A STUDY OF SOME UNBALANCED FAULT CONDITIONS OF POWER SYSTEMS

by

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Much work has been done in an effort to apply digital numerical methods to the problems of electrical power systems fault and stability studies. Most of this effort has been expended in attempts to find ways of applying these methods to the classical types of solutions to these problems with varying degrees of success. However, the classical types of solutions are based on several simplifying assumptions applied to the basic machine equations which allow these equations to be reduced to various stages of linearity so that they may be easily solved. While the classical methods allow solution by conventional means, the simplifying assumptions utilized invariably introduce inaccuracies. These methods have been very useful and quite adequate in the past, but the growing size and complexity of our modern power systems, the interconnections of our systems to form vast power pools, the increasing usage of higher voltages and larger machines, and the loss of spinning reserve due to inability of construction to maintain pace with demand have all combined to create an increasingly apparent need for more sophisticated and more accurate methods of solving these problems. With the advent of the large scale digital computer, a few pioneers made some significant breakthroughs in more modern methods of solution of the basic equations with fewer simplifying assumptions and therefore better accuracy. Such men as Blackwell (1), Duke (2), Gilchrist (3), and Koenig (1) have opened the door to several methods of solving the basic equations by the use of modern circuit theory and numerical methods.

While the work of these men was confined to solution of problems involving only faults of a balanced nature, such as a sudden load change on a machine or a balanced three-phase fault on a system, their work provided the breakthrough necessary for continued research in the area. This thesis is largely a continuation and expansion of the work previously done by Blackwell, Gilchrist, and Koenig with emphasis on the solutions of unbalanced fault conditions of various types. Utilization is also made of the now classical works of such pioneers as Evans and Wagner (4), as well as the modern resources of the family of IBM publications (5, 6, 7).

The method is checked by use of a field study contributed by Tennessee Valley Authority.

1.2 Classical Methods

The classical method of determining the currents and voltages associated with unbalanced fault conditions on a power system consists of the formulation and reduction of the positive-, negative-, and zero-sequence networks associated with the system, the interconnection of these networks according to the fault type, and the re-expansion and reconversion of the networks in order to determine the currents and voltages at various points in the system. The method makes use of a voltage bus in the positive-sequence system which is assumed to be of constant magnitude and angle during the fault. All machines in the system are assumed to consist of linear, bi-lateral, passive impedances in series with this constant voltage. While this method has been very valuable in the past, and is still very valuable in many areas, it is inadequate in many modern studies.

Stability studies have been handled classically by the methods outlined by Kimbark (8), and Crary (9), which are based upon many simplifying assumptions, and which can be handled only by iterative solution methods. While such methods are easily performed on a computer, the simplifying assumptions do not allow the system equations to adequately describe the actual system. Nonlinearities in the machines involved in a study are usually handled by use of the so-called subtransient, transient, and steady-state impedances and voltages. In addition, resistances in the system are generally neglected, which allows for easier manipulation and more conservative results. This method of stability study gives adequate results when the criterion for stability is that the system remain stable under a balanced three-phase fault. However, power system engineers are in the process of trying to change these criteria. The classical method of stability study is not very appropriate for use with unbalanced fault conditions, as the equations become extremely difficult to solve. With stability becoming increasingly important in our modern technically oriented society, engineers need a method which will give more accurate results for stability studies.

1.3 Historical Background

The variables used in the equations of this thesis are closely related to those set forth by Blondel (10), or by Park (11). However, the nonlinear time-varying differential equations were first used by Koenig and Blackwell (1), and Gilchrist (3). The basic machine equations were simplified only by the assumptions of fundamental frequency representation and constant inductance and resistance coefficients, resulting in the standard system of differential equations for synchronous machines which are nonlinear in the speed, torque and current variables. While the original work was programmed directly on a digital computer, the advent of modern programs such as Pactolus and CSMP has greatly simplified the programming required for solution of the equations.

Other digital computer programs are currently in use by many power engineers. However, they all rely on the conventional methods of representing the system and they all utilize a slightly modified form of the classical solutions.

