure 7 shows a plot of P_e as a function of δ. Assume the equilibrium angle is δ_o, then if the load on the motor is increased it will decelerate or slow down with respect to the generator and δ will therefore increase. Correspondingly, the delivered power P_e will increase until it exceeds the new load, at which time the motor will begin to accelerate until its rotational frequency approaches that of the generator again. Without damping, $\delta(t)$ would oscillate about δ_o unless P_m is insufficient to meet the new load. (Actually the case is more complicated than this since $\dot{\delta}$ must change sign, not just $\ddot{\delta}$. However, the basic idea is not modified.) If the increase in load is too great, the motor will stall. At the nodes of $P_e(\delta)$ where P_m sin δ changes sign (at 0 or π), the generator no longer delivers power, but, in fact, acts as a motor. It must be removed from the system; it cannot regain synchronism. A repeat of the above analysis will show that if the initial angle were δ_u (Fig. 7), then the motor-generator would not be stable. In practice in multi-machine networks, a machine is considered to be out of synchronism when δ differs by more than 120° from electrically "close" machines.

We can now return to our original question concerning the response time of the system. For small perturbations, the system will oscillate about δ_o and Eq. (2.10) can be linearized. Then, for small ϵ

$$\sin(\delta_o + \epsilon) = \sin \delta_o \cos \epsilon + \cos \delta_o \sin \epsilon$$

$$= \sin \delta_o + \epsilon \cos \delta_o + O(\epsilon^2) \, , \qquad (2.11)$$

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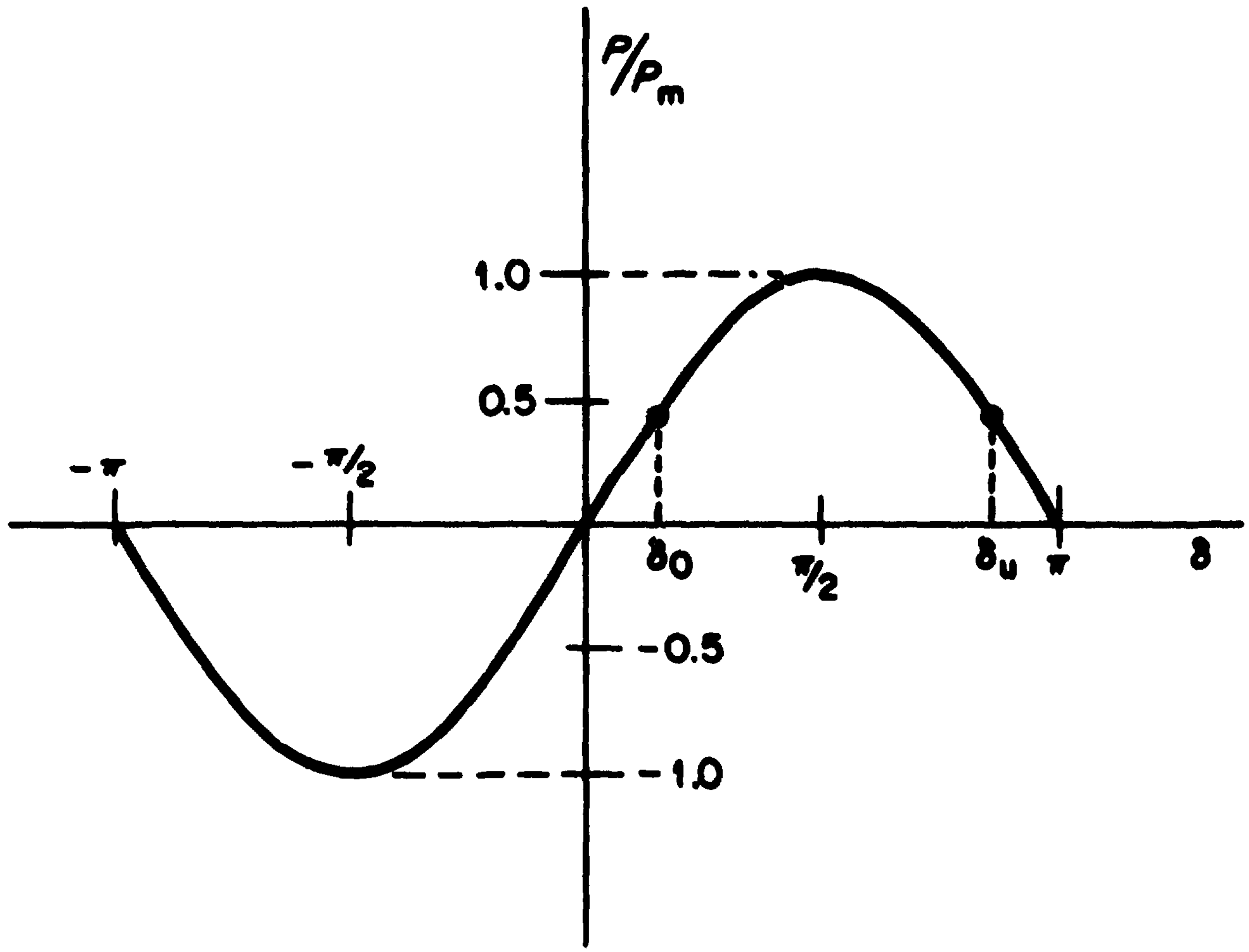

Fig. 7. P_e as a Function of δ for a Generator Driving a Motor.

where

$$\delta = \delta_0 + \varepsilon$$

Equation (2.10) becomes

$$M\ddot{\varepsilon} = P_a - P_m \cdot (\sin \delta_0 + \varepsilon \cos \delta_0) = -(P_m \cos \delta_0) \cdot \varepsilon \equiv -P_m' \varepsilon \quad , \tag{2.12}$$

where we have used the equilibrium identity

$$P_a = P_m \sin \delta_0 \quad . \tag{2.13}$$

Equation (2.12) is just that of harmonic oscillation with natural frequency

$$\sigma_m = \sqrt{P_m'/M} = \frac{2\pi}{T_m} \quad . \tag{2.14}$$

Note that

$$P_m' = P_m \cos \delta_0 = \frac{d}{d\delta} (P_m \sin \delta) \Big|_{\delta = \delta_0} \tag{2.15}$$

is just the incremental power gradient (frequently called the synchronizing power). For typical machines the period, T_m, is of the order of a second, so that after a perturbation, stable machines will oscillate or swing, with small oscillations, about their equilibrium value with roughly this same period. Thus the period, T_m, defines a second important time scale for stability studies and is directly related to the mechanical response time of the machines.

A third important time scale is the response time of the generator and load control circuitry. The effects of the generator governors become important about one or two seconds after a perturbation since the governors respond rather slowly and gradually. The governor response is difficult to model, and it is therefore again convenient to consider the response in each of two intervals: (1) the short time transient response, which is that before generator control becomes significant, and (2) the later time dynamic response, which is strongly dependent on the generator control systems. As earlier mentioned, the tripping of circuit breakers is an important class of perturbations which can affect the transient response since relay response time is between 1 and 15 cycles. Typical generator tripping relays excite breakers when there is a 60% or more voltage reversal for a time of 10 cycles, with the excited breakers opening about three cycles later.

One cannot completely partition a response into transient and dynamic stability components. Certainly both aspects must be considered since a system which is quite stable during the transient period, but which is completely unstable dynamically, results in just as unfortunate a collapse as if stability were lost very early. However, one can be certain that a system which has an unstable transient response will not likely regain synchronism. A study limited solely to the early time response can therefore be quite informative if not always conclusive, and this is the primary limitation on this study. However, some knowledge of the dynamic response can be gained, as will be seen.

2. Method of Solution

Because of the nonlinearity of Eq. (2.7), one must solve the coupled equations numerically. We have used the versatile digital computer program of the Philadelphia Electric Company.[10]

Initially the load flow of the network at equilibrium must be found by solving Kirchhoff's laws[9] for the given electrical network using an iterative technique. This determines the voltages, power flows, and initial equilibrium angles of the machines. For the complete load flow of n machines, there are n equations with n + 1 unknowns; and, with the specification of an initial reference phase $\delta_1 |\, t = 0$, a unique solution for all other δ_i's can be obtained (i.e., again it is not the absolute angles which are important, but the relative angles. One must, of course, know the self and mutual admittance Y_{jk} of the network between each j^{th} and k^{th} terminal, and the voltage magnitudes E_i of the machines. The determined δ_i's then completely specify the power output for each machine at equilibrium.

More specifically (recalling that the electrical quantities are complex) we have for the power output for the i^{th} machine

$$P_i = E_i^* I_i \tag{2.16}$$

and

$$I_j = \sum_k Y_{jk} \cdot E_k \quad . \tag{2.17}$$

Then defining the phase δ_i between E_i and J_i

$$E_i = |E_i| \, e^{i\delta_i} \quad . \tag{2.18}$$

Equation (2.17) can be used to eliminate I_i in (2.16), expressing the power of each machine in terms of Y, E, and δ. The angle ' can be found by iteration. (An example is given in Section 3 of this chapter.)

In this study, a solved base case representing the peak summer power flow of a projected 1977 transmission network is used. The digital stability program could be used once a suitable model for the EMP faults was determined. Chapter III discusses the model in detail.

3. Swing Curves - An Illustrative Example

As an illustrative example of stability calculations, consider the simple two-machine problem illustrated in Fig. 8. The power delivered by each generator is a function of the difference in angles of the two machines, i.e., of $\delta_1 - \delta_2 \equiv \Delta$. The power delivered by each machine for the two-machine problem is of the form

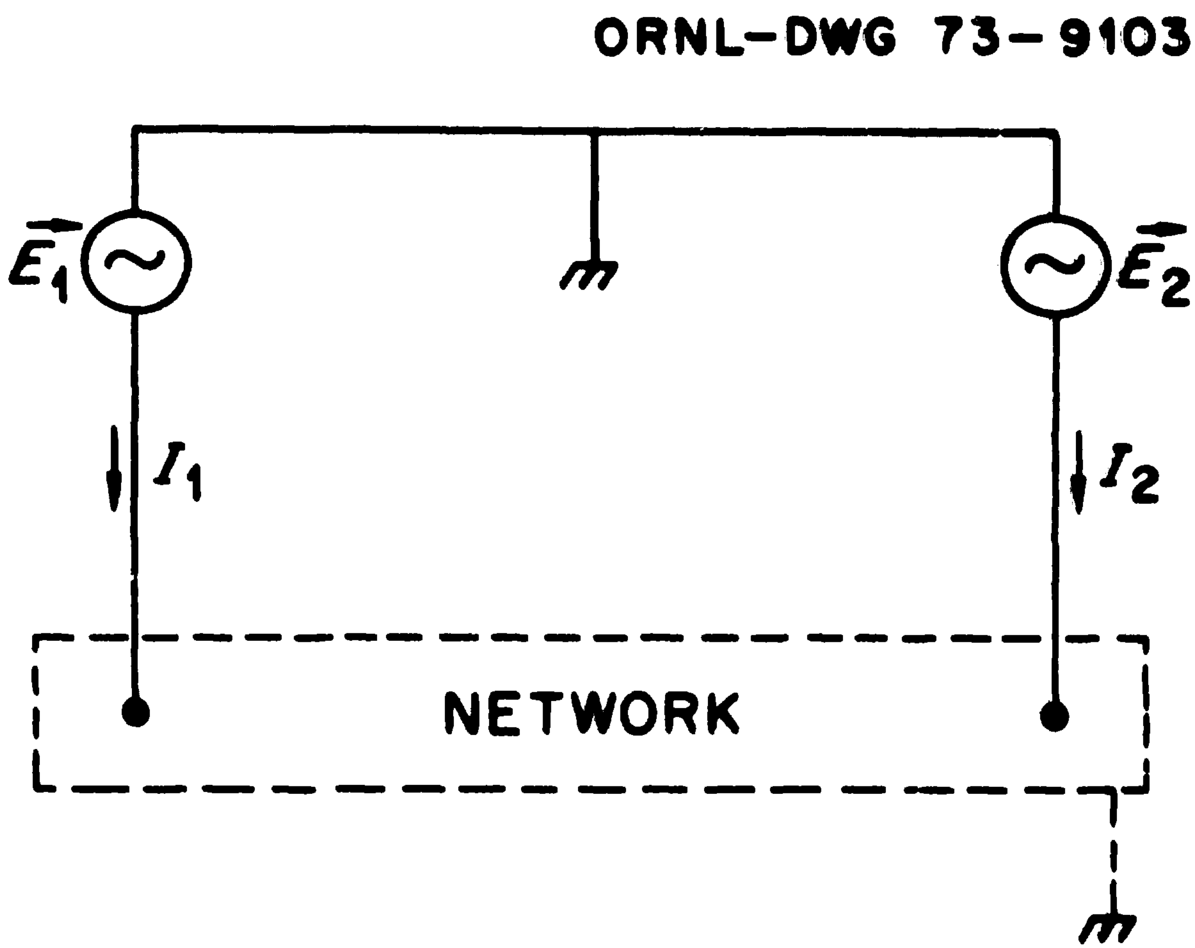

Fig. 8. A Schematic Diagram of a Two-Generator Problem.

$$P_{e,1} = a_1 - b \cos(\beta + \delta_1 - \delta_2) \qquad (2.19a)$$

$$P_{e,2} = a_2 - b \cos(\beta - \delta_1 + \delta_2) \qquad (2.19b)$$

where β is related to the impedance phase of the circuit. The angles δ_i are found by using Eqs. (2.16) through (2.18). During equilibrium $P_{e,i}$ and the angles δ_1 and δ_2 are constant. However, a perturbation such as a fault modifies the original circuit changing a, b, and β, and therefore P_1 and P_2 change resulting in a net torque on the machines. The angles δ_1 and δ_2 then begin to change as given by Eq. (2.7).

The effects of the perturbation, of course, depend upon many factors such as the duration of the fault, its location, its severity, etc. Two typical results for the change in the δ's as a function of time are illustrated in Fig. 9. The machine angle curves labeled A represent an unstable case in which the fault was not cleared with sufficient rapidity. The case labeled B is the response for a more rapid clearing of the fault, and the curves indicate that the generators remain in synchronism since the machines swing back to equilibrium. Appropriately, the curves are called swing curves and show the deviation of the machine angles from equilibrium as a function of time.

A general criterion for loss of synchronism is that when two electrically close machines differ in phase angle by more than 120°, the machines are said to be out of step. Thus, when the angular difference in the δ's of two such machines exceeds this angle, the machines will not be in synchronism with each other. The restoring torque will not be sufficient to resynchronize the machines. A loss in synchronism is quite apparent from the swing curves.

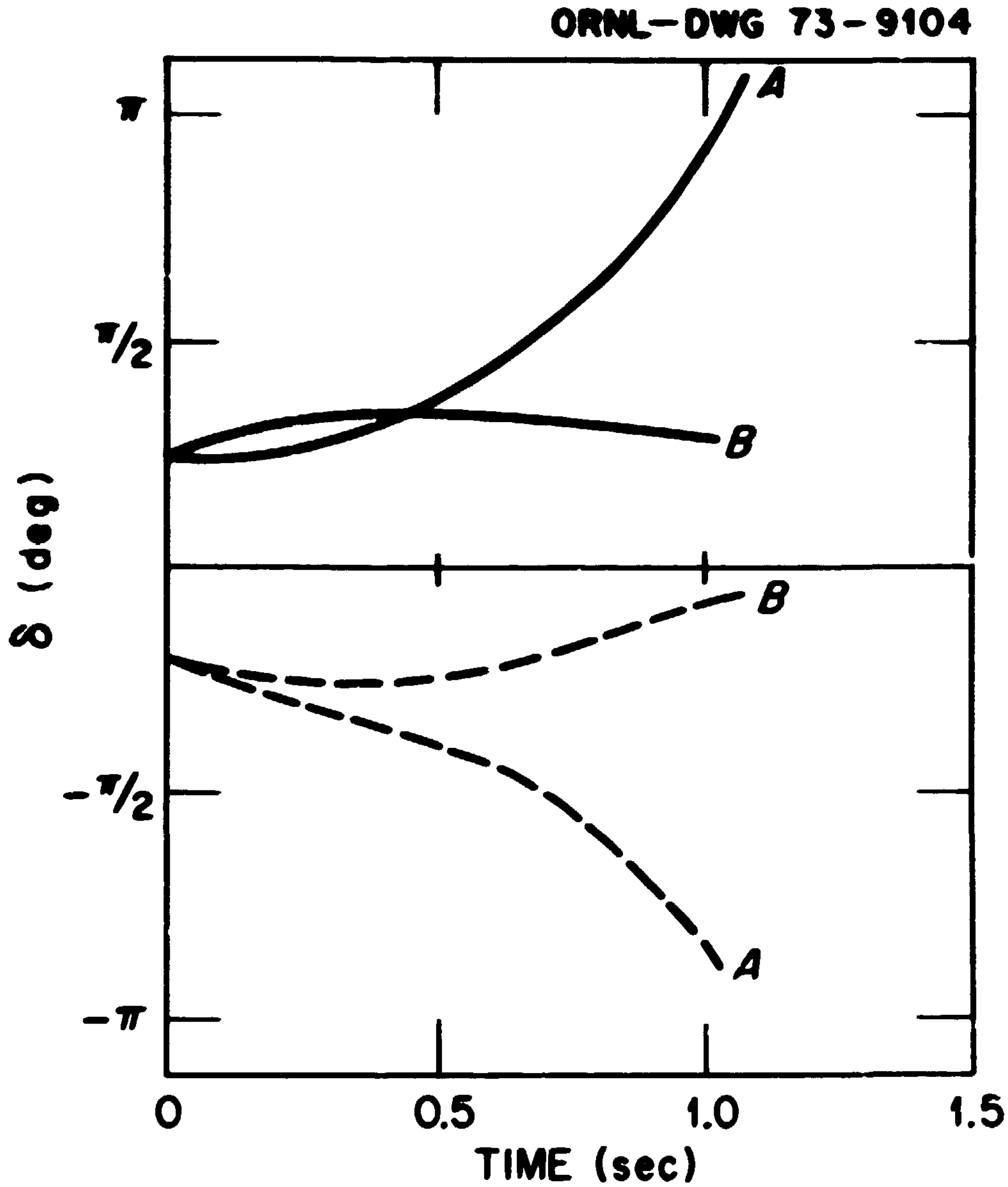

Fig. 9. Typical Swing Curves for the Two-Generator Problem.

CHAPTER III

MODELING OF EMP-INDUCED PERTURBATIONS

A. THE DESCRIPTION OF THE MULTIPLE-FAULT MODEL

The general characteristics of EMP-induced perturbations were discussed in Chapter I, Section D. There it was noted that, within the limitations and simplifications mentioned, the principal disturbance affecting the transient response is multiple faults on the distribution system. The response from the perturbation can be calculated by using standard digital computer stability programs. However, in using thse programs two modifications must be made. Firstly, one must simulate the faults which occur on the distribution systems (not on the transmission system as is the usual case). Secondly, many faults must be simultaneously applied on the distribution systems connected to the transmission network over a large area. Fortunately both of these modifications can be easily handled with no reprogramming of the basic stability program of Ref. 10.

A fault on a distribution system will couple to the connecting transmission network through some effective impedance Z, with Z determined by the location and nature of the particular fault on the distribution system. Faults should occur primarily on the low voltage side of the major substation transformers shown in Fig. 3. The characteristic impedance Z will then be determined primarily by the primary-to-secondary impedance of the transformer at that point, i.e., a fault on the low voltage side of the transformer will couple to the transmission systems with an effective impedance Z nearly equal to that of the typical transformer. This impedance is due to the leakage flux of the non-ideal transformer and is almost pure reactance. Faults occurring on the distribution system far from the major substation will have a much larger effective impedance. Consequently, the faults close to the major substations will produce the most severe perturbation of the transmission system. We are assuming that the voltage insulation of the transmission network feeding the major substations is sufficiently good that FMP will not intrude faults on the transmission system. This assumption is not without justification as earlier discussed.

Figure 10 illustrates the model for simulating the effect of distribution system faults on the transmission system. In normal transient studies, the load is considered to be on the major substation bus labeled S. However, by defining an additional bus, D, we can simulate faults on or close to D by connecting bus D to bus S by a "transmission line," D-S, having an impedance Z. Then the effects on the transmission network produced by a fault on or near D can be calculated simply by faulting D, a standard option in the stability program.

The procedure is essentially as follows. The bus D is grounded (or is faulted with a 3-phase fault, leaving the transmission line looking at the predominantly reactive load from the leakage flux of the non-ideal substation transformer. This modifies the network [the Y_{jk} in Eq. (2.17)] resulting in a modification of the a's, b's, and β's of equations similar to (2.19). The swing angles $\delta_i(t)$ are then calculated from Eq. (2.7) using the new circuit parameters, i.e., the new Y_{jk}'s. If the fault (or faults) are then removed or modified at a later time t_1, a new set of circuit parameters will specify the power transfers. The machine angles $\delta_i(t)$ can be calculated for $t > t_1$ using the new power transfers the value of $\delta_i(t_1)$, and Eq. (2.7). Even if all faults are removed and the circuit is returned to its initial configuration, the machine angles will vary in time since $\dot{\delta}_i(t_1)$ are non-zero and the $\delta_i(t_1)$ are not at their equilibrium values. Thus the net torque on each rotor will still be non-zero. The swing curves $\delta_i(t)$ will then show if the i^{th} machine loses stability. We are not directly interested in the effects of the perturbation on bus D, itself, nor on the line D-S: these circuits are introduced merely to simulate the effect of distribution faults on the transmission network.