Most of these programs are handled in the form of matrices, but this merely results in a more convenient means of handling data.

1.4 Justification of the Study

This study was undertaken in an effort to show that more meaningful results can be obtained through the solution of the nonlinear machine equations under unbalanced fault conditions. The advent of the modern high speed digital computer, with its associated programs, made the solution of such a system of equations possible. Changing the stability criteria from that of a three-phase fault to that of a phase-to-phase fault or a two-phase-to-ground fault is currently under study, and it is conceivable that a single-phase-to-ground fault will be settled upon by some systems, since about 70 per cent of all faults are single-phase-to-ground on the lower voltages (12), while this fault type accounts for almost 100 per cent of all initial faults on an EHV system with its greater line spacing. However, according to the experience of TVA on their 500 KV system, roughly 65 per cent of these faults evolve into the two-phase-to-ground type due to the extreme voltage gradients encountered on EHV systems.

1.5 The Proposed Problem

The problem proposed in this thesis is that of attempting to utilize the nonlinear synchronous machine equations derived by Koenig and Blackwell (1) for the solution of transient stability studies in power systems under other than balanced fault conditions. Much previous research has been done in the utilization of these equations under balanced conditions, although such conditions are relatively rare in an actual system (12).

1.6 Experimental Verification

In 1969, Tennessee Valley Authority conducted some staged fault tests on their 500 KV system. As a by-product of these tests, data became available which allowed the thesis method to be compared to an experimental field study. The Paradise steam plant, located in Kentucky, consists of three machines. Units 1 and 2 are connected to the TVA 161 KV system. The machine studied here, Unit 3, is connected to the TVA 500 KV system via a 90 mile 500 KV line which terminates at the Davidson substation in Nashville, Tennessee. This effectively places Units 1 and 2 approximately 200 electrical miles from Unit 3, even though they are all housed in the same building.

During the field tests, oscillograms were made of the 161 KV system voltage, as reference, and of the Unit 3 terminal voltage. Each time the reference voltage went through zero in a positive direction, a "pip" was inserted on the record. This allowed the relative phase difference between the reference voltage, representing the system, and the terminal voltage of the machine to be measured on a cycle by cycle basis. The relative phase angle between the positive zero crossing of the reference voltage and the terminal voltage agrees with the classical definition of the power angle under steady-state conditions. Therefore, the decision was made to designate this as the power angle.

1.7 Definitions of Terms

For the purpose of this thesis, a power system is defined as an interconnected group of synchronous generators, powered by steam turbines and operating at a nominal frequency of sixty hertz, for the purpose of generating three-phase electrical power and transmitting this power from the point of generation to some other point in the system. A fault is defined as any abnormal condition within the system, although the types of fault utilized here are the ones most commonly encountered in an actual system, *i.e.*, a single-phase-to-ground, phase-to-phase, two-phase-to-ground, and, for purposes of illustrating previous research in the area, the three-phase balanced fault. The term "stability" as used herein simply means that the machine under study remains in synchronism with the rest of the machines in the system, and that these machines remain synchronized with each other.

The torque angle, α, is defined as the angle between the rotor position and the position of the synchronously rotating stator field. This is defined by

$$\alpha = \theta(t) - \omega t - \pi/2 \qquad (1.7\text{-}1)$$

where $\theta(t)$ is the rotor position and a dependent variable in the given equations, ωt is the position of the synchronously rotating field of the stator, and ω is the constant frequency of the infinite bus. The torque angle may also be considered the angle between a reference voltage and the generated voltage of the machine. Since the equations used in this thesis are given by Reference 1 as the terminal equations of a machine, the torque angle is normally used herein in connection with the voltage equations. Since inert circuit elements such as lines, transformers, etc., have power angles which are fixed for a given load and are defined as the angle between the sending end voltage and the receiving end voltage, the connection of these devices between the terminals of the machine and the fault will serve only to change the reference, not to change the validity of the swing curves.

CHAPTER 2

THE SINGLE MACHINE ON AN INFINITE BUS

2.1 Introduction

This thesis makes use of the most basic type of system, that of one machine connected to an infinite bus through a short transmission line. This system was chosen because of its simplicity, and because it serves to illustrate the principles involved without unduly obscuring the problem. It is the classic textbook system. While it is very seldom encountered in the field, any system can be simplified and reduced to such a system. The term "infinite bus" is herein used to mean a source large enough such that the voltages of the terminals are independent of the currents over the range under consideration. A diagram of the system is shown in Figure 2.1-1.

2.2 Stability

Classically, a system is expected to remain stable during a three-phase fault occurring anywhere on the system. For most systems, this criterion is still in use, although an effort is currently being made by Tennessee Valley Authority to establish a stability criterion of a less severe nature, a two-phase-to-ground fault being presently under study. The purpose of

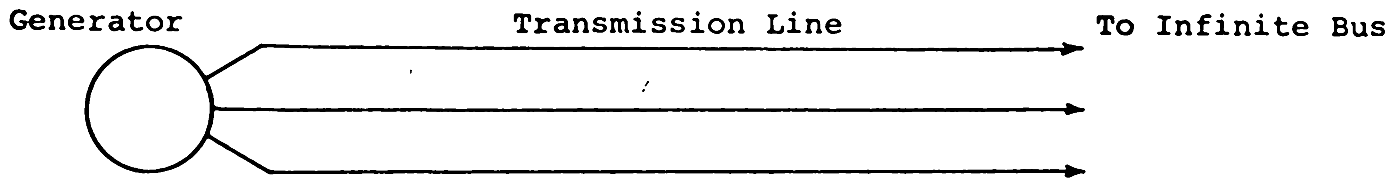


Figure 2.1-1. Single Machine on an Infinite Bus

such a study is to try to achieve a more realistic stability criterion in view of the changes which have taken place in power systems in recent years. This was brought about largely because of the Northeast blackout of 1965. In order to perform a study of this nature, it is necessary that new methods of handling unbalanced fault conditions be developed. It is hoped that this thesis will be of some assistance in this area.

2.3 Types of Faults

The types of faults most commonly occurring on a system are those involving all three phases, two phases and ground, two phases only, and one phase and ground. The relative frequency of occurrence of these fault types vary widely, but Westinghouse (12) gives an average percentage occurrence as:

Three-Phase Faults	5%
Two-Phase-to-Ground Faults	10%
Phase-to-Phase Faults	15%
Single-Phase-to-Ground Faults	70%

These figures represent what is called an average voltage level system, i.e., voltage levels below 200 KV. In an EHV system, especially at voltage levels of 300 KV and above, the spacing between phases is such that the likelihood of any fault being initially other than a single-phase-to-ground fault is extremely remote, although the voltage gradients involved are of such magnitude that a large percentage of these faults evolve into the two-phase-to-ground type if not cleared in a very short time.

2.4 The System Equations

The system equations used here are

$$v_s^o = (R_s^o + L_s^o \frac{d}{dt}) i_s^o \tag{2.4-1}$$

$$\begin{bmatrix} v_s^d \\ v_s^q \\ v_r \end{bmatrix} = \begin{bmatrix} R_s^+ + L_s^+ \frac{d}{dt} & -\dot{\theta} L_s^+ & \sqrt{2}\, L_{sr}^+ \frac{d}{dt} \\ \dot{\theta} L_s^+ & R_s^+ + L_s^+ \frac{d}{dt} & \sqrt{2}\, L_{sr}^+ \dot{\theta} \\ \sqrt{2}\, L_{sr}^+ \frac{d}{dt} & 0 & R_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_s^d \\ i_s^q \\ i_r \end{bmatrix} \tag{2.4-2}$$

$$\dot{\theta} T = -\sqrt{2}\, L_{sr}^+ \dot{\theta} i_r i_s^q + \dot{\theta} J \frac{d^2}{dt^2} \theta \tag{2.4-3}$$

the so-called direct- and quadrature-axis equations. A complete derivation of these equations is given by Koenig and Blackwell (1). These equations have the distinct advantage of separating the real and imaginary quantities involved so that they may be easily handled by a computer. They are nonlinear in the speed variable, $\dot{\theta}$, and for any given speed may be reduced to a set of linear equations. However, in stability studies, the machine speed plays a vital role, and they will be used here in their nonlinear form. They have some slight disadvantages in that they do not take into account nonlinearities due to the effects of saturation, although these effects are minimized in the problems to be discussed. Any attempt to include the effects of all the nonlinearities present in machines of this type led to intractable mathematics. The equations are written for a round-rotor machine, although the effects of saliency could be included if necessary.