Multiple faults can be approximated in a simple manner. Since we are not interested in the distribution system except for its effects on the transmission system, all distribution buses which are to be faulted may be connected together. Equivalently, we represent all faulted

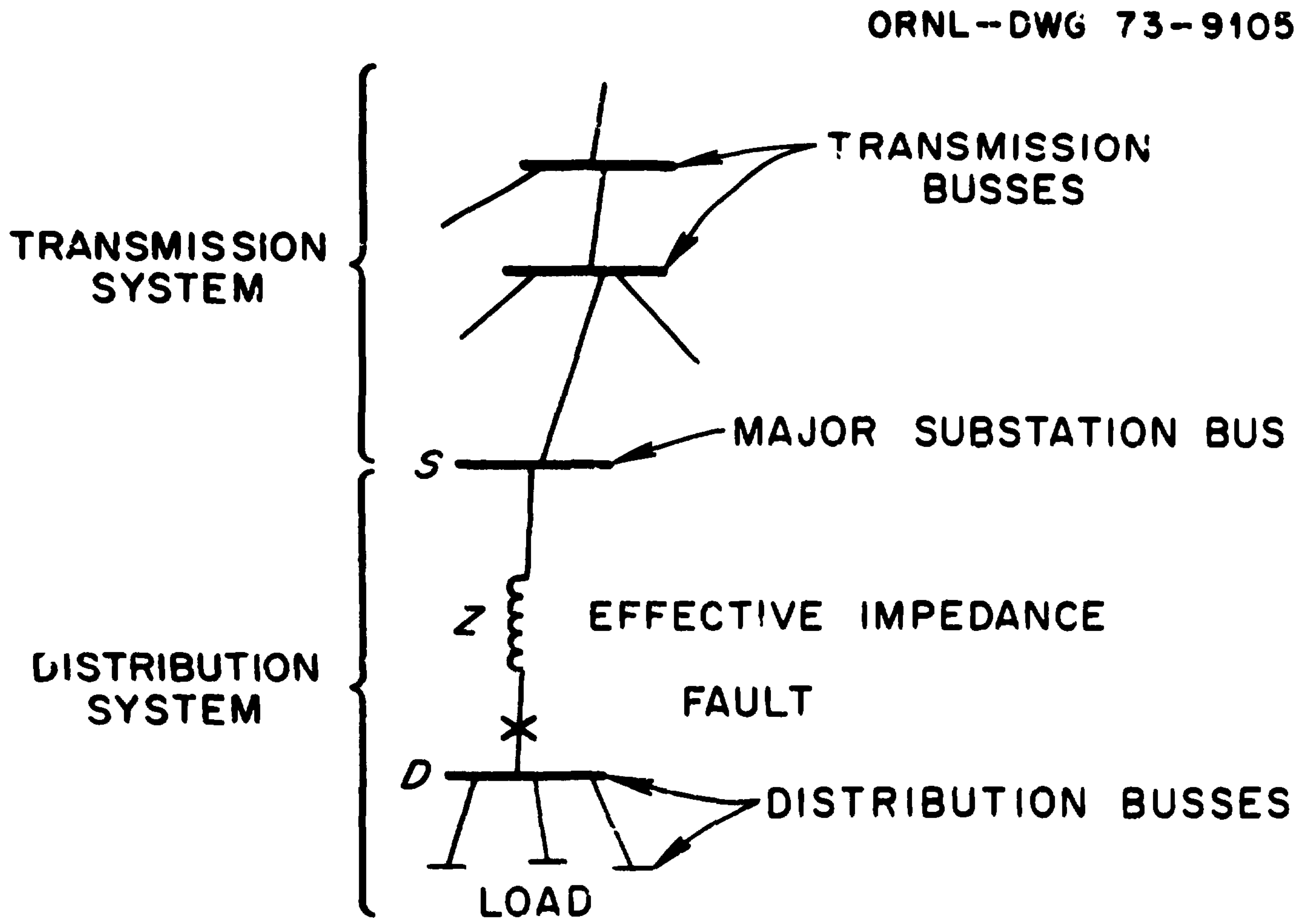

Fig. 10. A Network Diagram Illustrating the Interconnection of the Transmission System and the Distribution System.

distribution points by a single bus on which one fault is placed. (This bus is designated by $\tilde{D}$.) Then the various points T_i of the transmission network that are to be connected to faulted distribution lines are modeled by connecting each T_i to $\tilde{D}$ with a characteristic impedance $\underset{\sim}{Z_i}$. The model is illustrated in Fig. 11. The effect on T_i by faulting $\tilde{D}$ can then be calculated in the same manner as described above.

A number of important parameters must be specified. In particular, we must ascertain what points on the transmission network should be connected to faulted distribution systems, i.e., which transmission buses should be included in the set T_i. Both the number of faults per unit area within the faulted area, as well as the geographical extent of the perturbed region, must be specified. We refer to this complicated variable as the fault density function, $\rho(\vec{r})$. The density is specified by the number of faults <u>within</u> the faulted area per unit area, not by the total number of faults averaged over <u>both</u> faulted and unfaulted areas. Thus $\rho(\vec{r})$ is zero outside the faulted area.

The fault density function $\rho(\vec{r})$ depends on the severity of the EMP-induced currents, which, as pointed out earlier, is difficult to estimate. The density was estimated in the following manner. Within the perturbed area of the transmission network (such as the TVA network) we first arbitrarily assumed that all major buses having a load of 100 megawatts or more would be connected to faulted distribution systems. These buses specified the set T_i, thus specifying a particular fault density. Then, calculations were done using different densities in order to determine the change in the system's response. The size of the perturbed area is determined by the height of burst of the detonations. In order to determine the importance of the geographical extent of the perturbations, several stability runs were made with the perturbation applied to increasingly larger areas.

Another important parameter set which must be specified is the impedances, Z_i, connecting each T_i to $\tilde{D}$. We refer to this set as the effective fault impedance, $Z(\vec{r})$. The dependence of the response on Z_i was determined by the following procedure. First, all Z_i's were chosen as equal and fixed at the impedance of a typical major substation

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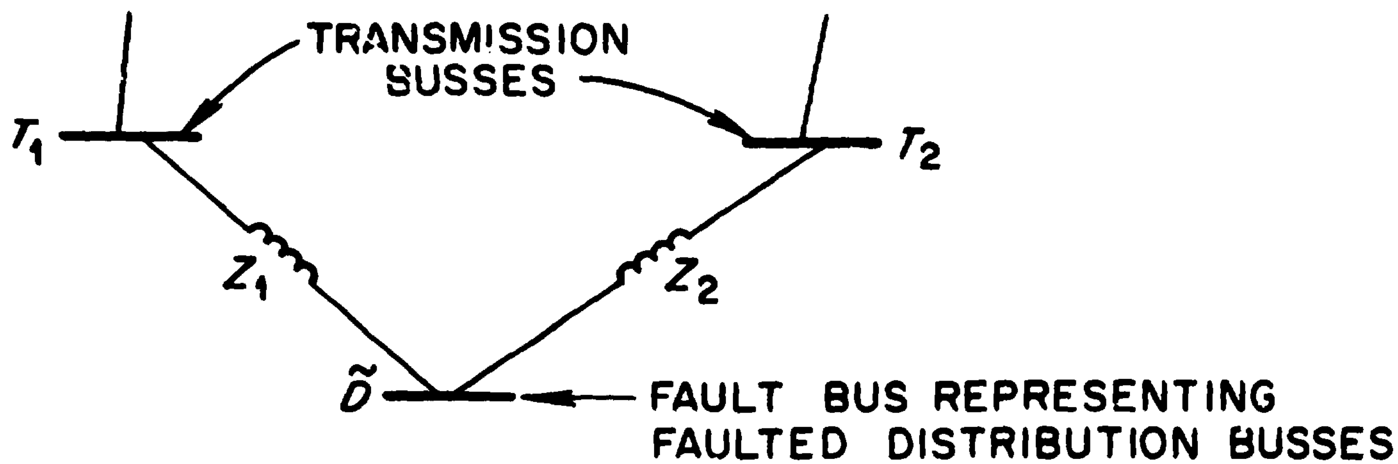

Fig. 11. The Model Used to Simulate the Perturbation of the Transmission System from Multiple Faults Occurring on the Distribution System.

transformer. (The impedance is very nearly purely reactive.) Then calculations for different values of the impedance were made. Finally, to be certain that using the same impedance for all Z_i's is a reasonable approximation, Z_i was randomly chosen between specified limits with the average of the set corresponding to a previously used value. A comparison of the calculated responses (i.e., of the swing and voltage curves) then allows one to determine the dependence of the response on the impedances.

Repetitive sets of multiple faults were easily modeled by reapplying the single set model after the desired time delay from the previous pulse. The duration of the repetitive faults was chosen to correspond to typical distribution relay times as in the non-repetitive fault case. A detailed discussion of the importance of relay times for multiple pulses is given in Chapter IV. For two or more repetitive pulses, the time separating the pulses gives an additional degree of freedom. After many trial calculations using different time separations, it was found that the response was not strongly dependent on this time separation. A representative double pulse was then chosen for further study of the effects of repetitive pulses. The detailed characteristics of the pulses used are discussed in Chapter IV.

B. THE MODELING OF OTHER PERTURBATIONS

Many of the other EMP-induced perturbations mentioned in Chapter I, Section 4, can be incorporated in the stability studies using the digital program. Lock-out of distribution relays caused by multiple pulses will affect the transmission system chiefly by reducing the load on those buses feeding the affected distribution system. In order to simulate this effect and ascertain the importance of load shedding, the load on the buses T_i was reduced. Several stability runs were made with this load reduced by 10 to 50%, and the size of the area in which load reduction occurred was also varied.

The stability program could also model both the opening of transmission lines (caused by either proper or false operation of relays) and generator tripping. However, as discussed earlier, it was assumed in this study that EMP would not initially cause the transmission circuitry to open.

An estimate of the magnitude of reduction in generation needed to counteract the increase in system frequency accompanying multiple faults and load shedding can also be made. The results and procedural details are discussed in the next chapter.

The computerized tie-line and load-flow control systems were not modeled because of limited time and resources. However, the effect which tie lines have on connecting systems was studied. The stability program allows one to model opening of tie lines at any time during the stability run. We wished to determine whether significant effects are introduced because of the tie line connections and also if the opening of the tie lines before or shortly after the EMP-induced perturbation occurs significantly affects the response.

In Chapter IV we present the results and analyses from scores of stability runs which were made in order to determine the importance of the parameters discussed in this chapter and elsewhere.

CHAPTER IV

RESULTS OF NUMERICAL STABILITY CALCULATIONS

A. INTRODUCTION

This chapter discusses the results of the stability calculations using the model previously described. In Section B we present the results for perturbations consisting of single sets of multiple faults. Perturbations consisting of repetitive sets are discussed in Section C. By calculating the response from a wide variety of perturbations one can determine both the possible range of EMP-produced effects on the system's transient response and the important parameters specifying the EMP pulse. This approach is necessary since one cannot quantitatively specify a unique and universal EMP perturbation.

The unmodified transmission network used throughout this study for the base case was a projected peak summer power flow network for 1977, provided by the Tennessee Valley Authority (TVA). Over 1500 buses 2600 lines, and 300 generators were modeled. The transient response was calculated using the transient stability program and the solved base case of the projected 1977 power flow.

Several test runs of the model illustrated in Fig. 11 were made to ascertain whether or not the connection of the transmission buses T_i to the bus $\tilde{D}$ representing the distribution system through the impedances Z_i would introduce a false perturbation even when no faults were applied. No significant perturbation was in fact introduced.

The network was modified as specified, and the transient response was then calculated <u>without</u> faulting the distribution bus $\tilde{D}$. No significant deviations from equilibrium were produced, so that the circuit modifications of the model do not perturb the system by significantly modifying the load flow.

Several "representative pulses" for both the single set and the repetitive sets of pulses were chosen and defined by specifying the impedances, fault densities, area of coverage, and duration. Table 1 lists

Table 1. Several of the Representative Sets of Faults, Each Comprising a Perturbation

Number	Label	Number of Buses Faulted in the Perturbed Area	Geographic Area Covered by Perturbations	Effective Impedance	Comment
1	$\bar{F}$	Approximately 1/3 (78 out of 264)	Area 10 only (TVA)	10%	All buses with 100 MW or more load on TVA were faulted.
2	F'	As in No. 1 above plus 58 additional in areas 12 and 13	Areas 10, 12 (MO & AR), and 13 (IL & MO)	10%	Approximately same density in ll of faulted area as in above.
3	F''	As in No. 2 but 24 more buses on 4 additional neighboring networks	As in No. 2 plus 4 more networks	10%	Same density in areas faulted in No. 2, but with lower density in 4 added areas.
4	$\tilde{F}$	As in No. 1	As in No. 1	Z_i chosen randomly between 10 to 20% with average $Z = 15\%$	As in No. 1

four of the single-set pulses and also gives the notation we use in identifying each. This is by no means a complete list of all pulses used in the study. These representative pulses were selected because they illustrate the different system responses for different perturbations as outlined in Chapter I, Section D, and Chapter III. The pulses were selected as "representative pulses" after scores of stability runs were made using many different pulses.

Four different groups of machines were chosen to illustrate typical swing curves in order to facilitate the comparison of the responses from different perturbations. Table 2 lists the different groups of machines, their locations, and their power outputs at equilibrium. The machine location names and area designations are given for the convenience of those familiar with current Tennessee Valley Authority (TVA) names.

The distribution relays are an important consideration in determining the effects of EMP. Typical distribution relays take about 0.133 to 0.25 second (8 to 15 cycles) to open when clearing a faulted line. (One cycle is 1/60 of a second.) The open relays will then reclose in about 0.25 second (15 cycles) after opening. If the line is still faulted, they will again open in an additional 0.133 second and remain open for about a second before reclosing. If, after reclosing, the line is still faulted, or if the line is refaulted within the next minute or so, the relays open and remain opened until manually reclosed. They are said to be locked open. As a result of this programmed sequence, repetitive bursts occurring shortly after the initiation of the clearing sequence which also refault the lines will cause the relays to respond in the same manner as if the lines had remained uncleared and consequently will lock the relays open. The relay time sequence will determine the duration of the faults, since EMP merely initiates the faults which then remain until the lines are cleared. Since EMP will not fault a distribution line which has no voltage, open lines will probably not be affected by EMP. Thus, a second EMP pulse arriving after the opening of a relay removing the line will not affect the line. There will, therefore, be about 15 cycles when a second EMP pulse will have little effect. We ignore this limitation of double pulses, but this simplification should have no significant effect.

Table 2. Machine Groups Used for Comparison

Group No.	Machine Bus Number	Area	Machine Location	Machine Torque, (MW)
1	1639 Generator #1	10 - TVA	Paradise	535
	1639 Generator #2	10 - TVA	Paradise	535
	1606 Generator #1	10 - TVA	Bull Run	443
	1606 Generator #2	10 - TVA	Bull Run	443
	1756 (System Ref.)	14 - AEP*	Ohio	1369
2	1546 Generator #1	10 - TVA	Paradise	675
	1546 Generator #2	10 - TVA	Paradise	675
	1666	10 - TVA	Kingston C	195
	1668	10 - TVA	Cumberland	1268
	1756 (System Ref.)	14 - AEP*	Ohio	1369
3	1088	15 - Carolina and Virginia	URQ	260
	1441	10 - TVA	KY HY	190
	1447	10 - TVA	SHAWF	294
	1485 Generator #1	10 - TVA	COLBT	527
4	8	1 - EDE	ASBRY	200
	40	6 - KGE	GILL	319
	251	1 - EDE	SEMPP	450
	803	8 - Miss.	WILSN	400
	1756 (System Ref.)	14 - AEP*	Ohio	1369
5	1666	10 - TVA	Kingston C	195
	1669	10 - TVA	CUMBF	1268
	1676	10 - TVA	BR FYG	065
	1699	14 - AEP*	KAM	800
	1702	14 - AEP*	TLC	600

*American Electric Power

B. THE RESPONSE FROM A SINGLE SET OF MULTIPLE FAULTS

We first discuss the transient response obtained from a single application of multiple faults (corresponding to the perturbation caused by a single EMP pulse). The time duration of the faults was chosen to be that of the opening time of typical distribution system relays. All faults were applied simultaneously since the difference in arrival time of the EMP pulse over the network's area is only a small fraction of a cycle, and such a time delay is of no consequence.

The typical single fault duration was chosen to be 0.2 second. Each of the representative sets of faults given in Table 1 was applied for this duration and the network then returned to its original configuration. The fault duration time was then changed in order to determine the dependence of the response upon this parameter. All faults applied were 3-phase faults (the most severe case) since it was much easier to determine an effective impedance for this situation. This is a reasonable assumption because 3-phase faults may typically occur if EMP induces faults at geometrical discontinuities. However, if the voltage on one of the three lines is near a voltage node, it is possible that the EMP pulse may fault only two of the three lines of the 3-phase system, creating a two-line-to-ground fault. But the basic characteristics of such a perturbation will not differ in principle from the 3-phase fault.

The system response from five different single pulse perturbations will be separately discussed with emphasis on the effect of changing the various pulse parameters. We again remind the reader that the five cases are only representative of scores of pulses used in this study.

All voltages and impedances are given as per unit or percent quantities[9] (a per unit quantity multiplied by 100). Equilibrium values are typically near 1 per unit.

1. Faults Applied to the TVA Area Only

The perturbation $\bar{F}$ of Table 1 was applied for 0.2 second. The perturbed area was restricted to that of the Tennessee Valley Authority

(TVA-Area 10). After 0.2 second from the time that the faults were first applied, the network was returned to its normal configuration, i.e., the T_i lines, the faults, and the bus $\tilde{D}$ were removed. Calculations of the transient response was continued to 1.25 seconds.

The swing curves of several machines are shown in Figs. 12 through 15. All machines of Fig. 12 are in the TVA network except that labeled 1756, which is a far away reference machine located in Ohio (see Table 2). The numbers refer to the bus numbers to which the machines are connected. Most TVA machines remained in synchronism with bus 1606, and Fig. 14 shows a typical group. Recall that a machine is considered to be out of step when its machine angle δ differs by more than about 120° from the electrically "close" machines. Most non-TVA machines remained in synchronism with the reference machine 1756, as shown in Fig. 15. Note the tendency for the TVA machines as a group to separate from non-TVA machines. Furthermore, TVA generators at bus 1639 lost synchronism with the remainder of the TVA system, and the swing curves of Fig. 13 also indicate that the two generators at bus 1546 lost synchronism. Thus two effects can be observed. First, machines within the TVA system lost stability and second, the entire group of TVA machines have swing curves which differ in slope from the non-TVA machines. We presently discuss this latter effect.

An increase in machine angle $\delta(t)$ implies that the frequency of the particular machine has increased which can be estimated in the following manner. A change in frequency Δf will result in $\delta(t)$ increasing linearly in time as

$$\delta(t) = \delta_0 + 360 \cdot \Delta f \cdot t \quad , \tag{4.1}$$

where angles are measured in degrees and Δf is the increase in frequency in hertz. After the fault perturbation is removed, the swing curves tend to become linearly increasing as the system damps to a new equilibrium frequency. They are only approximately linear not only because the transient oscillations take several seconds to damp out, but also because the power transfer does not depend linearly on δ. However, by

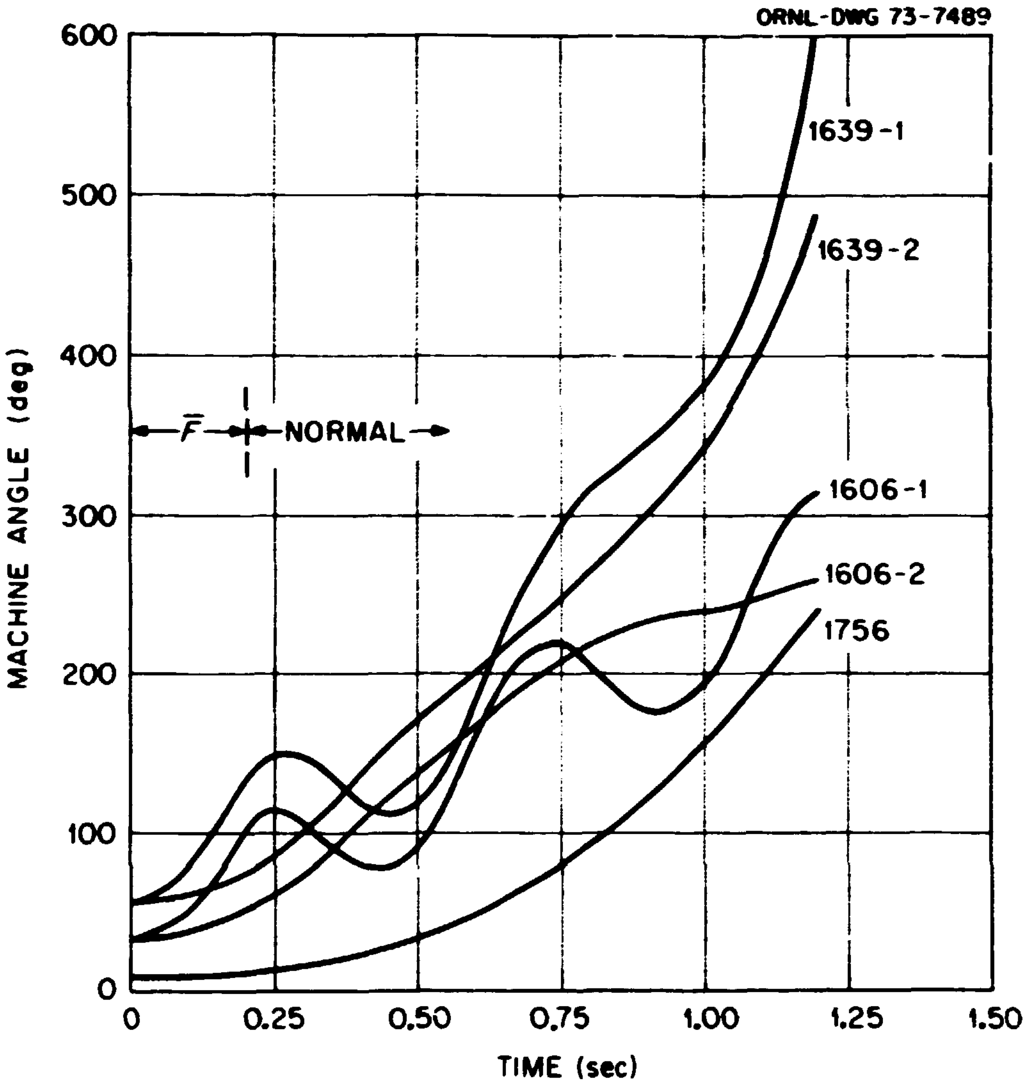

Fig. 12. Swing Curves for a Single Occurrence of Fault Set $\bar{F}$ of Table 1 for Machine Group No. 1 of Table 2.

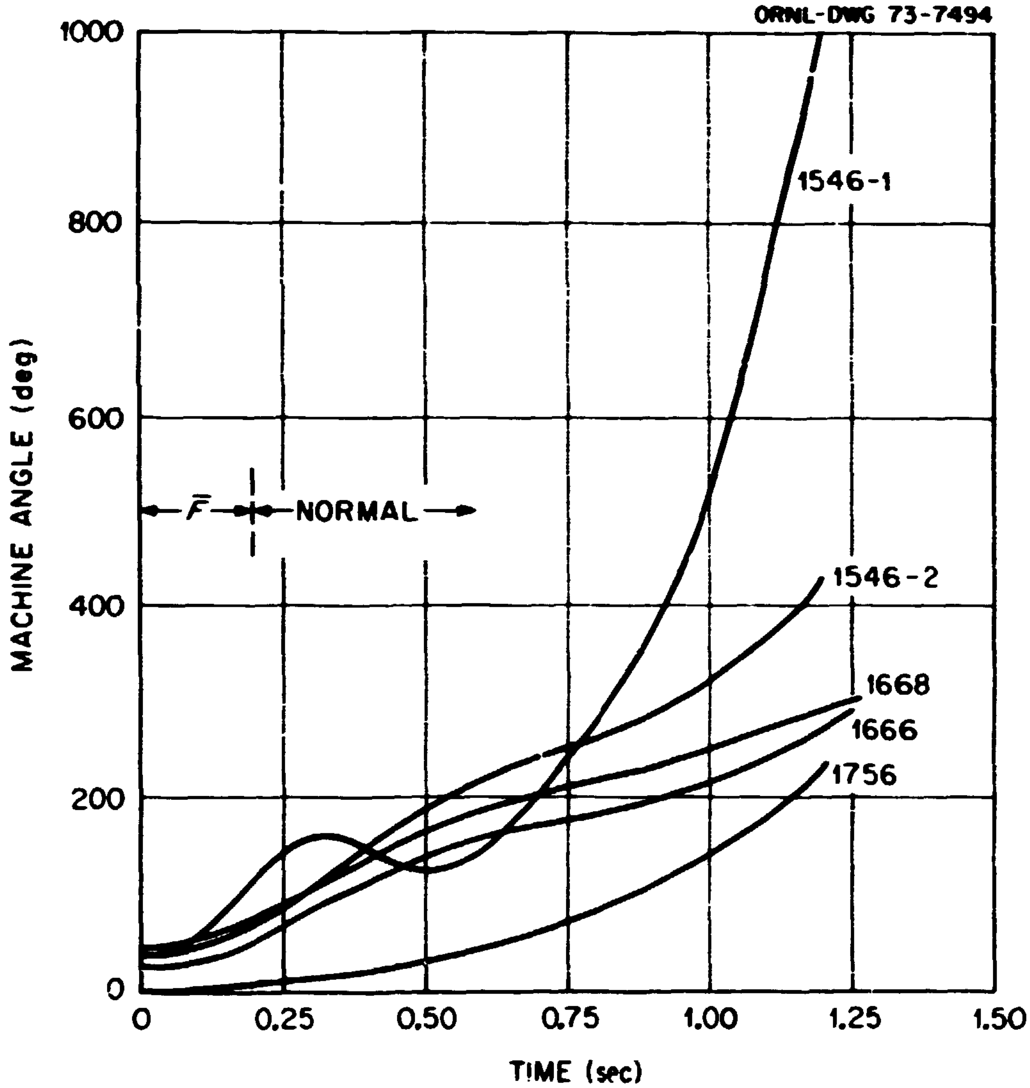

Fig. 13. Swing Curve for a Single Occurrence of Fault Set $\overline{F}$ for Machine Group No. 2.

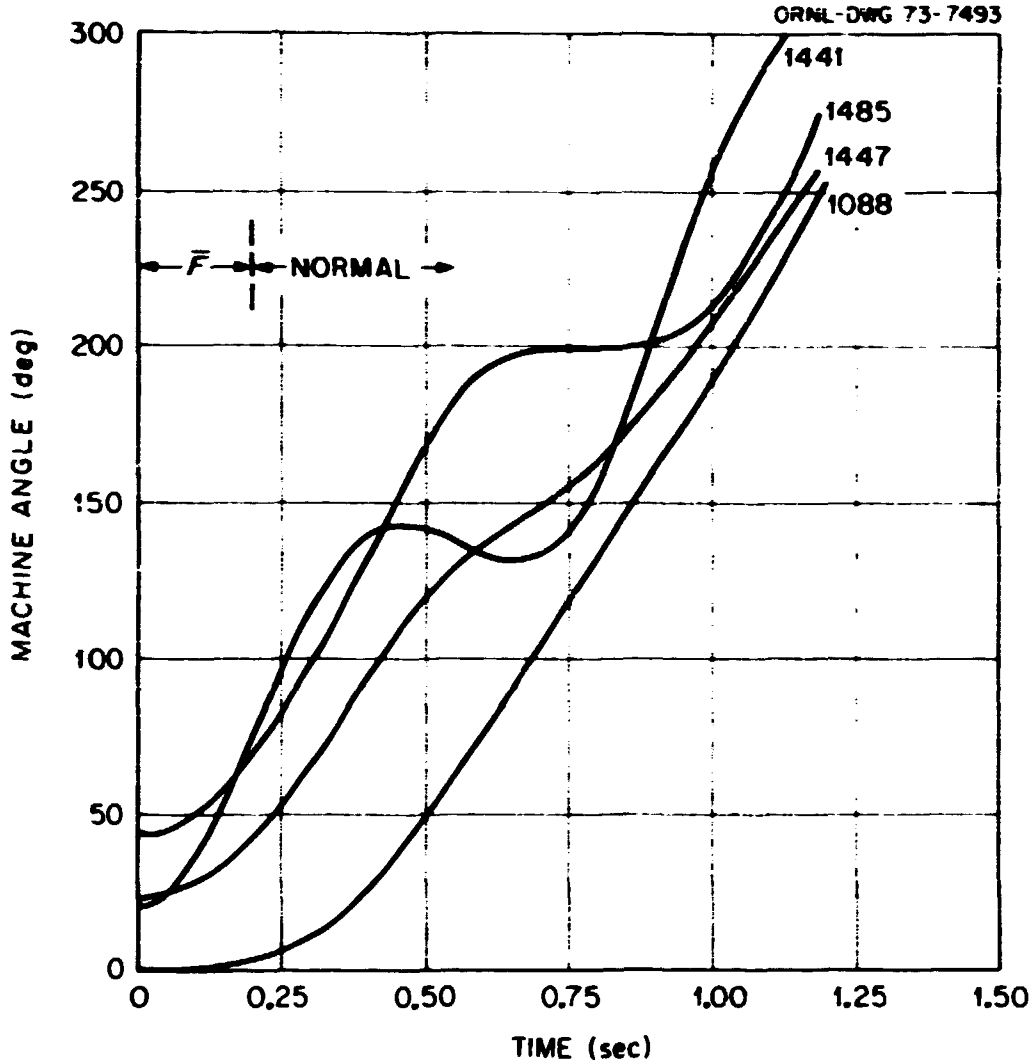

Fig. 14. Swing Curves for a Single Occurrence of Fault Set $\overline{F}$ for Machine Group No. 3.

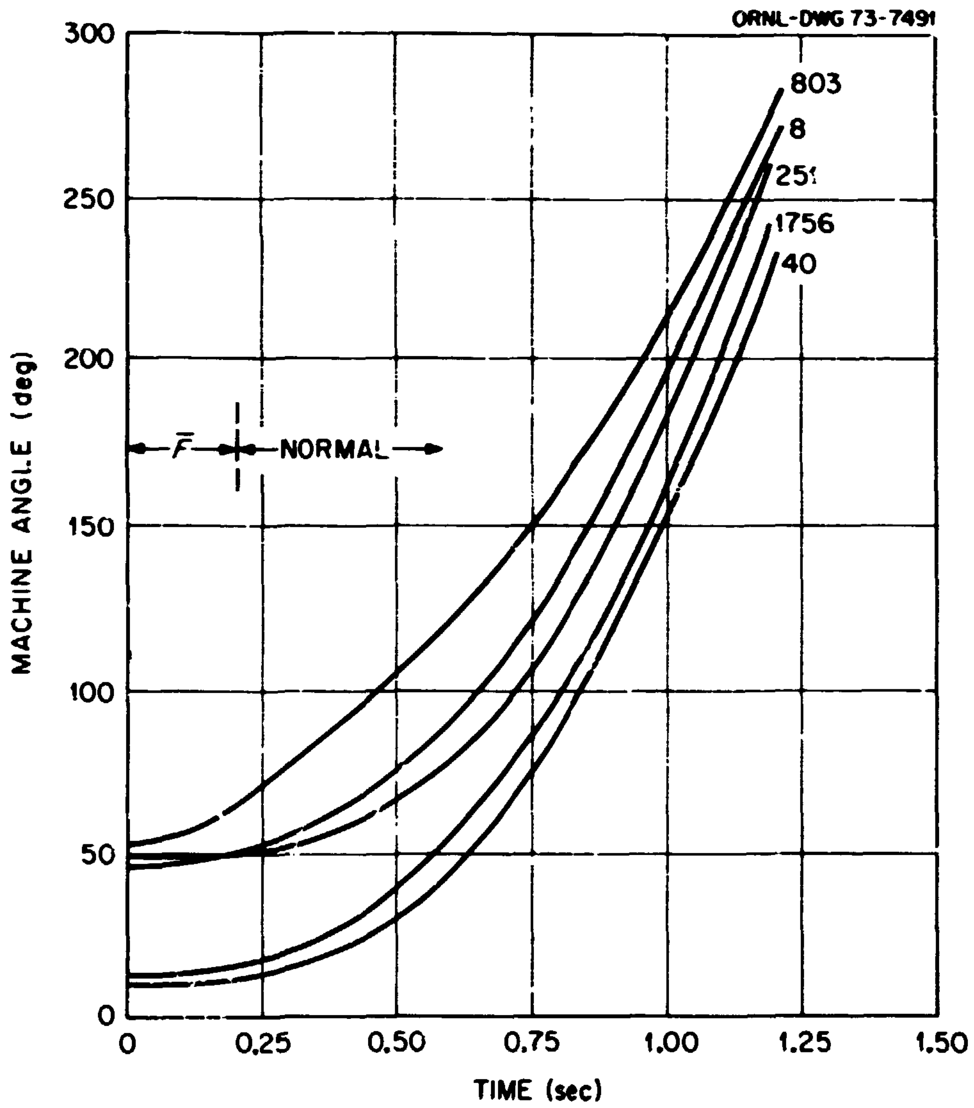

Fig. 15. Swing Curves for a Single Occurrence of Fault Set $\overline{F}$ for Machine Group No. 4.

averaging many swing curves together, an approximate Δf can be obtained from the "average slope" of the swing curves.

It is instructive to compare the change in frequency of the perturbed area, Δf_p (which in the present case is the TVA network), with that of the unperturbed area, Δf_u. Ignoring the machines which have lost synchronism with their adjacent neighbors (as will always be done in calculating Δf), $\Delta f_p \simeq 0.75$ hertz while $\Delta f_u \simeq 1.1$ hertz. In this case, $\Delta f_p < \Delta f_u$, probably because several TVA generators lost synchronism and therefore reduced the total TVA power output. The increase in Δf_u shows that there is a significant coupling between the perturbed areas, and it will be shown later that this coupling is quite important.

The uniform increase in frequency of all machines is somewhat peculiar to multiple-fault perturbations. The system frequency increases primarily due to the change to a predominantly reactive load, resulting in a great decrease in power absorbed by the load, even though large current surges are produced, and there is a widespread decrease in voltage on the transmission lines connected to $\tilde{D}$. Thus, although the faults cause large current surges, the voltages decrease greatly (by as much as 60% at many machine buses) resulting in a greatly decreased power output of the generators for the duration of the faults. Since the applied torque of the machines is not decreased initially, the machines accelerate.

Unless the generator governor systems can handle the increase in frequency, the entire system affected will speed up excessively, possibly resulting in the tripping of overspeed relays which then disconnect the generator from the network. However, if the estimates of Δf for the perturbation considered above are in the ball park, the governor systems may be able to handle the overall frequency increase and prevent loss of synchronism. In any case, typical governor systems begin to have an effect at about one to two seconds after the initial perturbation occurs.

In summary, the transient response to a perturbation covering only the TVA network area results in (i) several TVA machines losing stability, (ii) an increase in frequency of TVA machines, and (iii) a somewhat greater increase in the frequency of the unperturbed networks.

2. The Effect of Increasing the Size of the Perturbed Area

In the first case considered, the fault perturbation was applied rather uniformly over the TVA transmission network. Generally, the transmission system consists of several groups of transmission networks (of which TVA is but one). Internally these networks have a strong electrical connection but are less strongly connected to adjacent networks. Figure 16 pictorially shows some groups of networks close to the TVA network. Not all networks of the base case are shown. The power flow between the different networks is given for the equilibrium case. (The number in each circle is used to designate the particular area and corresponds with that given in Table 1 and 2.)

In order to determine the effect of increasing the extent of the perturbation, the size of the perturbed area was increased as specified by fault set F′ of Table 1, and was applied for a duration of 0.2 second, the same duration as in case 1. The perturbation was extended to areas 12 and 13 of Fig. 16. Area 13 (Illinois-Missouri exported about 1090 megawatts to TVA through connecting tie lines in the equilibrium load flow, while Area 12 (Missouri-Kansas) exported about 550 megawatts to Area 13. The three areas, 10, 13, and 12, comprising the perturbed area form a connected link. The average fault density in the entire perturbed area was about the same as case 1. Figure 17 and 18 show typical swing curves.

The interesting difference between the responses of this case and the former is that the perturbed and non-perturbed area machines remained in synchronism much better when the perturbation covered the larger area. For instance, the four machines at buses 1639 and 1546 did not lose synchronism for the larger area perturbation. In fact, only one small machine (not shown) lost synchronism as compared to more than half a dozen machines losing synchronism in the first case. Thus for the second case, even though the perturbation was more severe, covering a much larger area and consisting of about 70% more faults, the system remained more stable in the transient time interval.

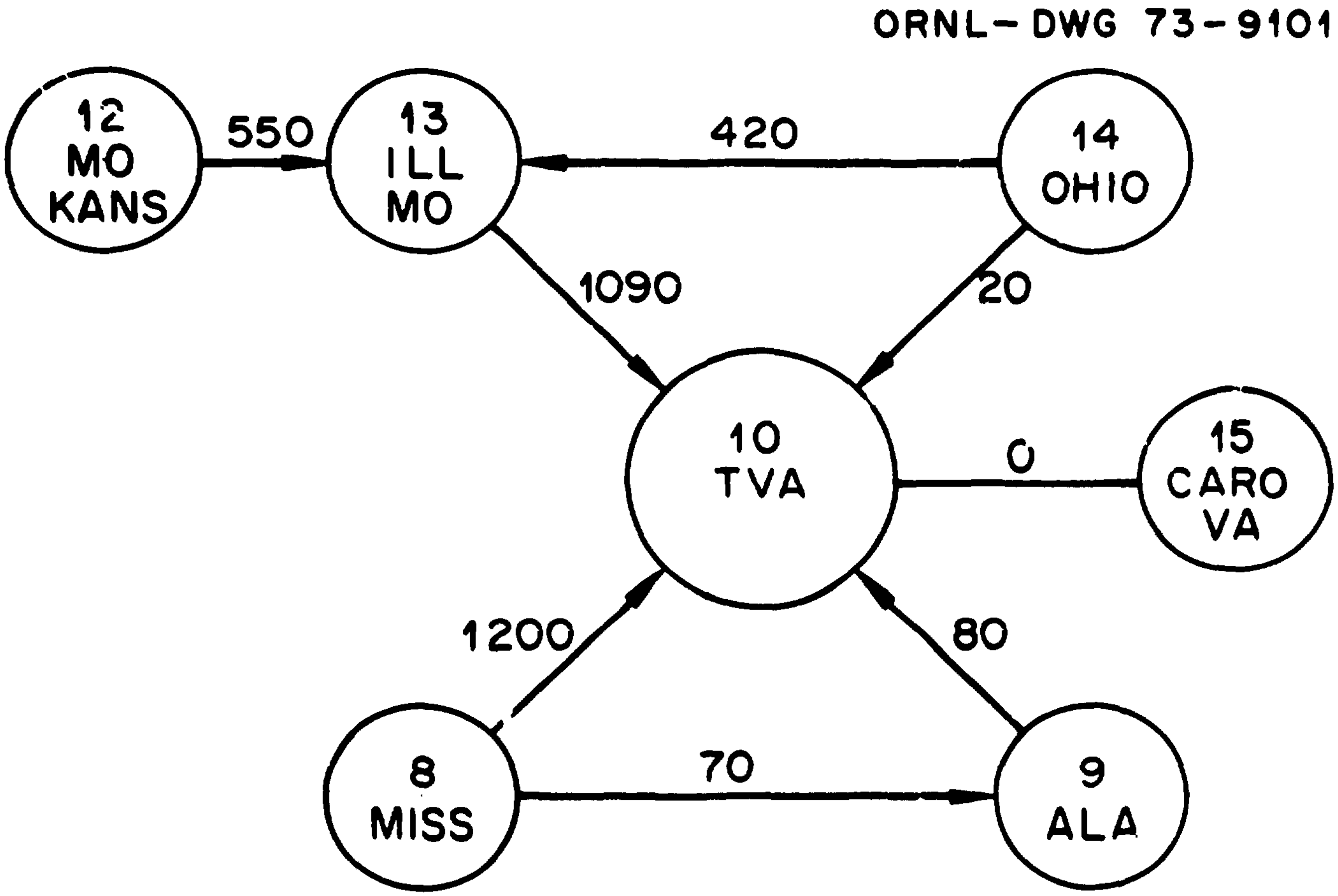

Fig. 16. Several Groups of Networks in the Vicinity of the TVA Network.

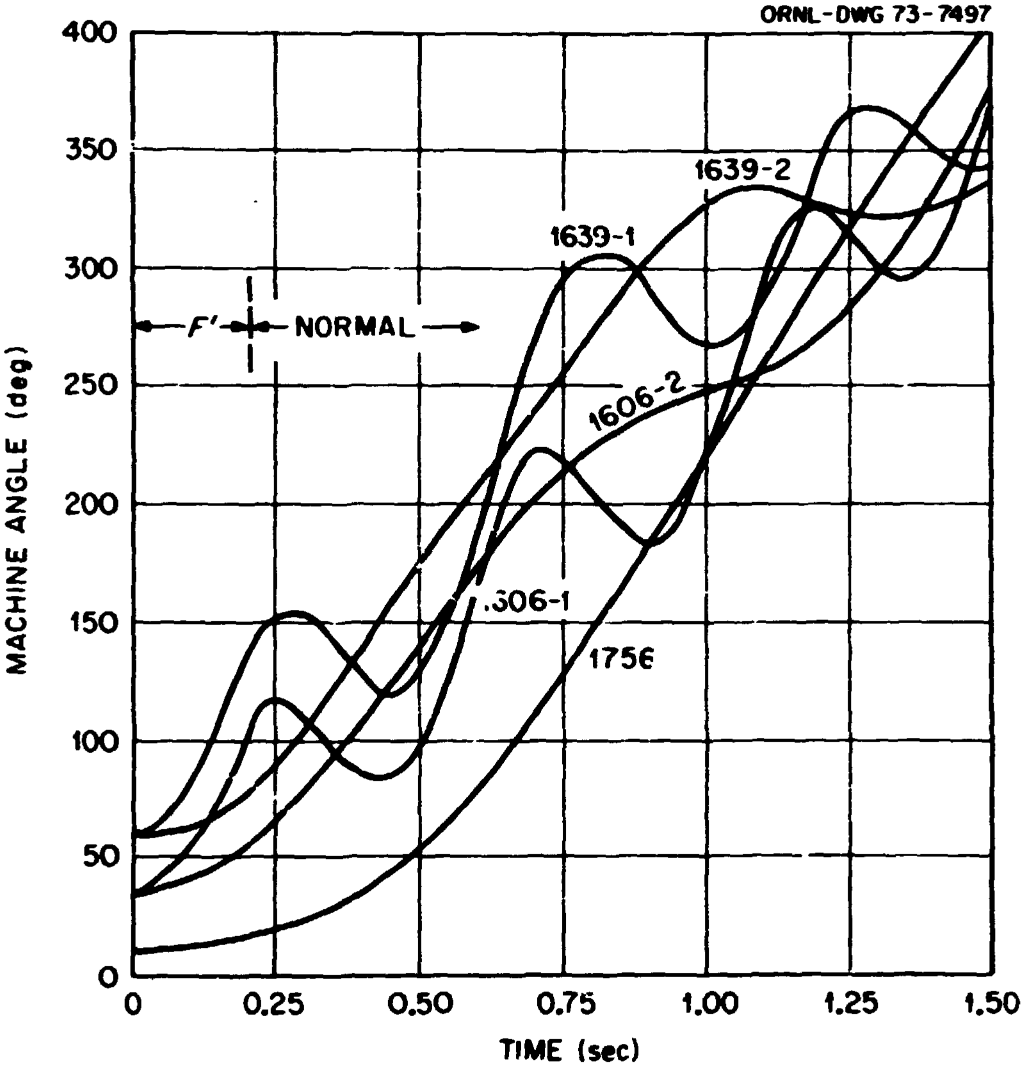

Fig. 17. Swing Curves for a Single Occurrence of Fault Set F' of Table 1 for Machine Group No. 1 of Table 2.

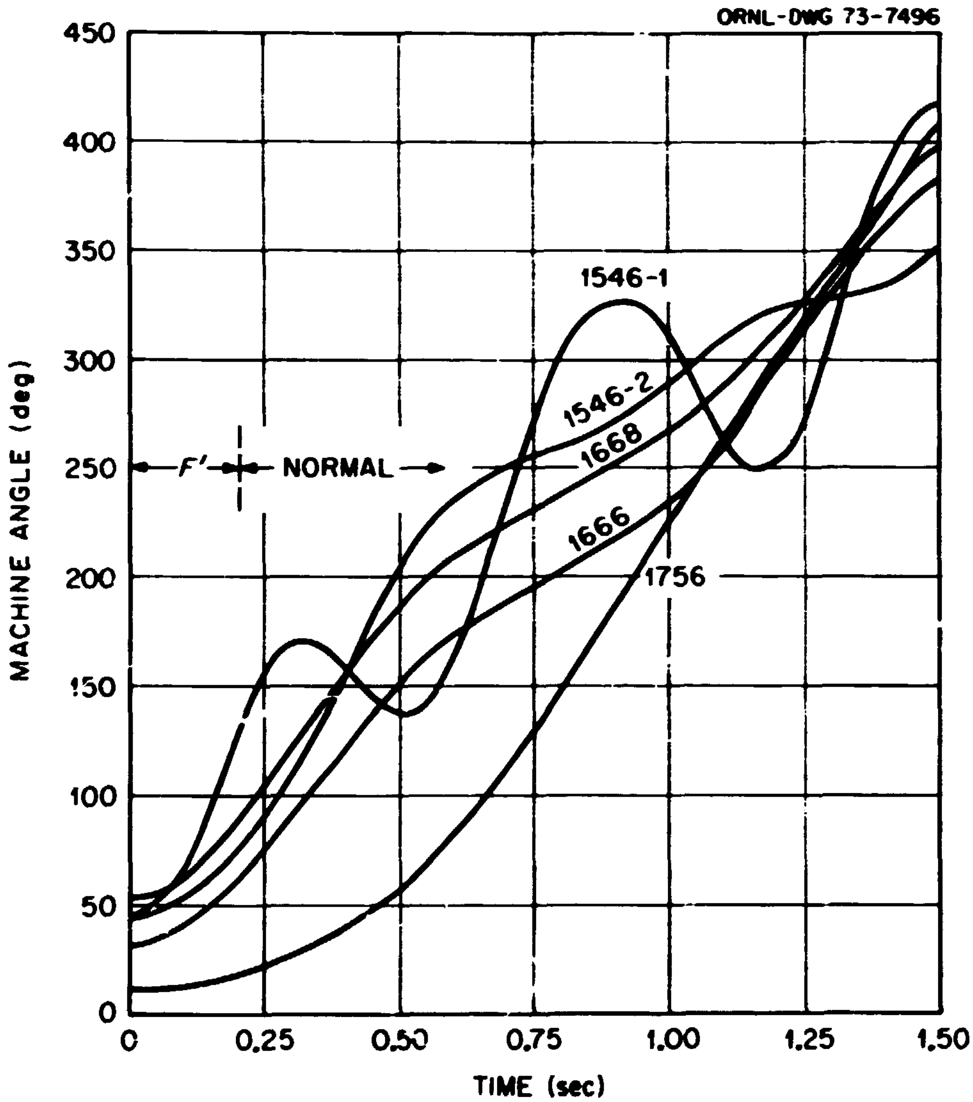

Fig. 18. Swing Curves for a Single Occurrence of Fault Set F′ for Machine Group No. 2.

At 1.26 seconds after applying the perturbation, the change in δ (not Δf) of the TVA buses was nearly the same in case 2 as in case 1, but the reference bus angle changed by about 50% more in case 2. Note also that the swing curves for the second case are much more linear than in the first. From Eq. (4.1) the linearity would imply that the machines in case 2 are no longer accelerating and have somewhat stabilized at a "new equilibrium" system frequency. The continued acceleration observed in the first case, even after one second, would indicate that the perturbed and unperturbed areas were still interacting or interfering with each other. The net change in frequency, Δf, calculated by linearly extrapolating the late time part of the swing curves, is about the same for both cases.

The difference in response of the two cases given so far can be partially understood in a simple way. In case 1, the perturbed area (TVA) is strongly connected internally and less strongly connected with its neighbors, as pictorially illustrated in Fig. 16. Consequently, when the perturbation is applied solely to TVA, the frequency of this area tends to separate from the adjoining areas causing the perturbed and unperturbed synchronous regions to interfere or beat with each other. Since there are so many ties with other areas which are unperturbed, the interference is strong. The result is that machines within the perturbed area lose synchronism. However, as the size of the perturbed area is increased to include adjacent areas, the connecting perturbed networks hang together much better since there is less adjacent unperturbed areas with which to interact. We shall return to this phenomenon when the results for double pulses are given.

3. Faults Applied to a More Extensive Area

In order to further verify that the difference in response observed in the previous two cases was the result of increasing the size of the perturbed area, the size was increased still further to include four additional areas, all connecting TVA. Because of practical limitations the fault density in the four added areas was considerably less than on areas 10, 12, and 13, but the major loads were still faulted. Figure 19 shows the response from such a perturbation (fault set F′ defined in Table 1).

The effect of the additional faults was minimal. The swing curves of the TVA machines shown and the other machines were quite similar to case 2. The change in frequencies was nearly the same as the previous two cases: $\Delta f_u = 1.1$ hertz and $\Delta f_p = 0.6$ hertz. The response of the TVA network itself is therefore not strongly dependent on very far-away perturbations once the adjoining areas are perturbed. Thus as the size of the disturbed area is increased, the effect on the interior of the perturbed area "saturates" so that the response there does not change greatly.

4. Dependence of the Response on the Effective Impedance Z

In the examples presented above, the effective impedance Z_i from the distribution bus $\tilde{D}$ to each transmission bus T_i was set at 10%. Other stability calculations were made both with different average values of the effective impedance and with all Z_i randomly chosen between fixed limits. There was minimal difference between the responses of cases with randomly selected Z_i, and cases with all equal Z_i when the average of the Z_i of the former case was the same as Z of the latter.

Figures 20 and 21 show the swing curves for fault set $\tilde{F}$ given in Table 1. The fault duration time was 0.2 sec, and the fault density and area were identical to $\bar{F}$ in case 1, except the Z_i's were chosen randomly between 10 and 20% with the average value of 15%. Comparison should be made with Figs. 12 through 15.

All of the machines remained in synchronism during the transient period, including those which lost synchronism in case 1 when Z was equal to 10%. Note, however, the very large amplitude of oscillations of some machines, e.g., on bus 1546, indicating that these machines were strongly affected and nearly lost stability. The change in the frequency of the unperturbed area was about the same as case 1 ($\Delta f_u = 0.95$ hertz).

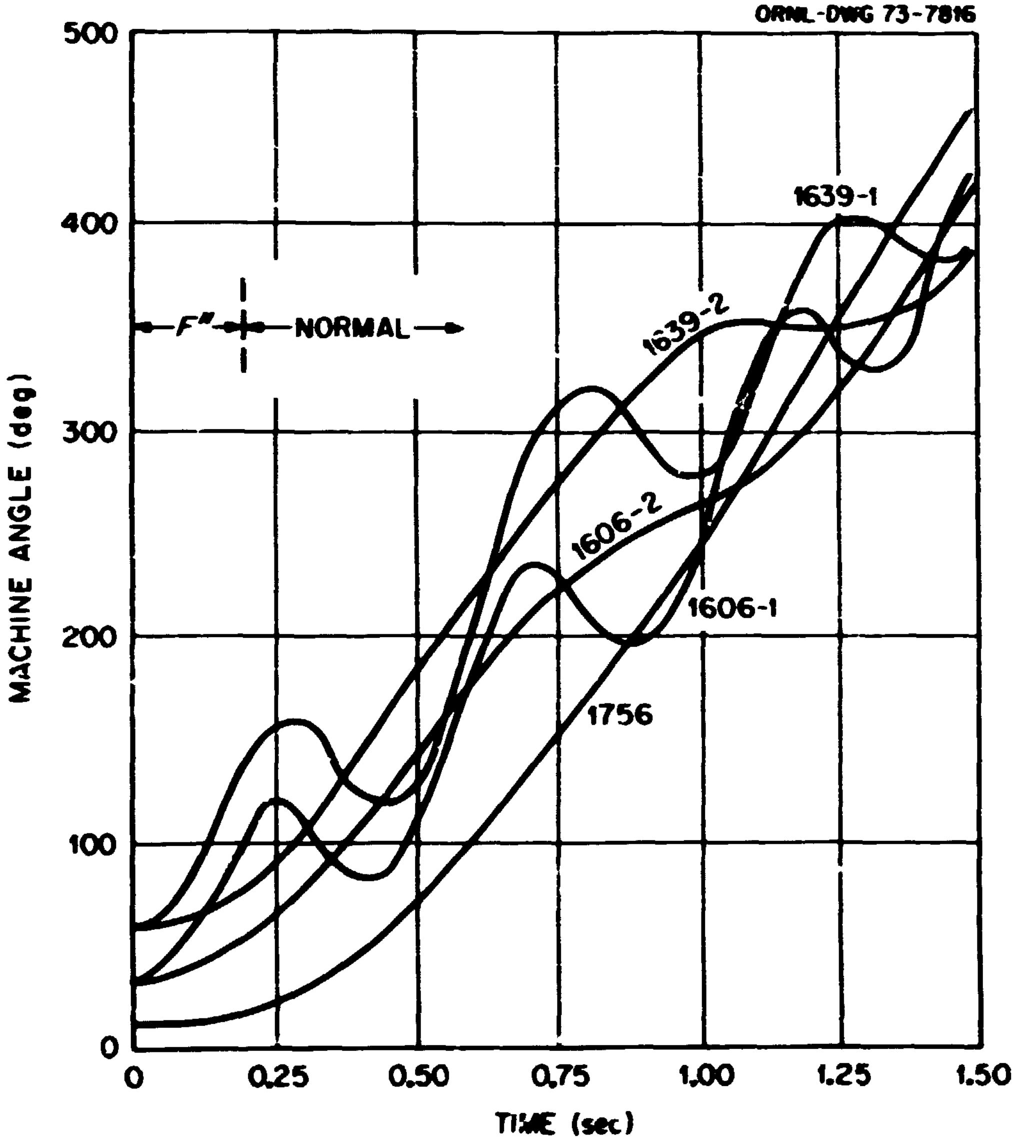

Fig. 19. Swing Curves for a Single Occurrence of Fault Set F'' for Machine Group No. 1.

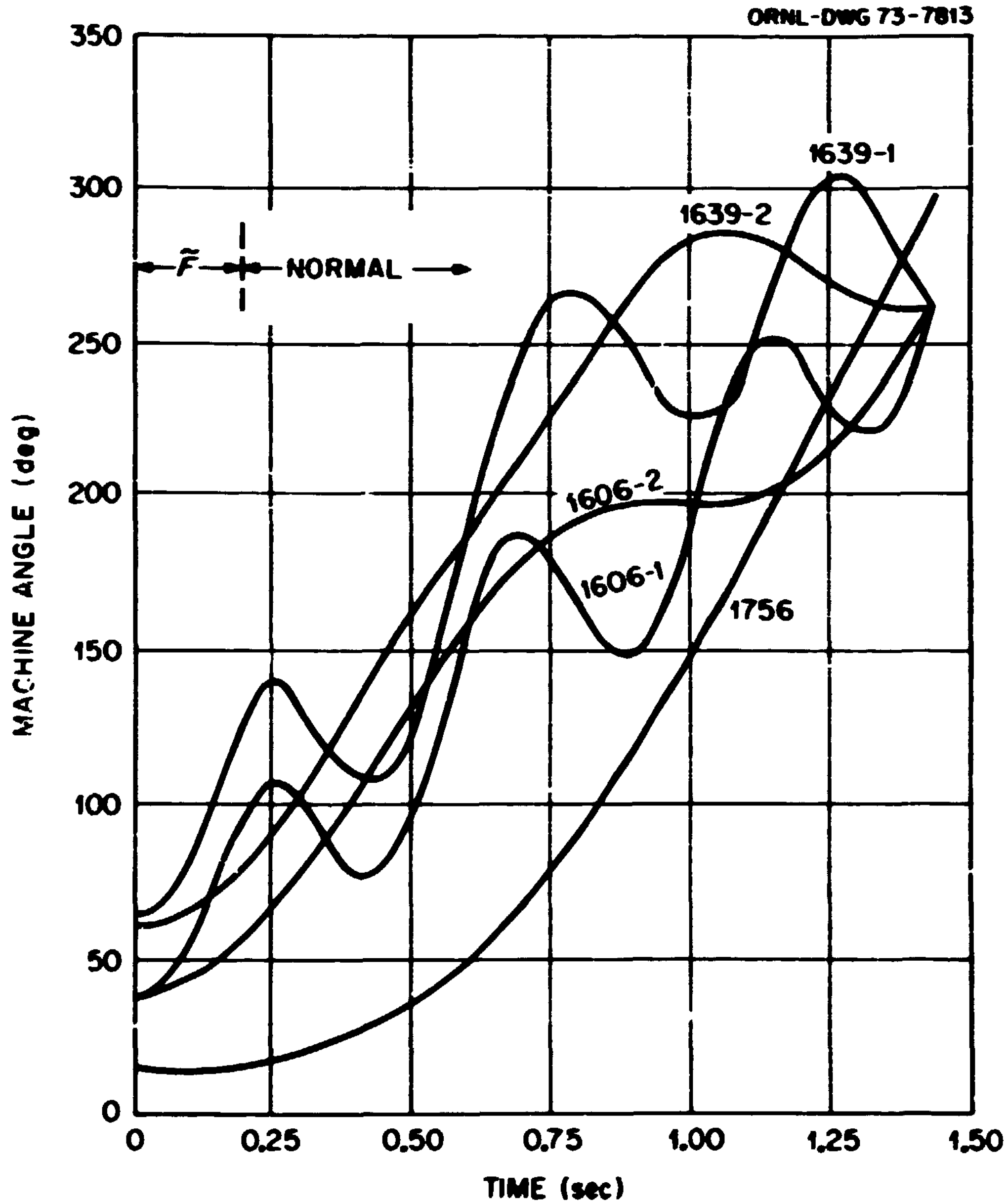

Fig. 20. Swing Curves for a Single Occurrence of Fault Set F for Machine Group No. 1.

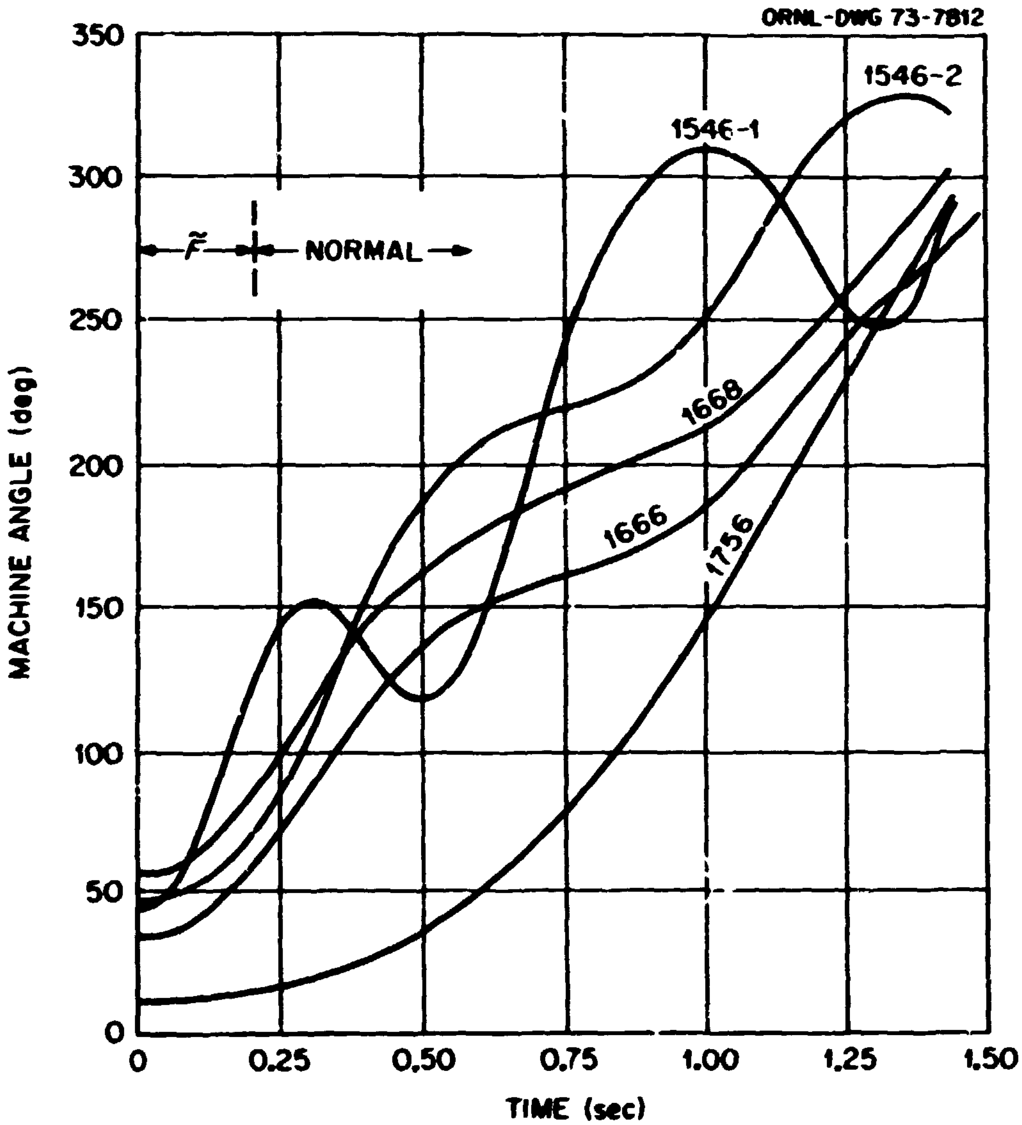

Fig. 21. Swing Curves for a Single Occurrence of Fault Set $\tilde{F}$ for Machine Group No. 2.

For a single pulse perturbation, the effective impedance strongly affects the system response, as one would expect. By changing Z_{eff} from 10 to 15%, the system kept in synchronism much better. Consequently, if EMP produced faults only on the very low voltage lines (which have a much greater impedance to the transmission lines) and not close to the major substations, then the effects of EMP on the transient stability would certainly be less severe.

5. Dependence of the Response on the Time Duration of the Faults

The duration of EMP-induced faults should be about 0.2 second since the distribution relays take this long to initially open. However, one stability run was made with fault set $\widetilde{F}$ of Table 1 applied for only 0.12 second in order to determine the dependence of the response on the fault duration time. A typical set of swing curves are shown in Fig. 22. The machines remained in synchronism much better than for the longer fault duration as one would expect for the shorter fault time. Yet some of the machines had large amplitude oscillations, indicating that they nearly became unstable. Clearly, a rapid clearing of faults is desirable; unfortunately, the longer (0.2 second) fault duration time corresponds more closely to present actual relay times. The more realistic time (0.2 second) was used in the remaining calculations.

C. THE RESPONSE FROM REPETITIVE SETS OF MULTIPLE PULSES

In the previous section the response to a single set of multiple faults was calculated. We presently turn to repetitive sets of multiple faults. Since the occurrence of two or more sets of repetitive faults introduces several new variables such as the number of pulses and the time separation of the pulses, the problem must somehow be simplified. If our study is limited to the transient response of the network, then quite natural restrictions can be applied to the parameters. For instance, with this limitation we are not interested in two or more

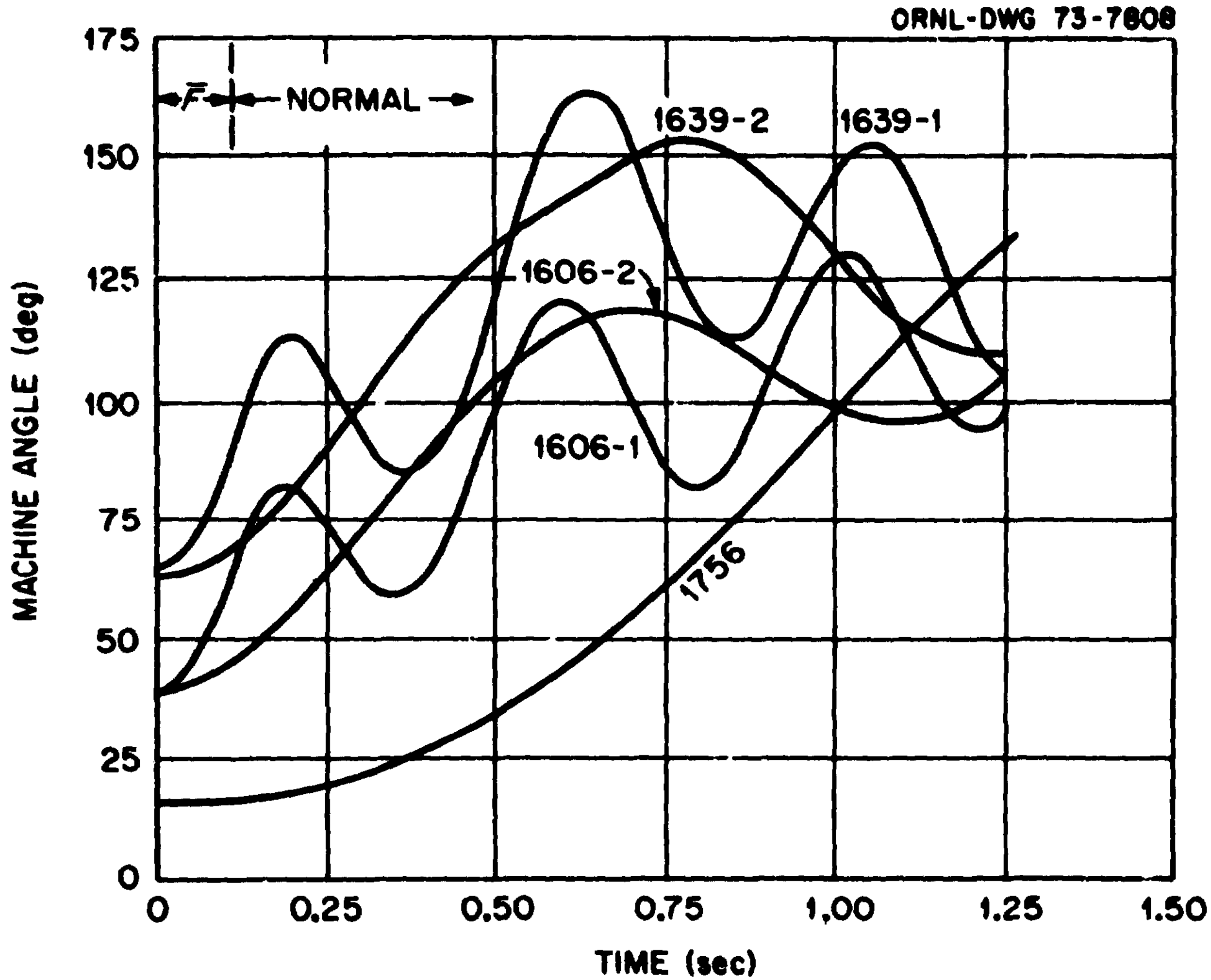

Fig. 22. Swing Curves for a Single Occurrence of Fault Set F̄ for Machine Group No. 1 with a Duration of 0.12 Second.

pulses separated by a time greater than the transient and dynamic response times, i.e., in pulses separated by a time greater than that for the system to return to equilibrium. The reaction of the system to such widely separated pulses would be no different from its reaction to individual single pulses.

Multiple pulses all occurring within the transient time period will produce the most serious perturbations, and we will henceforth limit this study to such cases.

The mechanical design of the distribution relays provides a similar limitation on the new parameters introduced by the multiple pulses. The relay design was previously discussed in detail in Section A. It was noted that a second EMP pulse occurring after the initial reclosing of the relays could refault the lines. The relays would then activate and reopen a second time about 0.133 second after the occurrence of the second set of faults. They would remain open for about one second before again reclosing. A third EMP pulse occurring shortly after the second closing would lock the relays open until manually reclosed. If the third pulse occurs before the second reclosing, the relays will already be open so the lines probably will not refault. We further simplify the problem in studying the transient behavior by representing multiple pulses by a 2-pulse model, with each pulse occurring within a second of each other. Such a simplification is necessary since the stability program cannot faithfully calculate the system response much beyond 1.5 seconds after the initial perturbation unless the dynamical controls are modeled which was beyond the scope of this study. However, this 2-pulse model should determine the primary disturbance from multiple pulses, and the pulse parameters are then conveniently restricted so that they are within manageable ranges.

Using the above simplifications, a representative double pulse was chosen to model the primary effects of multiple pulses. The first fault was chosen to have a time duration of 0.2 second (for the same reasons as in the single pulse cases, i.e., the relays take this long to initially open). Then the network was left unfaulted for the next 0.3 second. The second set of faults was then applied (after 0.5 second from the initiation of the perturbation) for a duration of 0.15 second. The second fault duration time is shorter than the first because the relays respond more rapidly on the second opening. In summary, a double pulse of chosen fault density and area of coverage was used. The system was faulted for 0.2 second, back to the unfaulted configuration for 0.3 second, faulted for 0.15 second, and finally back to the unfaulted configuration (at 0.65 second). We refer to this configuration as the standard double pulse.

The intermediate time between the two pulses was later varied to see if the response would differ significantly. The response did not greatly change for somewhat longer separation times between pulses.

1. A Double Pulse Applied to the TVA Area

Fault set $\bar{F}$ of Table 1 was used in the standard double-pulse configuration previously described. Typical swing curves are shown in Figs. 23 through 26. The effect of the perturbation was much worse than of the single-pulse perturbation of the same fault set (case 1 of Section B). Many more TVA machines lost synchronism. In particular, Fig. 25 shows a much greater angular spread in δ of the TVA machines than occurred in the equivalent single-pulse case (Fig. 14).

The average frequency increase of the stable TVA machines, Δf_p was 4 hertz, more than four times greater than for the single-pulse case: Δf_u = 1.4 hertz. In contrast to the frequency increase of machines which remained in synchronism, a typical frequency increase of a machine losing stability was 15 hertz. Such an increase would definitely trip the overspeed relays of the generator.

Figure 26 shows a distinct separation between perturbed and unperturbed area machines (see Table 2 and Fig. 16 for a list of the machine areas). This separation is merely a consequence of the difference in Δf_p and Δf_u, which is much greater than for the single-pulse case.

2. A Double Pulse Applied to a More Extensive Area

In order to determine the effects of increasing the size of the perturbed area while keeping the fault density of the perturbed area

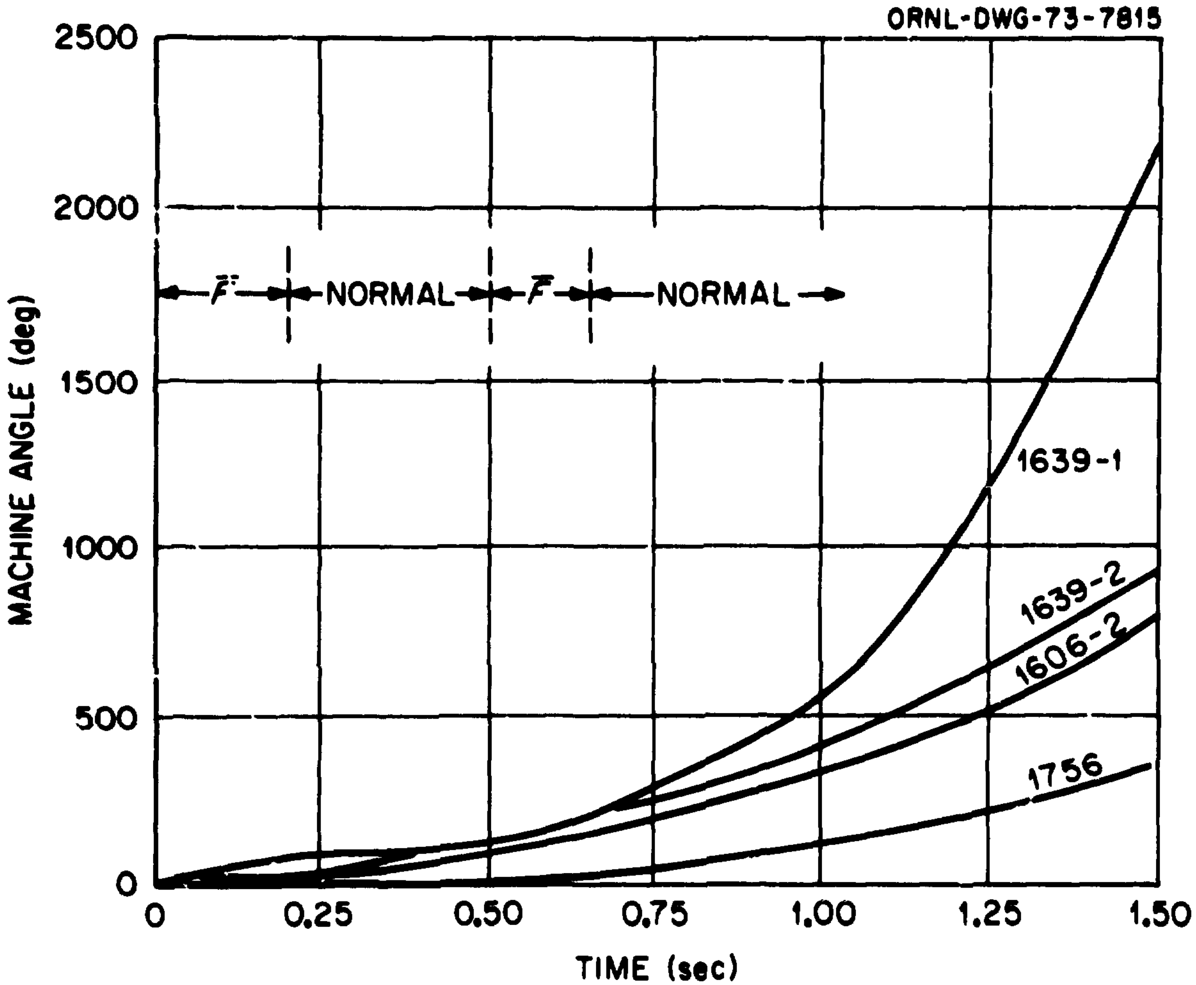

Fig. 23. Swing Curves for Two Occurrences of Fault Set $\bar{F}$ for Machine Group No. 1.

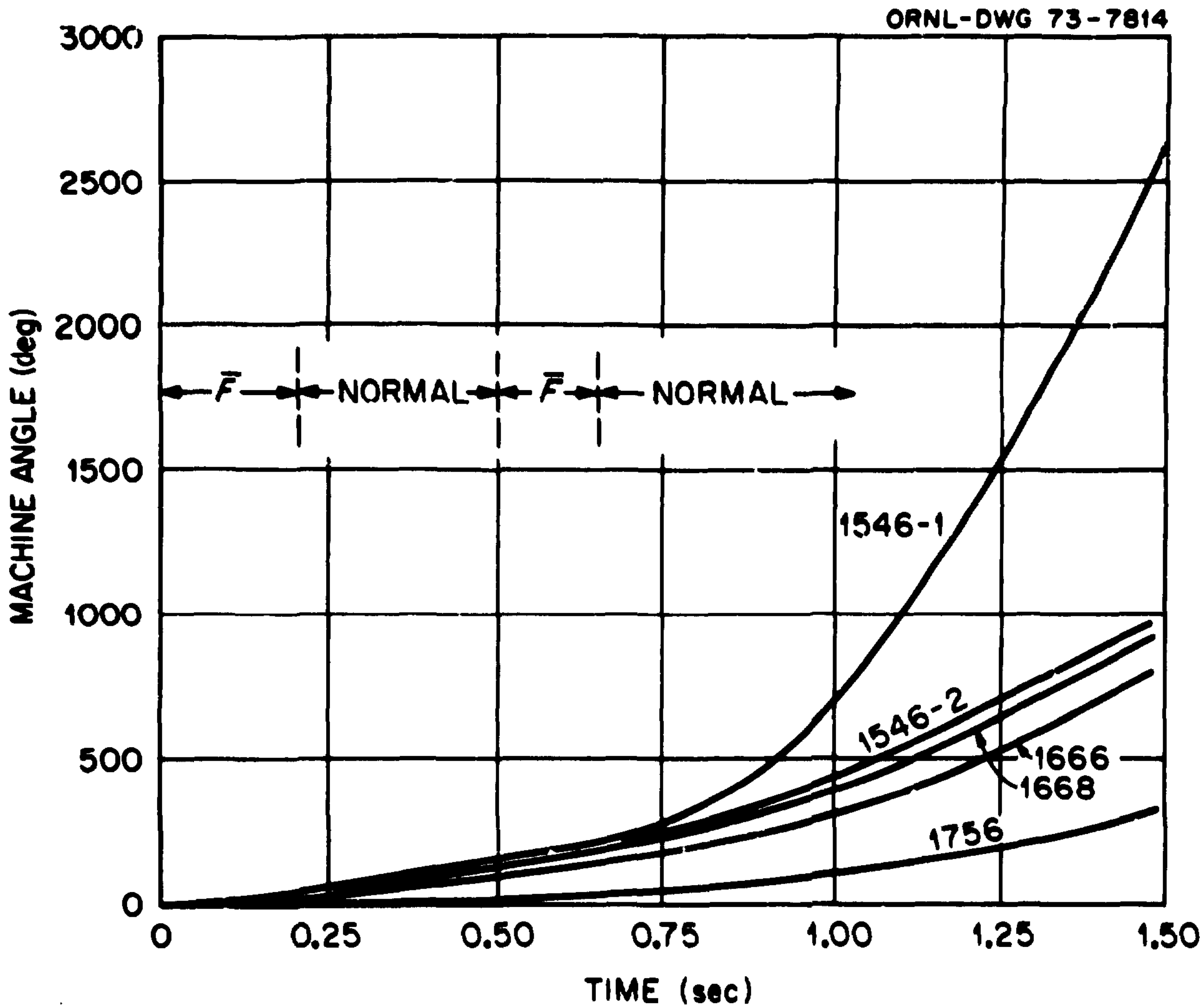

Fig. 24. Swing Curves for Two Occurrences of Fault Set F̄ for Machine Group No. 2.

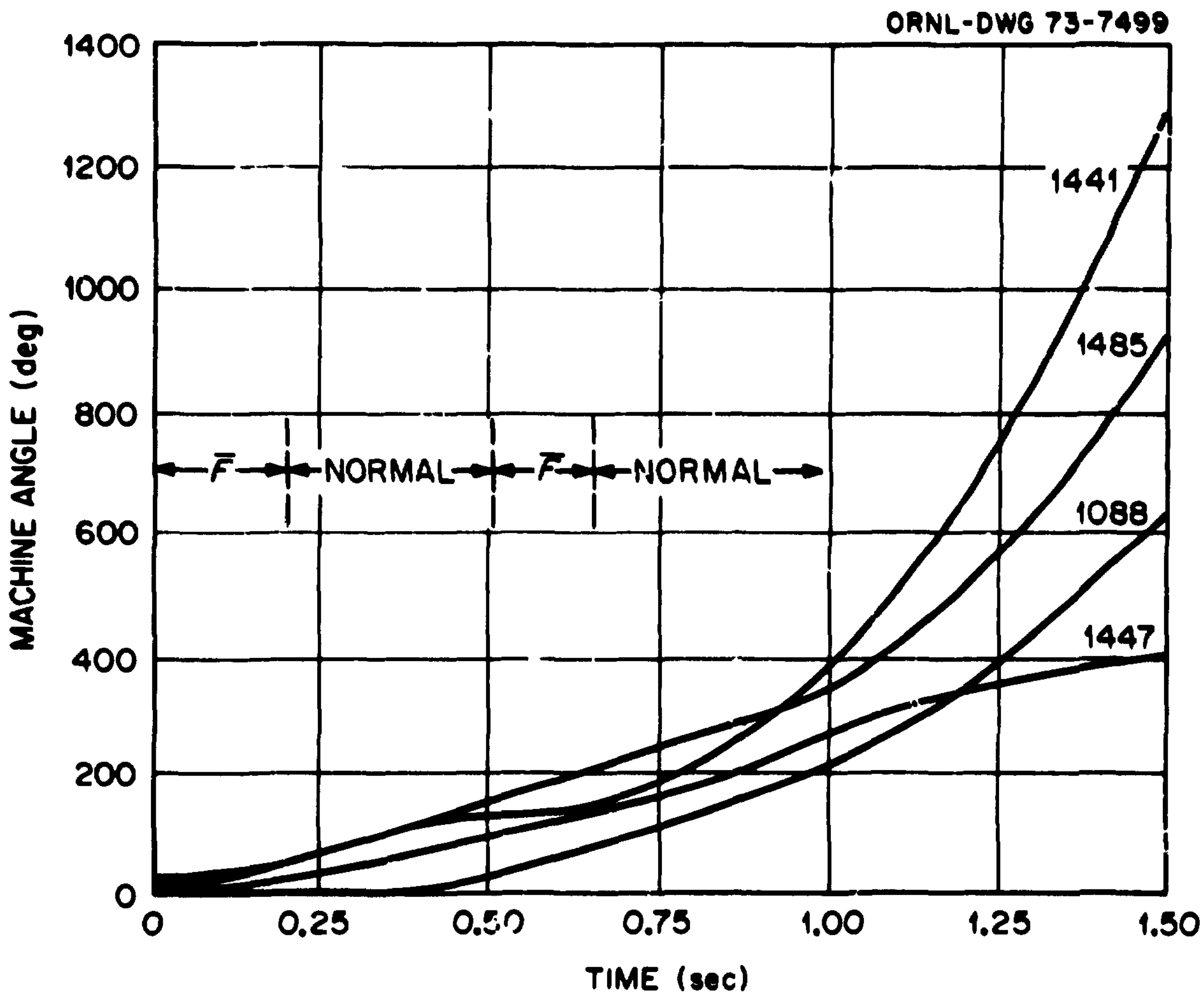

Fig. 25. Swing Curves for Two Occurrences of Fault Set $\overline{F}$ for Machine Group No. 3.

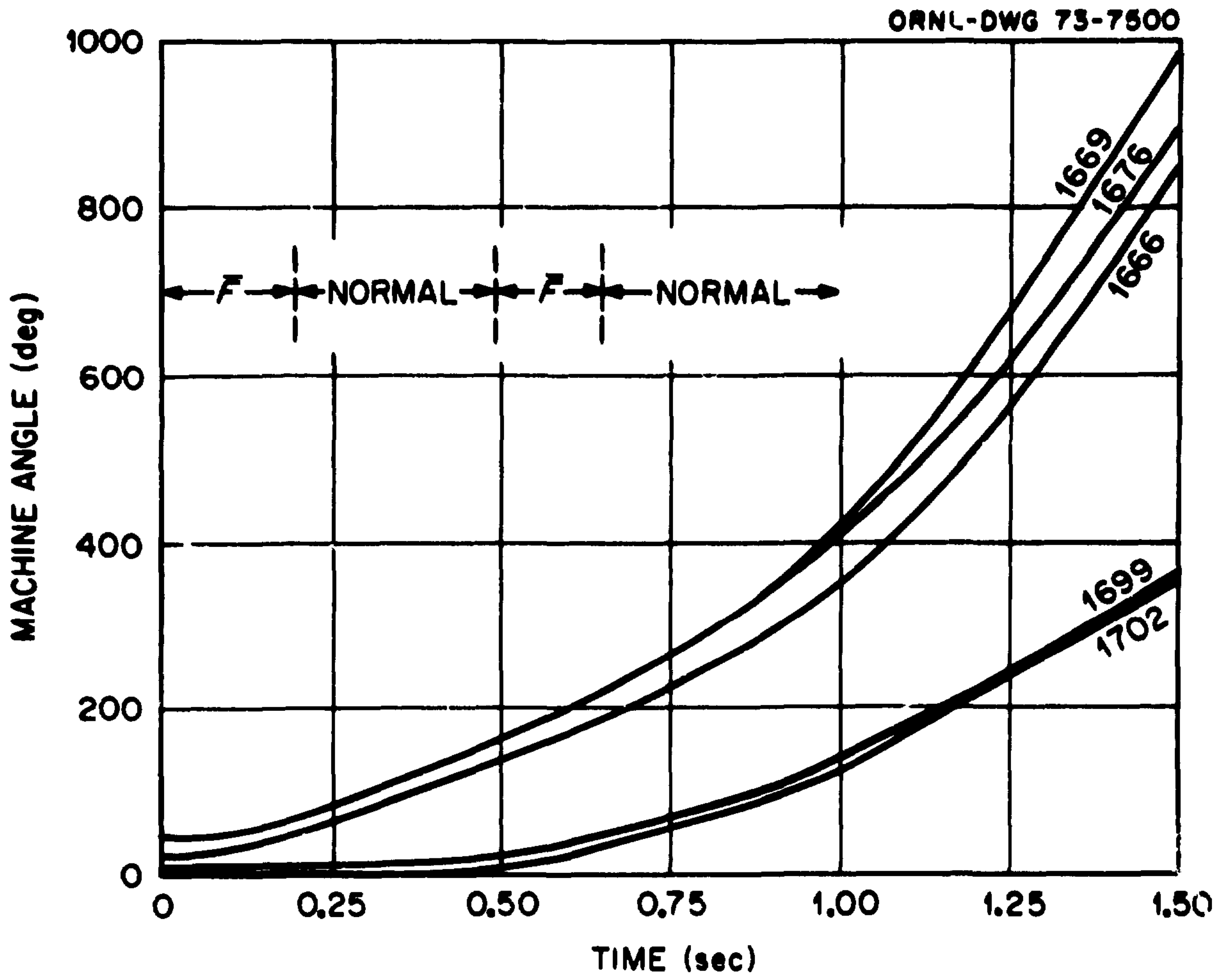

Fig. 26. Swing Curves for Two Occurrences of Fault Set $\overline{F}$ for Machine Group No. 5.

constant, fault set F′ was used in the double-pulse configuration. The comparative single-pulse calculation was given in Section B, case 2. Again, as in the single-pulse case of larger area coverage, the perturbed and unperturbed areas remained in synchronism much better, with fewer generators losing synchronism (compare Fig. 30 with Fig. 26). Only bus 1639 badly fell out of step. The increase in the average perturbed and unperturbed frequencies was $\Delta f_p = 2$ hertz and $\Delta f_u = 1.4$ hertz respectively, both nearly twice as great as for the single-pulse case. But Δf_p was much smaller for fault set F′ than for set $\bar{F}$.

In particular note the remarkable difference in the behavior of the group of machines shown in Figs. 25 and 29. In Section B, case 2, a simple explanation was given for the improved response from the perturbation of larger areas. This improvement suggests that the transmission system would be more stable to EMP-type perturbations if the adjacent transmission groups were not tied together. A test of this hypothesis will be given in the following example. In any case, the machine control system must be able to damp the large frequency increases if the system is to remain stable during the dynamic time period.

3. The Effect of Opening the Tie Lines Before Application of the Perturbation

The original set of faults, $\bar{F}$, was again used in the double-pulse configuration to perturb the TVA area as in case 1. However, the major tie lines connecting adjacent networks were opened before the faults were applied to see if the perturbed area's stability was improved. It was hoped that the opening of the tie lines might eliminate the interference between the perturbed and unperturbed areas and improve the stability. If this interference causes the loss of synchronism, then the effect of opening tie lines should be similar to that of perturbing a larger area as done in case 2.

In all, seven major tie lines were opened immediately before the perturbation was applied. (It was impractical to open all tie lines, but all high voltage, 500 kilovolt, connections were opened.) Although some local areas were affected by the tie line opening, in general, the system was not severely disturbed.

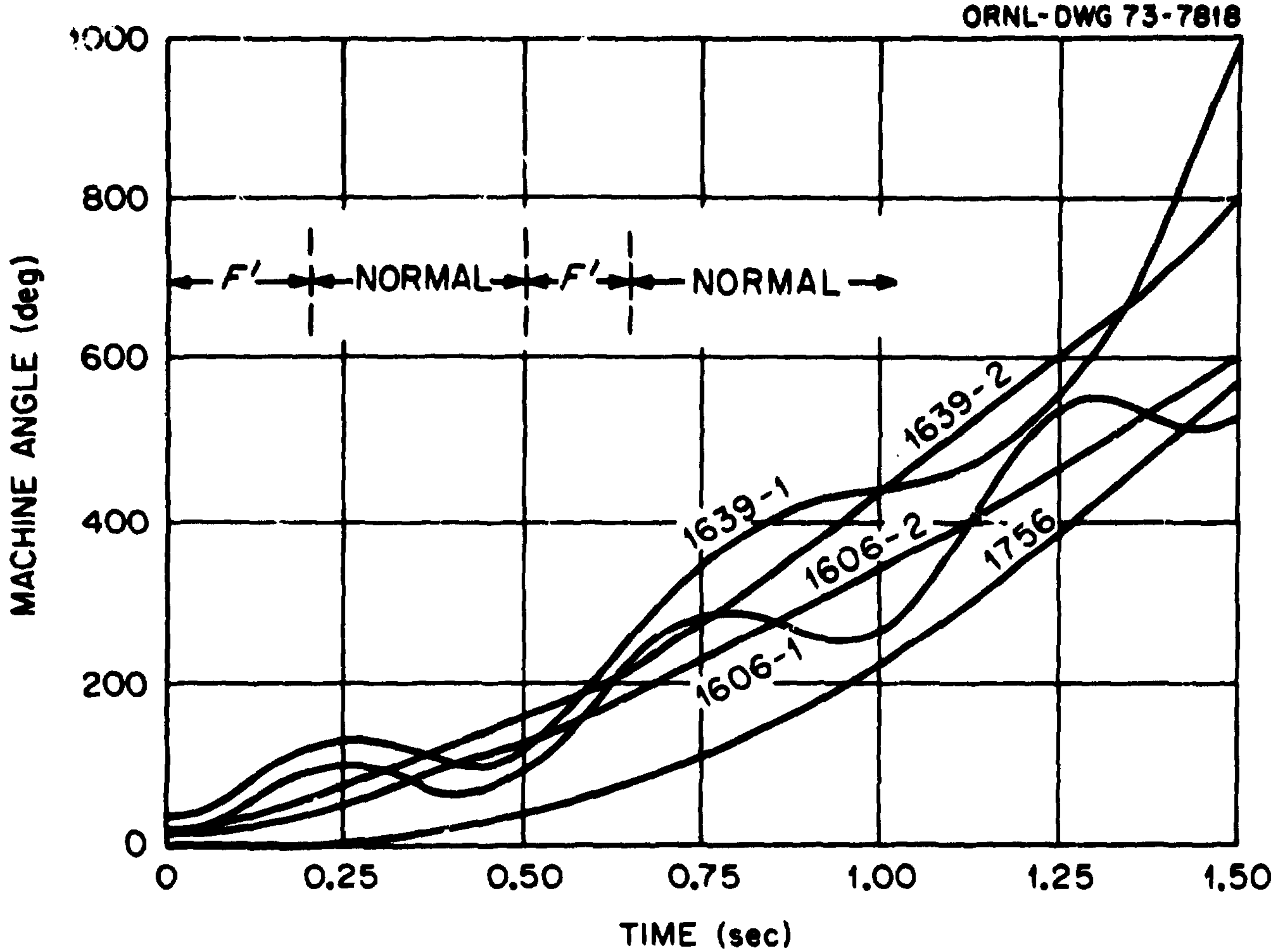

Fig. 27. Swing Curves for Two Occurrences of Fault Set F′ for Machine Group No. 1.

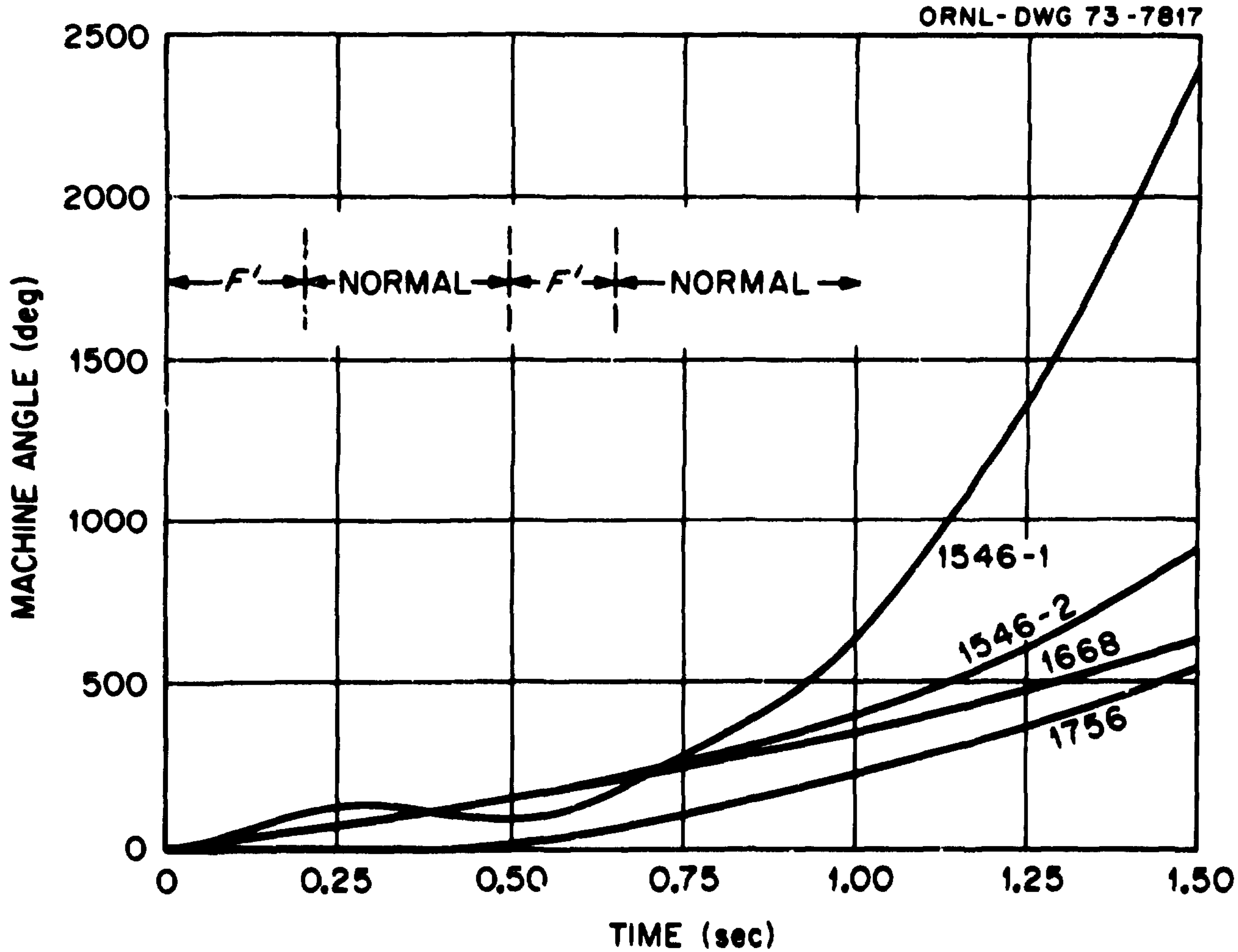

Fig. 28. Swing Curves for Two Occurrences of Fault Set F′ for Machine Group No. 2.

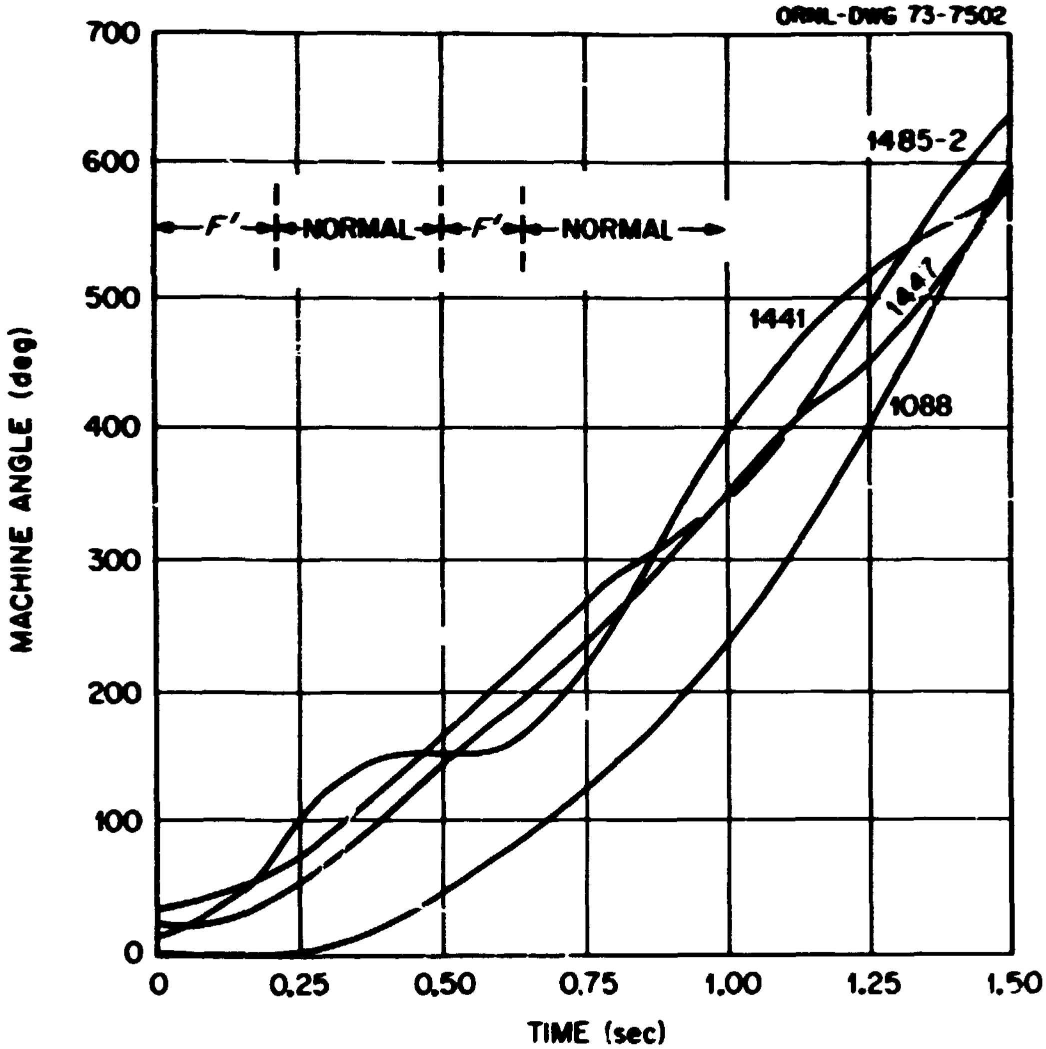

Fig. 29. Swing Curves for Two Occurrences of Fault Set F′ for Machine Group No. 3.

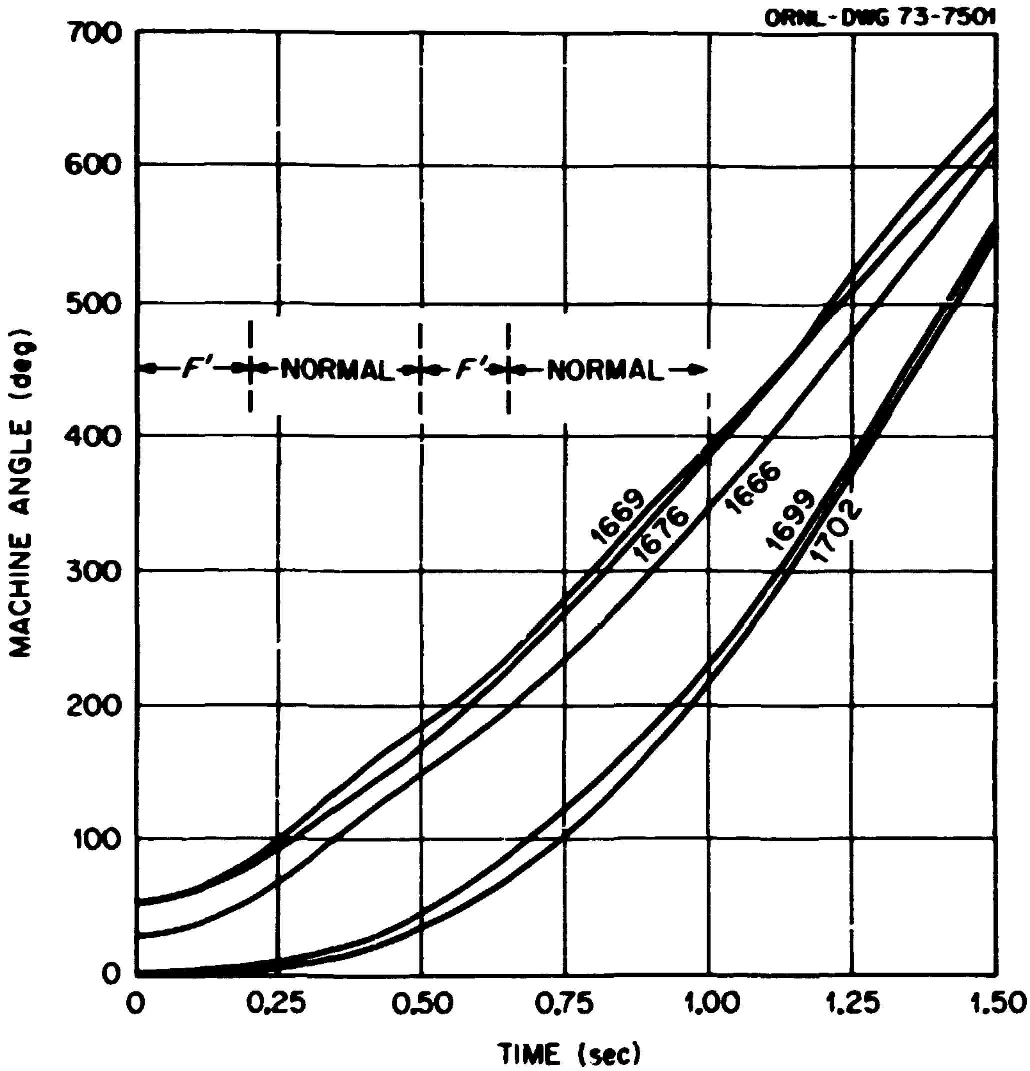

Fig. 30. Swing Curves for Two Occurrences of Fault Set F′ for Machine Group No. 5.

Figures 31 and 32 show the results of the double pulse during fault set $\bar{F}$, except with the major TVA tie lines open. The TVA system held together much more strongly than in the comparative case with the tie lines closed (compare Fig. 31 and Fig. 23 and Fig. 32 and Fig. 26). Only one major TVA machine (not shown) lost synchronism. Both figures illustrate that the TVA network swings separately from the unperturbed area, as one would expect since the two areas are no longer connected. (This also shows that the removal of solely the high voltage tie lines is sufficient to remove most of the interaction.) The frequency change Δf of the perturbed and unperturbed areas can now differ greatly since there is no interaction between them. The average frequency increase for the TVA machines was $\Delta f_p = 4$ hertz with the tie lines open. This is not too much greater than for the case when the tie lines were closed (then $\Delta f_p = 3$ hertz).

In summary, a multiple-fault perturbation has a much less severe effect on the perturbed area when there are no unperturbed areas connecting and interacting with it. This partitioning of the system by the opening of tie lines before EMP severely perturbes the system may provide a means of minimizing the effects of EMP on the transmission system.

4. The Dependence of the Response on the Effective Impedance

The dependence of the response on the effective impedance was discussed in Section B, case 4, using a single pulse. We now present the results for the double pulse using the same set of faults and effective impedances. The fault set $\tilde{F}$ previously defined was used. Figures 33 and 34 show typical swing curves. In contrast to the single-pulse case, this double-pulse case using the larger effective impedance set $\tilde{F}$ did not differ substantially from the original set $\bar{F}$. The average frequency increases were about the same for both double-pulse cases as was the overall instability.

The single-pulse perturbation was probably more affected by the impedance increase because the system was then just on the verge of

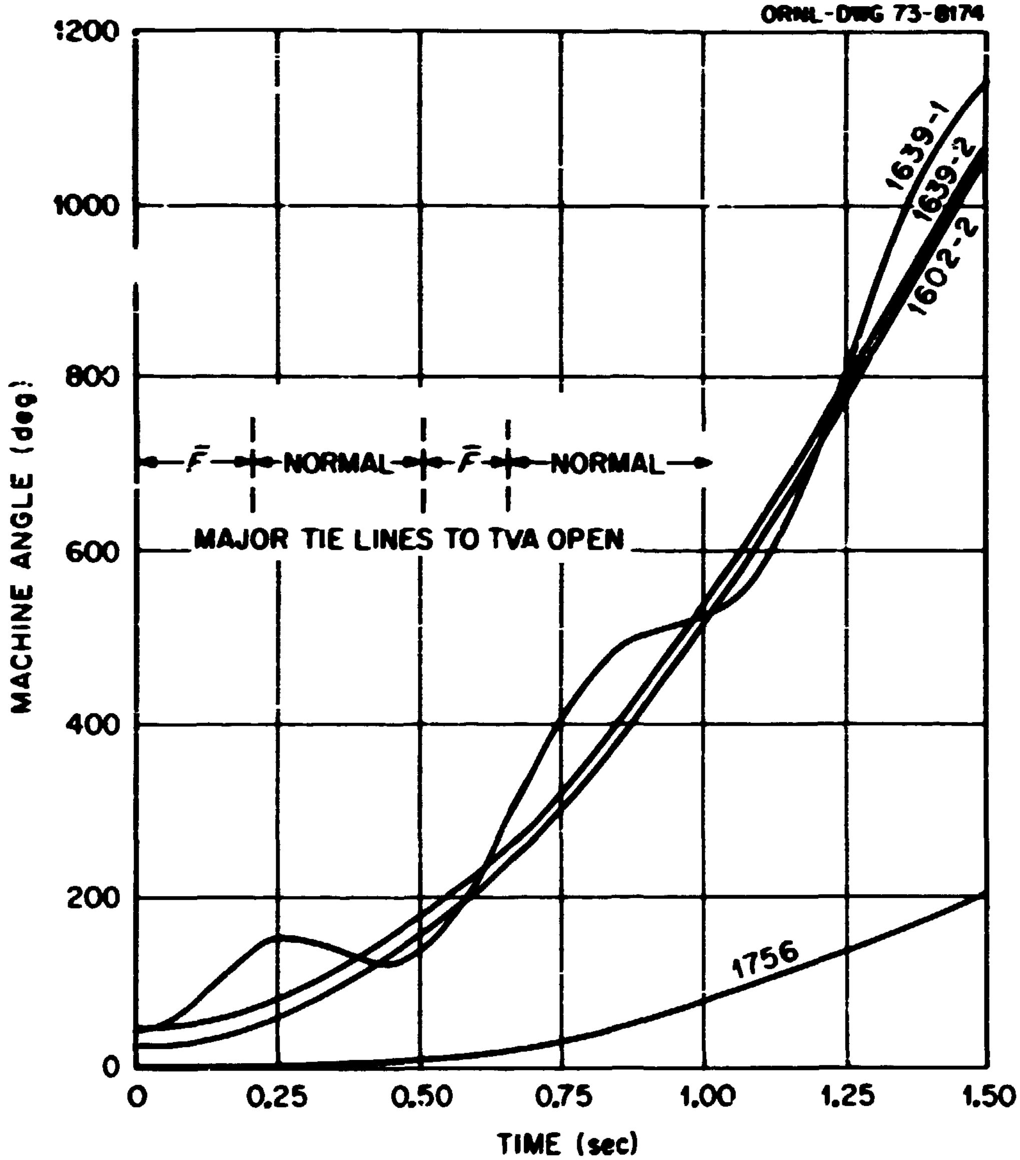

Fig. 31. Swing Curves for Two Occurrences of Fault Set $\bar{F}$ with Major TVA Tie Lines Initially Open for Machine Group No. 1.

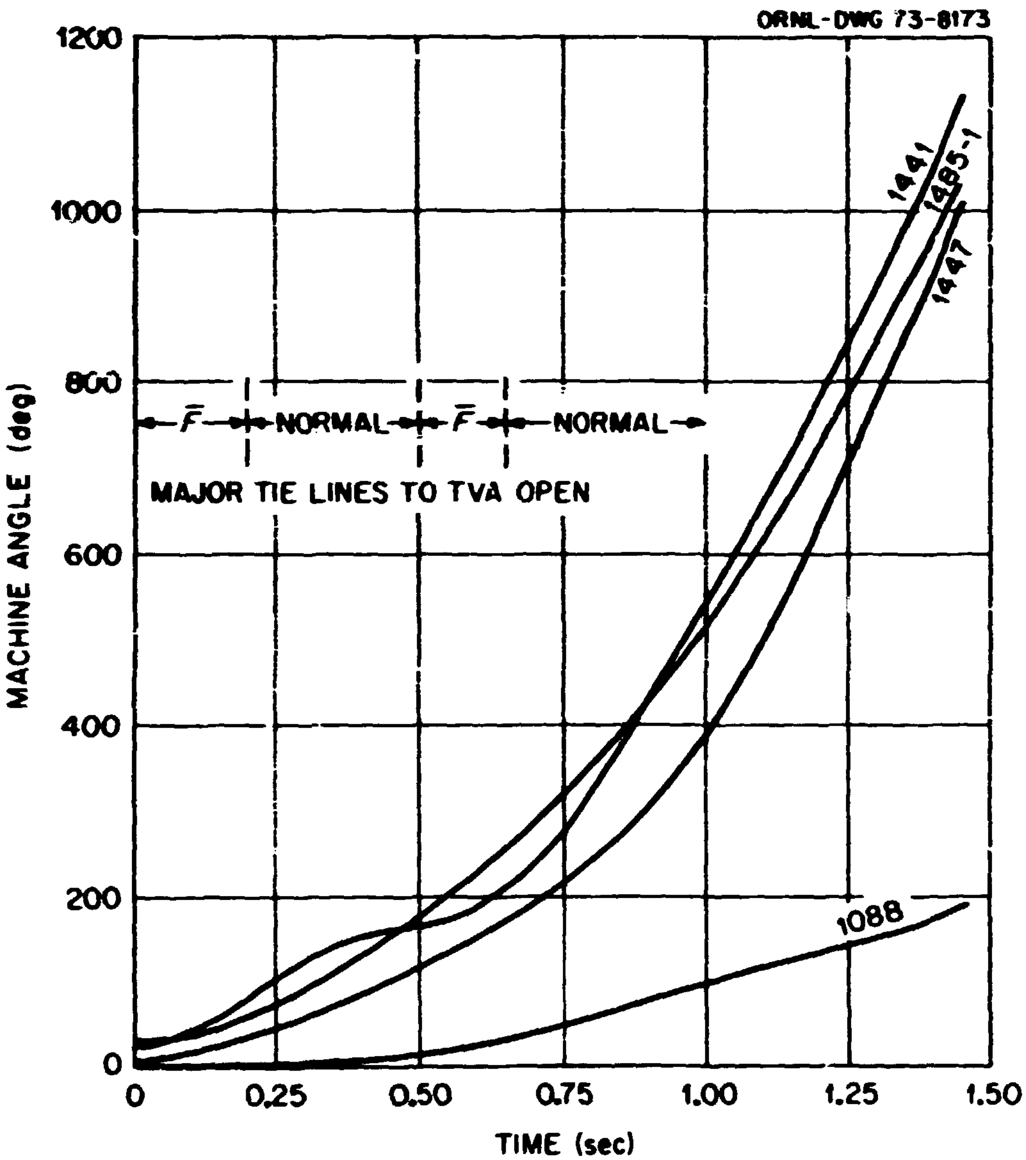

Fig. 32. Swing Curves for Two Occurrences of Fault Set F̄ with Major TVA Tie Lines Open for Machine Group No. 3.

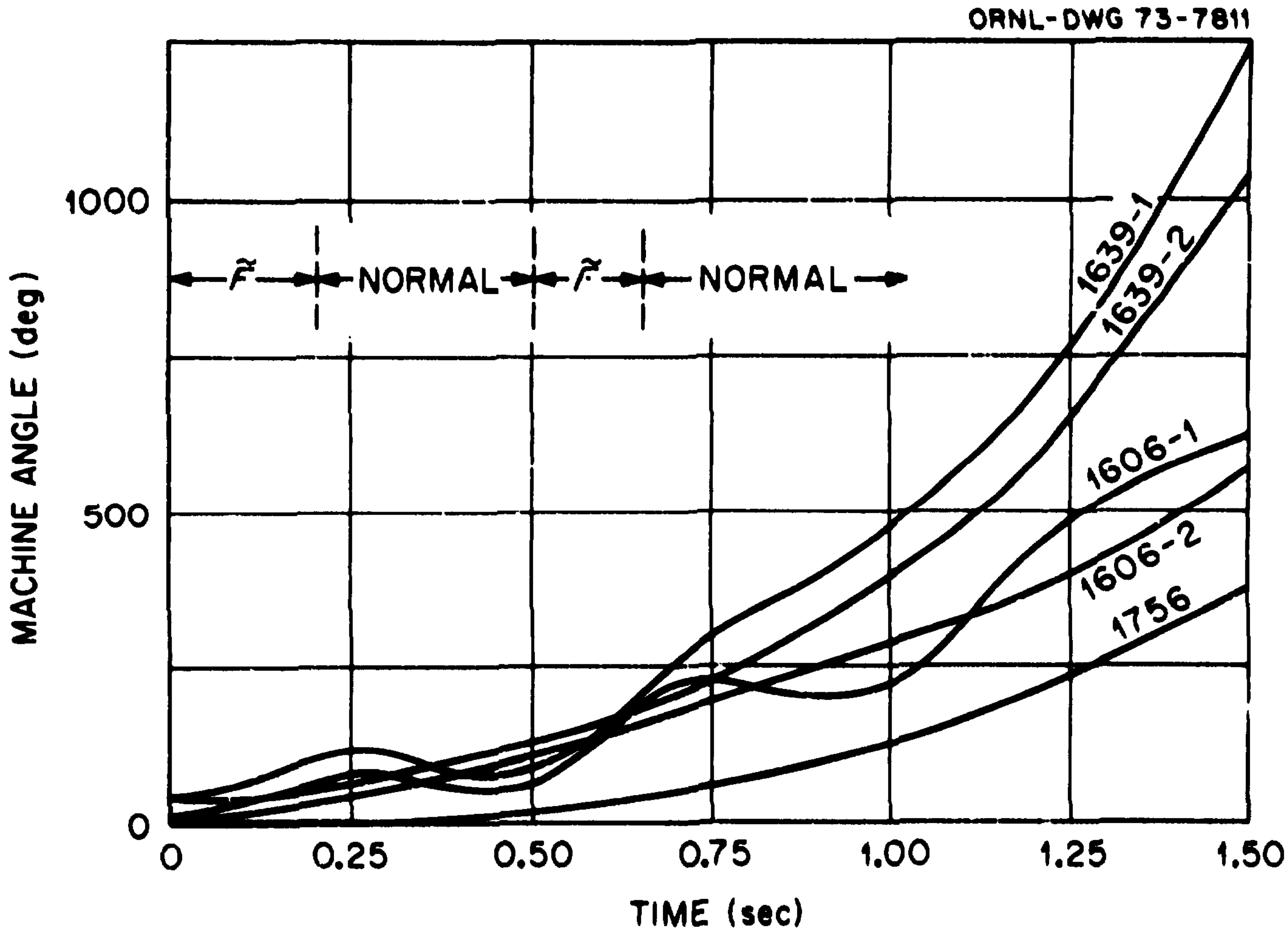

Fig. 33. Swing Curves for Two Occurrences of Fault Set $\tilde{F}$ for Machine Group No. 1.

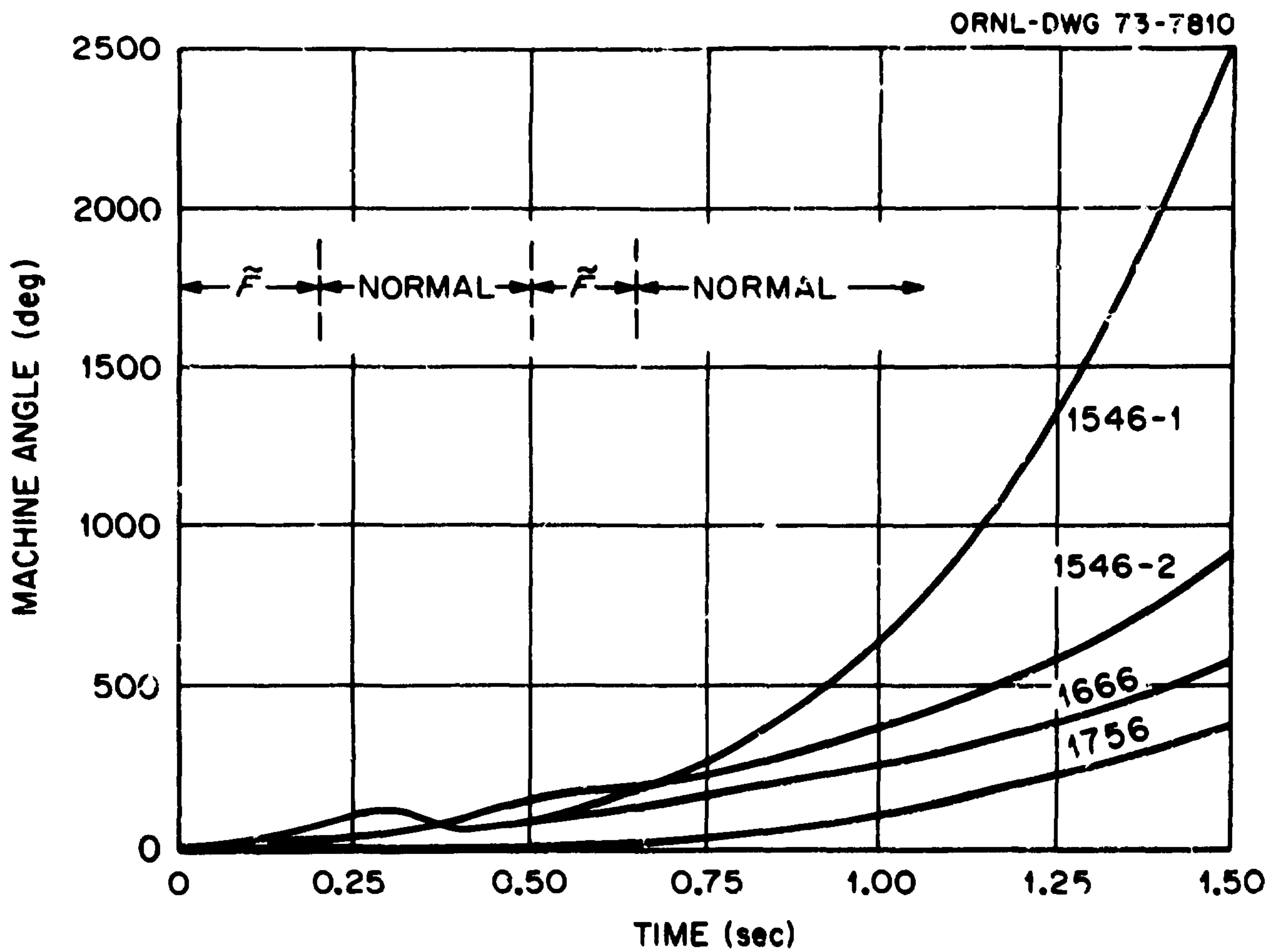

Fig. 34. Swing Curves for Two Occurrences of Fault Set F̃ for Machine Group No. 2.

having major instabilities, i.e., the higher Z perturbation was then about the most severe that the transmission system could experience without having many machines lose stability. But when the perturbation consists of a double pulse, it so disturbs the system that it is unstable even for the larger effective impedance, and consequently the response is not strongly dependent on the impedance in this instability range.

5. The Effect of Major Load Reduction

In the introduction of this section, we discussed how multiple pulses can lock open the distribution system relays until they are later manually reclosed. With the relays open, the load on the isolated lines will be removed from the transmission network resulting in a net reduction of load. Since the generators cannot react instantaneously to such a load reduction, the machines will accelerate. A load reduction will affect the response primarily in the dynamic, rather than the transient time interval. However, stability calculations were made to determine if a major load reduction might exacerbate the instabilities produced by a double-pulse perturbation. The distribution load on a line is removed whenever the relays are open to isolate that line. Since the clearing time following the first fault is shorter than that following the second, it is reasonable in our model to reduce the load after the second fault.

The standard double-pulse perturbation was applied to the network using fault set $\overline{F}$, and the load was reduced on a chosen subset of transmission buses after the removal of the second fault set (at 0.5 second). The important variable is the fraction of load reduced, and the results do not vary greatly for a reduction in load on different sets of transmission buses as long as this reduction occurs over a reasonably large area (and not on just a few buses!). Figures 35 and 36 show typical swing curves for a 30% reduction on bus set F′, i.e., on areas 10, 12, and 13 of Fig. 16. About 11,000 megawatts of load was removed uniformly over a multi-state area. After 1.5 seconds, the increase in average system frequency was about the same (just a little more) as the comparative double pulse with no load shedding (Section C, case 1). Surprisingly some machines seemed to swing together better than in the comparative

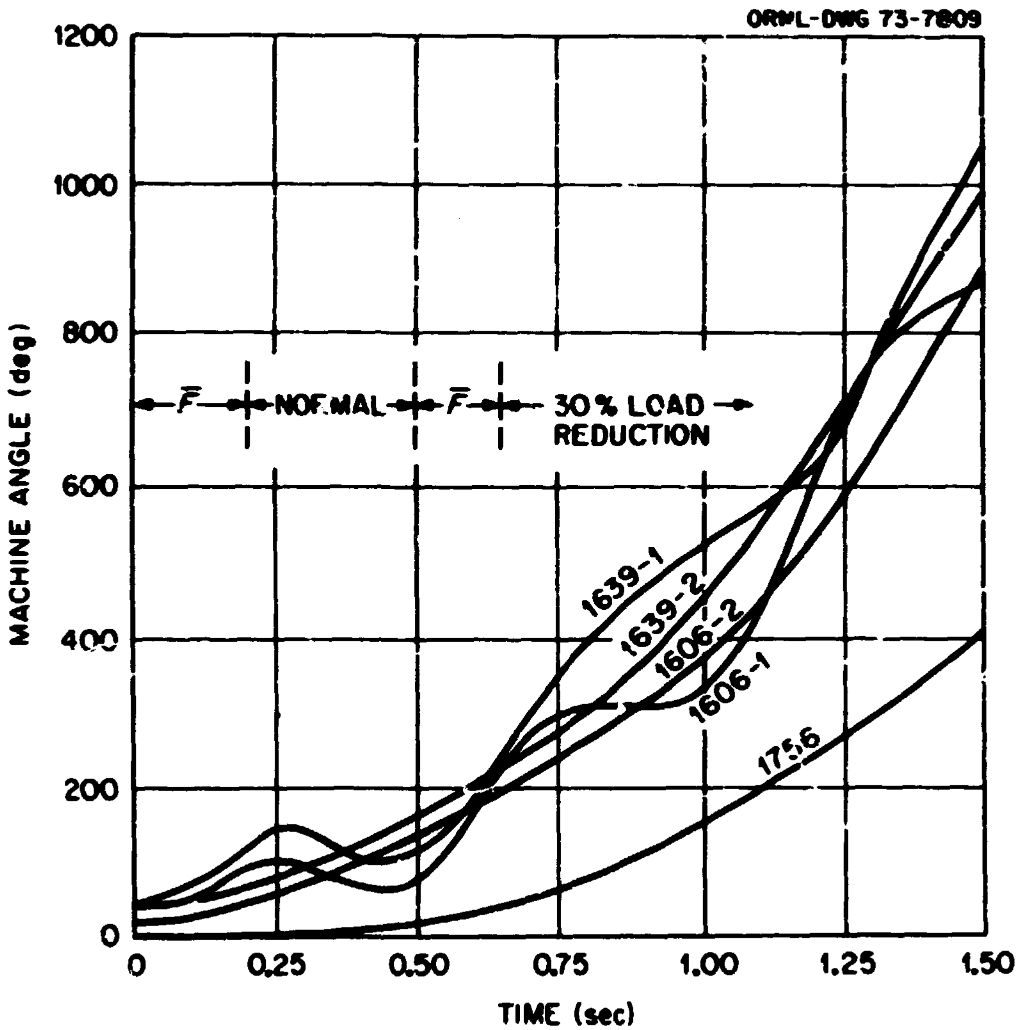

Fig. 35. Swing Curves for Two Occurrences of Fault Set F̄, Followed by a 30% Reduction in Load, for Machine Group No. 1.

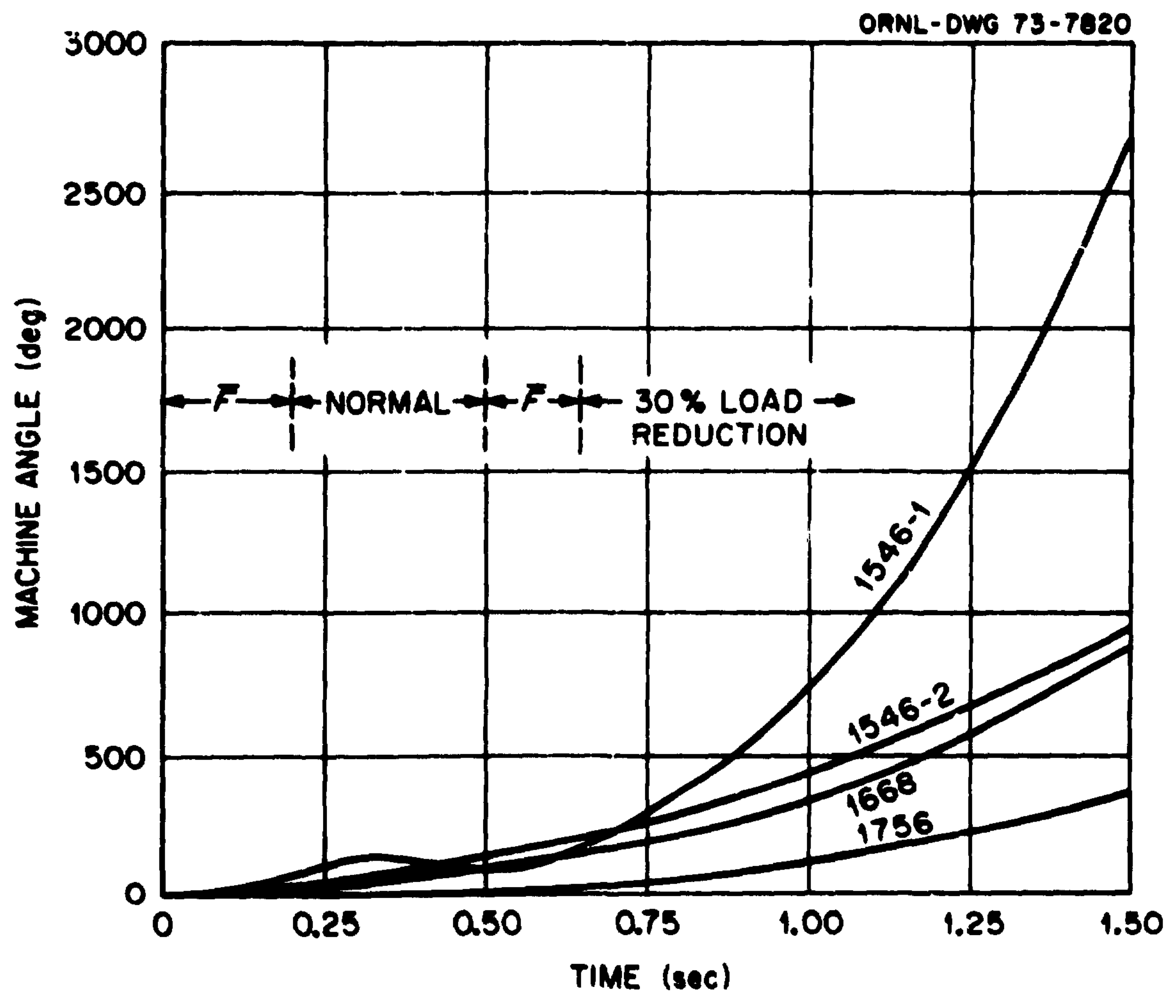

Fig. 36. Swing Curves for Two Occurrences of Fault Set $\overline{F}$, Followed by a 30% Reduction in Load, for Machine Group No. 2.

case with no load reduction, a rather peculiar result since even without load reduction the entire system accelerated considerably. But even though some of the machines were more stable, about the same total number of generators lost synchronism as in case 1.

Apparently a major load reduction does not greatly affect the transient stability, but it may pose a serious threat to the dynamic stability which is beyond the scope of this study to determine. The load reduction results in a frequency increase which differs in principal from that produced by the multiple faults. The latter is caused by the extensive drop in voltage during the duration of the faults, with the average acceleration being reduced after the clearing of the faults. But because of the slowness of generator control action, a uniform load reduction will result in a net accelerating torque on the machines for a longer time, so that the total net frequency increase may be greater. In case 7 below, the frequency increase caused by multiple faults will be compared to that caused by a reduction in generation (which is just the opposite of, but analogous to a load reduction).

6. Effect of Changing the Fault Density

All of the previous calculations of Sections B and C were made using the same fault density in the perturbed area but differed in the size of the perturbed areas, the effective impedances, the number of pulses, etc. Many studies using different fault densities were also made, and we presently give an illustrative example. The representative double pulse was used. The fault density was reduced by randomly removing one-third of the buses from fault set $\overline{F}$ of Table 1, thus reducing the fault density applied to the TVA area to two-thirds of that in case 1 of this section. Figures 37 and 38 show typical swing curves for this case.

The difference in responses of the two cases was not surprising. Some TVA machines remained in synchronism much better for the reduced density perturbation (compare Fig. 27 with Fig. 23), while other machines (Figs. 38 and 24) still fell out of step. The change in average frequency of the TVA machines, Δf_p, was about 1 hertz for the low density

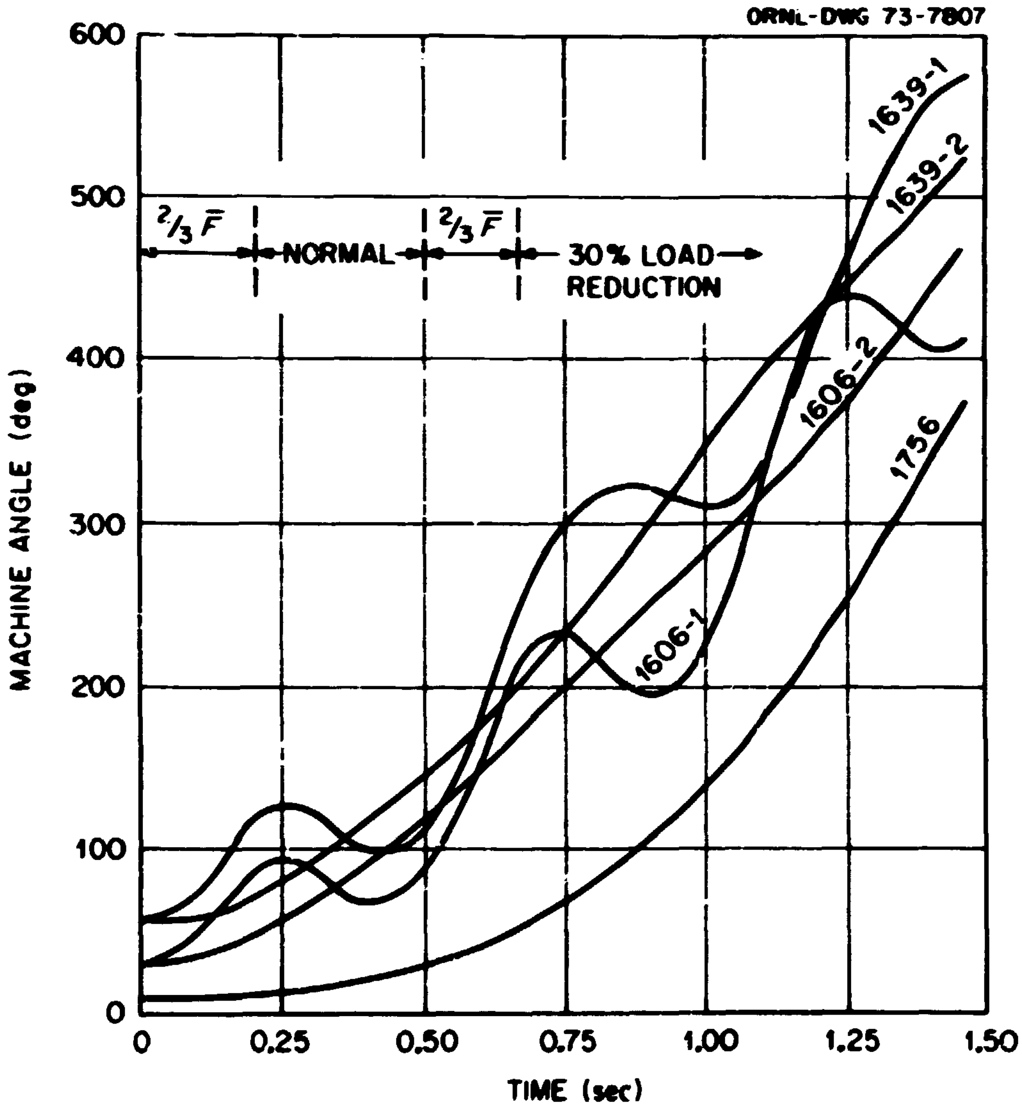

Fig. 37. Swing Curves for Two Occurrences of a Fault Set of Smaller Density, Followed by a 30% Reduction in Load, for Machine Group No. 1.

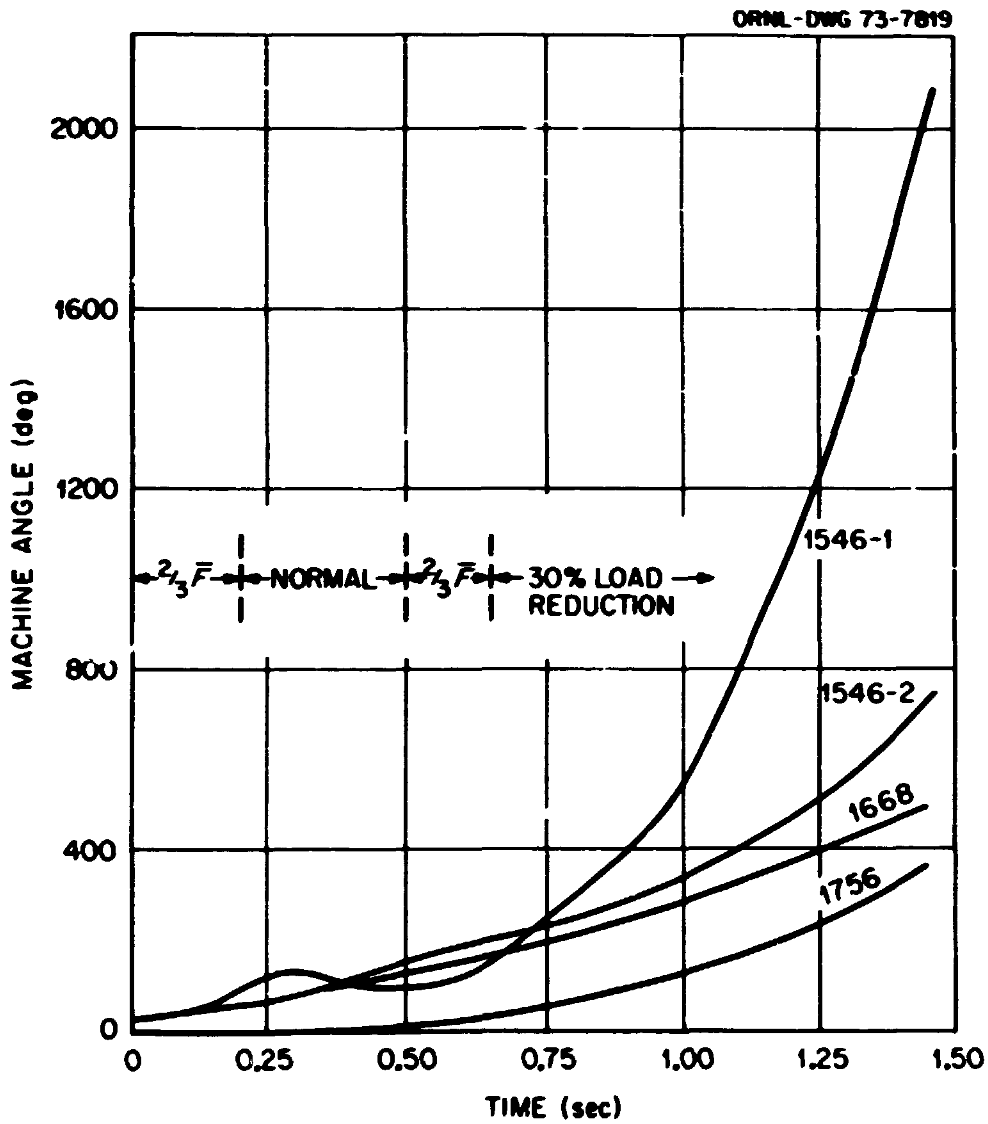

Fig. 38. Swing Curves for Two Occurrences of a Fault Set of Smaller Density, Followed by a 30% Reduction in Load, for Machine Group No. 2.

perturbation as compared to 4 hertz for that of higher density. But the increase in frequency for machines outside of the perturbed area was nearly the same for both densities.

The fault density is certainly an important factor in determining the effect of EMP on the transmission system's stability. Unfortunately it is not presently known what range of fault densities EMP may produce. The density used in the majority of cases of this study should not be too unrealistic if the distribution lines electrically close to major substations are faulted. These calculations would be more realistic if, instead of the sharp cutoff between perturbed and unperturbed areas, the density decreased gradually at the outer boundary of the perturbed area (i.e., the edge of the line of sight of the detonation). The gradual change would occur near the perimeter of the circles of Fig. 2 since the EMP field decreases there for increasing distance from ground zero. However, this modification of the fault density should not change the response significantly; the important parameters are the size of the faulted area and the average density within the faulted area, as previously discussed.

7. The Change in Average System Frequency

Earlier, we briefly discussed how EMP-induced perturbations result in an increase in the average system frequency. It is important to know the seriousness of the frequency increase during the dynamic time period resulting from multiple faults. One measure of the severity of the effect is the decrease in power generation necessary to counteract the frequency increase. But the present stability program cannot reliably calculate the dynamic time period response. A crude estimate of the amount of generation which must be shed to counteract this frequency increase, Δf, can be made by determining the change in frequency for a given change in generation, ΔP_g, i.e., by determining $\Delta f/\Delta P_g$. However, one cannot merely reduce generation by ΔP_g in a particular transmission group (such as TVA) and measure Δf, for then a large amount of power will be supplied by the tie lines (as illustrated in Chapter II, Section A, and Fig. 5).

We used the stability program to estimate $\Delta f/\Delta P_g$ for the dynamical time period in the following manner. First, the principal TVA tie lines were opened. Then a number of TVA generators with known total megawattage ΔP_g were tripped. The swing curves were then linearized and the increase in frequency from equilibrium Δf was obtained from the slope of the extrapolated curves [see Eq. (4.1)] thus giving $\Delta f/\Delta P_g$. One great difficulty in this procedure is that it is difficult to linearly extrapolate the swing curves. After a sudden reduction in generation, the swing curves oscillate about a line of negative slope for only a second or less, but then the curves swing upward, sometimes quite steeply. The upswing occurs because the voltage drops on the machine buses reducing the electrical torque and results in a net accelerating torque.

If the swing curves are linearly extrapolated in the intermediate region before the upswing (i.e., before the machine angles start to increase) and $\Delta f/\Delta P_g$ is determined as described in this section, the following results are obtained. With the major TVA tie lines open, 24% of TVA generation was tripped (6,200 megawatts out of a total of 25,500 megawatts), and the frequency decreased by about 0.55 hertz. This gives $\Delta f/\Delta P_g$ equal to about 9×10^{-5} hertz/megawatt. For a generation reduction of 45% (about 11,000 megawatts) the frequency changes by about 1.1 hertz, which is reasonably proportional to a 24% reduction.

For case 1 of Section B, Chapter IV, this approximation gives the frequency increase from the EMP fault perturbations which would be roughly equivalent to a 30% decrease in the load using the above determination of $\Delta f/\Delta P_g$. Note that in this estimate we have tacitly assumed that $\Delta f/\Delta P_g$ resulting from a reduction of ΔP_g of <u>generation</u> is of the same magnitude (and of opposite sign) as that resulting from a ΔP_g decrease in <u>load</u>. We remind the reader that this is a very crude estimate as illustrated in the following example. If we use the above procedure to estimate the equivalent decrease in load needed to cause the frequency increase of case 1 (Section C, Chapter IV) where $\Delta f_p = 4$ hertz, one would need to terminate about 24,000 megawatts or nearly <u>all</u> of the generation, a clearly absurd result! However, the above estimates may give some indication of the seriousness of the frequency increase in the dynamic time interval resulting from simultaneous multiple faults over a large geographical area.

D. A SUMMARY AND COMPARISON OF EMP-INDUCED AND NON-EMP-INDUCED PERTURBATIONS

We briefly summarize the results of this chapter. Both a single set and repetitive sets of multiple faults severely perturb the transmission system, the latter disturbing the system much more severely than the former. Loss of stability of a significant number of generators in the perturbed area may occur from expected EMP-induced perturbations. The size of the perturbed area is a crucial factor in determining the magnitude of the disturbance of the system. An interaction or interference occurs between unperturbed and perturbed areas which tends to exacerbate the instabilities. Consequently, the system may be more stable if tie lines between perturbed and unperturbed networks are opened prior to the disturbance in order to reduce such interactions. Other important parameters of the perturbations affecting the transient response are the fault density and the effective impedances (determined by the location of the faults).

Two examples of normal perturbations were given in Part 1 of Chapter II, Section A, with a discussion of the differences between EMP-induced and natural perturbations presented in Part 2 of that section. It should be clear that the two types of perturbations are really quite different, as are the responses from the perturbations. Certainly EMP may lead to a cascading type of failure not unlike the Northeast Power Failure. However, the initial EMP-induced perturbation affecting the transient response is quite different. The second example of Chapter II should also be contrasted with EMP perturbations. In the former case, the effects of the power deficit resulting from the loss of generators was greatly reduced by the power transfer from the adjacent networks as illustrated in Fig. 5. Thus the connecting networks help stabilize the system from the local perturbations. However, for EMP-type perturbations, the perturbed area is so extensive that a stabilizing effect from adjacent networks is not nearly as significant. In fact, a significant and destructive interference can result. Consequently, one should not naively compare the effects of EMP-induced perturbations with those of "natural" perturbations.

In conclusion, it is possible that EMP may induce a serious perturbation on the distribution networks which can cause a large portion of the transmission network in the perturbed area to lose synchronism, and consequently result in an immediate and massive power failure.

CHAPTER V

THE LIMITATIONS OF THIS STUDY AND SUGGESTIONS FOR FURTHER WORK

The philosophy of this study was to determine the transient response from EMP-generated perturbations using standard calculational techniques. Because of the limited scope of this report, necessary limitations were made. In this chapter, many of the approximations and limitations are discussed, and suggestions for further work are made.

A. DIFFICULTY IN DETERMINING A REALISTIC EMP-INDUCED PERTURBATION

Many different forms of perturbations were studied in this work. Clearly a large number of parameters are needed to specify the perturbation, all of which are dependent on the nature of the EMP pulse (or pulses) as well as on the coupling mechanism of the EMP field to the electric power system. Needless to say, it is difficult to specify "the representative disturbance." One must therefore be cautious about taking any of the representative disturbances used in this study as "the real thing."

Because of this uncertainty, preliminary calculations were made, varying the parameters specifying the perturbation over a wide range in order to determine which variables were important. Secondly, we hoped to determine the effect on the stability for different choices of parameters to provide some intuition for the possible range of effects that could be produced by different types of conditions. In this way, a general understanding of the synchronous behavior of the system when subjected to the unusual EMP-produced perturbations has been gained.

B. LIMITATIONS OF THE STUDY AND INADEQUACIES IN THE NETWORK MODEL

Due to the great complexity in calculating the system response, several simplifications were made which somewhat limit the applications of this study. Most important, machine excitation and voltage regulation were not modeled. The response could therefore not be calculated for times greater than 1-1/2 to 2 seconds after the initial perturbation. Consequently, the later time dynamic response could not be calculated at all. Because of the lack of realistic damping in the system, the later time transient response (between 1 to 1-1/2 seconds) may also be somewhat overly pessimistic. But the apparent major loss of synchronism found using this model, particularly for the multiple pulse cases, cannot be ignored. However, one should not expect this study to have precisely determined the behavior of the transmission system when subjected to expected EMP-induced perturbations.

Other insufficiencies were discussed elsewhere. We again mention the critical need to determine the effect of EMP on (1) the load tie line and control systems, (2) the generator control systems, and (3) the solid state transmission relays. Further study of these subsystems is needed before any final conclusion concerning the effects of EMP on the power system can be drawn.

It is possible that high altitude nuclear detonations could occur without having any blast damage. It was not the purpose of this paper to discuss various scenarios. However, if many low altitude or groundburst nuclear detonations occur causing significant blast damage to a significant part of the transmission network, then the transmission system will certainly lose stability. Moderate physical damage accompanying EMP would only enhance the instabilities calculated in this paper. Consequently, the transient disturbance as calculated for EMP perturbations alone should be considered as a minimal perturbation.

A further difficulty in all stability studies is the difficulty in representing the load, which is frequently expressed as a constant impedance load, and occasionally as a constant current or a constant megavolt amp load. However, all of these representations are simplifications since the nature of the load is not precisely known. In this study, the load was modeled as a constant impedance load. However, some calculations were made using the other two load representations in localized areas in which machines lost stability, in order to see if the different representations significantly affected the response. The results were negative. The local response changed very little. Machines which lost stability for the local load, modeled as constant impedance, also lost stability when the local load was modeled as constant current or constant megavolt amp load.

If EMP perturbations produced transmission line surges of sufficient magnitude to open relays, the effect on the stability would be severe. However, the power flow in the major lines in the perturbed area was monitored in most of the stability calculations. There were significant power surges, but they were not large enough to trip relays. Consequently, the transmission lines were not opened at any time, except for the tie lines in a few cases. If additional effects result in excessive power surges, such as might occur if many generators were tripped, then the possibility of the opening of transmission lines should be incorporated. The limited scope of this study could not estimate the likelihood of such events.

CHAPTER VI

GENERAL CONCLUSIONS

The results of this study indicate that the electric transmission system may be disturbed by EMP-induced perturbations sufficiently to cause much of the system to lose stability, resulting in a large power failure. Although the effects from EMP are complex, a model was defined which should reasonably represent the effects on the transmission system from induced perturbations on the distribution system.

Both a single set and repetitive sets of multiple faults severely perturb the transmission system; the repetitive sets of faults disturb the system much more severely. Loss of stability of a significant number of generators in the perturbed area can occur from expected EMP-induced perturbations.

The severity of EMP-type perturbations can perhaps be reduced by separating perturbed and unperturbed areas by opening the tie lines connecting these regions. The interference between the two areas would then be minimized. Furthermore, a perturbed area losing synchronism would then not result in the collapse of the areas which were not directly affected. However, further consideration of possible effects from such a tie line opening must be made before such a procedure is adopted.

As outlined in Chapter V, further study should be made of other possible EMP-induced perturbations which were not included in this work. Only then can final conclusions be drawn concerning the severity of disruption which EMP may induce.

REFERENCES

1. W. J. Karzas and I. R. Latter, Phys. Rev., 137, 1369 (1965).

2. D. B. Nelson, A Program to Counter the Effects of Nuclear Electromagnetic Pulse in Commercial Power Systems, ORNL-TM-3552, Part 1, October 1972.

3. J. H. Marable, J. K. Baird, and D. B. Nelson, Effects of Electromagnetic Pulse of a Power System, ORNL-4836, December 1972.

4. James K. Baird and Nicholas J. Frigo, Effects of Electromagnetic Pulse (EMP) on the Supervisory Control Equipment of a Power System, ORNL-4899, October 1973.

5. C. W. Ross and T. A. Green, "Dynamic Performance Evaluation of a Computer Controlled Electric Power System," Paper 71-TP-593-PWR, IEEE Summer Meeting and International Symposium on High Power Testing, July 1971.

6. Federal Power Commission, "Prevention of Power Failures, A Report to the President," Volumes I, II, and III, July 1967.

7. E. Levi, M. Panzer. Electromechanical Power Conversion, McGraw-Hill Book Co., (1966).

8. E. W. Kimbark, Power Supply Stability, Vols. I-III, John Wiley & Sons, (1948).

9. Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, 4th Edition, (1964).

10. W. W. Maslin, S. T. Matraszek, C. H. Rush, and J. G. Irwin, "A Power System Planning Computer Program Package Emphasizing Flexibility and Compatibility," IEEE Conference Paper No. 70-CP-684-PWR, (July 1970).