CHAPTER 3

THE BALANCED THREE-PHASE FAULT: A SAMPLE PROBLEM

3.1 Introduction

The sample problem utilized here was presented by both Gilchrist (2) and Koenig and Blackwell (1). It is used here for the purpose of comparison, since the same basic system will be used for all fault types to be discussed. It also serves to clarify the modification made on the basic equations to reduce the effects of saturation, etc., and to introduce the system under the simplest circumstances.

3.2 The Programmed Equations

In order to program Equations 2.4-1, 2.4-2, and 2.4-3, they are first put into normal form. The equations used in this research are those given by Koenig and Blackwell (1), as modified by the sample problem given in the next section. These equations are

$$\frac{d}{dt} i_s^o = (v_s^o - R_s^o i_s^o)/L_s^o \qquad (3.2\text{-}1)$$

$$\frac{d}{dt}\begin{bmatrix} i_s^{\,d} \\ i_s^{\,q} \\ i_r' \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \left(v_s^{\,d} - R_s^{+} i_s^{\,d} + \dot{\theta} L_s^{+} i_s^{\,q}\right)\frac{Lr}{K} - \left(v_f - R_f 1.6 - R_r i_r'\right)\frac{\sqrt{2}L_{sr}^{+}}{K} \\ \left(v_s^{\,q} - \frac{1.5\dot{\theta}}{\omega} - L_s^{+}\dot{\theta} i_s^{\,d} - R_s^{+} i_s^{\,q} - \sqrt{2}L_{sr}^{+}\dot{\theta} i_r'\right)\frac{1}{L_s^{+}} \\ -\left(v_s^{\,d} - R_s^{+} i_s^{\,d} + L_s^{+}\dot{\theta} i_s^{\,q}\right)\frac{\sqrt{2}L_{sr}^{+}}{K} + \left(v_r - R_r 1.6 - R_r i_r'\right)\frac{L_s^{+}}{K} \\ \dot{\theta} \\ \left[p + \left(\frac{1.5}{\omega} + \sqrt{2}L_{sr}^{+} i_r'\right)\dot{\theta} i_s^{\,q}\right]\frac{1}{J\theta} \end{bmatrix} \qquad (3.2\text{-}2)$$

Where $K = L_r L_s^{+} - \left(\sqrt{2}L_{sr}^{+}\right)^2$

3.3 A Sample Problem

Consider a system such as that shown in Figure 3.3-1, consisting of a round-rotor 60-cycle 2-pole 3-phase alternator connected to an infinite bus. The pre-fault, or initial, conditions are a steady-state power output of 0.5 per unit at a power factor of 0.85 lagging. The voltage at the infinite bus is considered to be 1 per unit in magnitude. The power output of the machine is considered constant during the fault, and the magnitudes of the symmetrical-component coefficient of the equations are as follows:

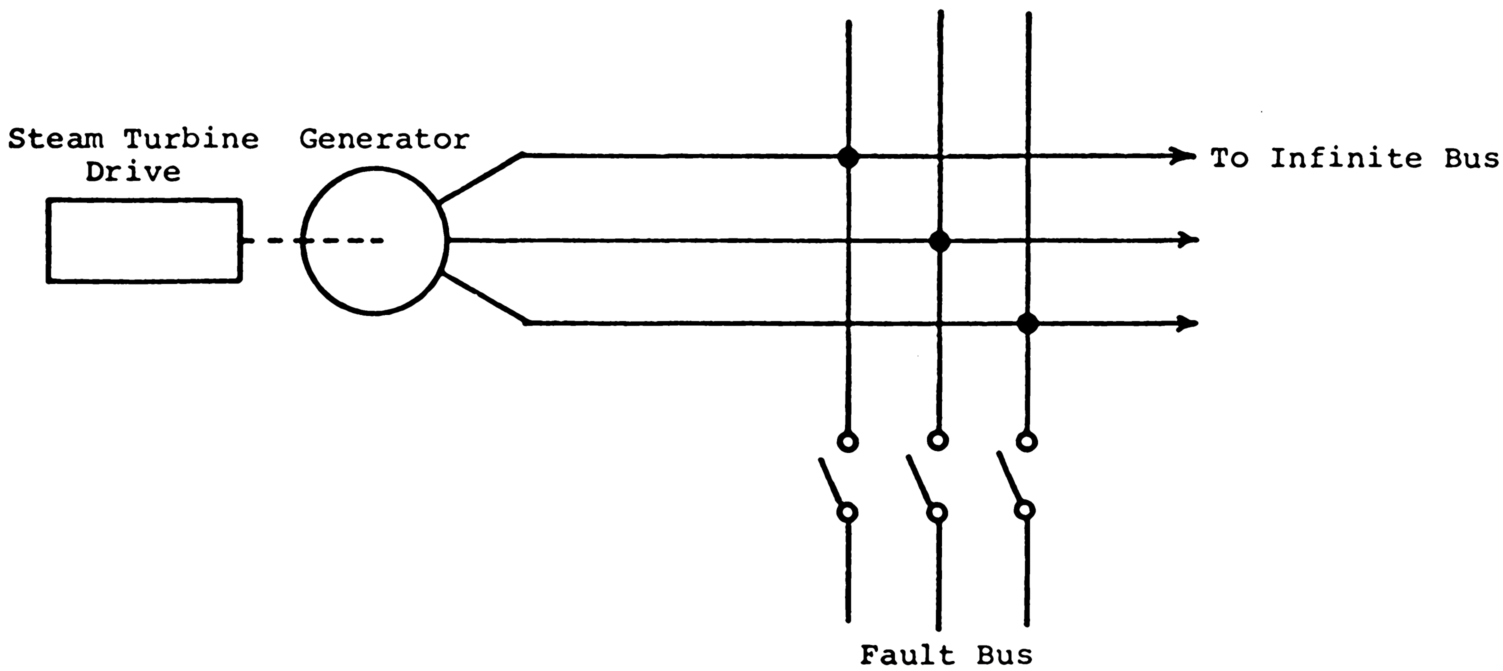


Figure 3.3-1. System for Sample Problems

$R_s^+ = 0.005$ pu $\quad R_r = 1$ pu $\quad \sqrt{2}\omega L_{sr}^+ = 0.6$ pu

$\omega L_s^+ = 1.2$ pu $\quad L_r = 6$ pu

evaluated at a rotor current of 1.6 units. The no-load voltage for this value of rotor current is 1.5 units. The mechanical damping coefficients are negligible, and the total momentum $M = \dot{\theta}J = 0.0159$ units.

Note that for this problem, Equation 3.2-1 is not needed, since the system remains balanced during the fault.

Since v_s^q and i_r are related by the no-load saturation curve of the machine, reference to Figure 3.3-2 will show that at no load

$$v_s^q = \sqrt{2}L_{sr}^+\dot{\theta}i_r \tag{3.3-1}$$

and the slope of this straight-line approximation is the coefficient $\sqrt{2}L_{sr}^+\dot{\theta}$. For the operation in the region of $i_r = 1.6$ units, Equation 3.3-1 becomes

$$v_s^q = 1.5 + 0.6\ i_r \tag{3.3-2}$$

which is a straight line tangent to the curve at this point. Therefore, the terms $\sqrt{2}L_{sr}^+\dot{\theta}i_r$ in Equation 2.4-2 and Equation 2.4-3 are replaced by $1.5\dot{\theta}/\omega + \sqrt{2}L_{sr}^+\dot{\theta}i_r'$ in order to reflect the operating point of 1.6 units. This results in Equation 3.2-2.

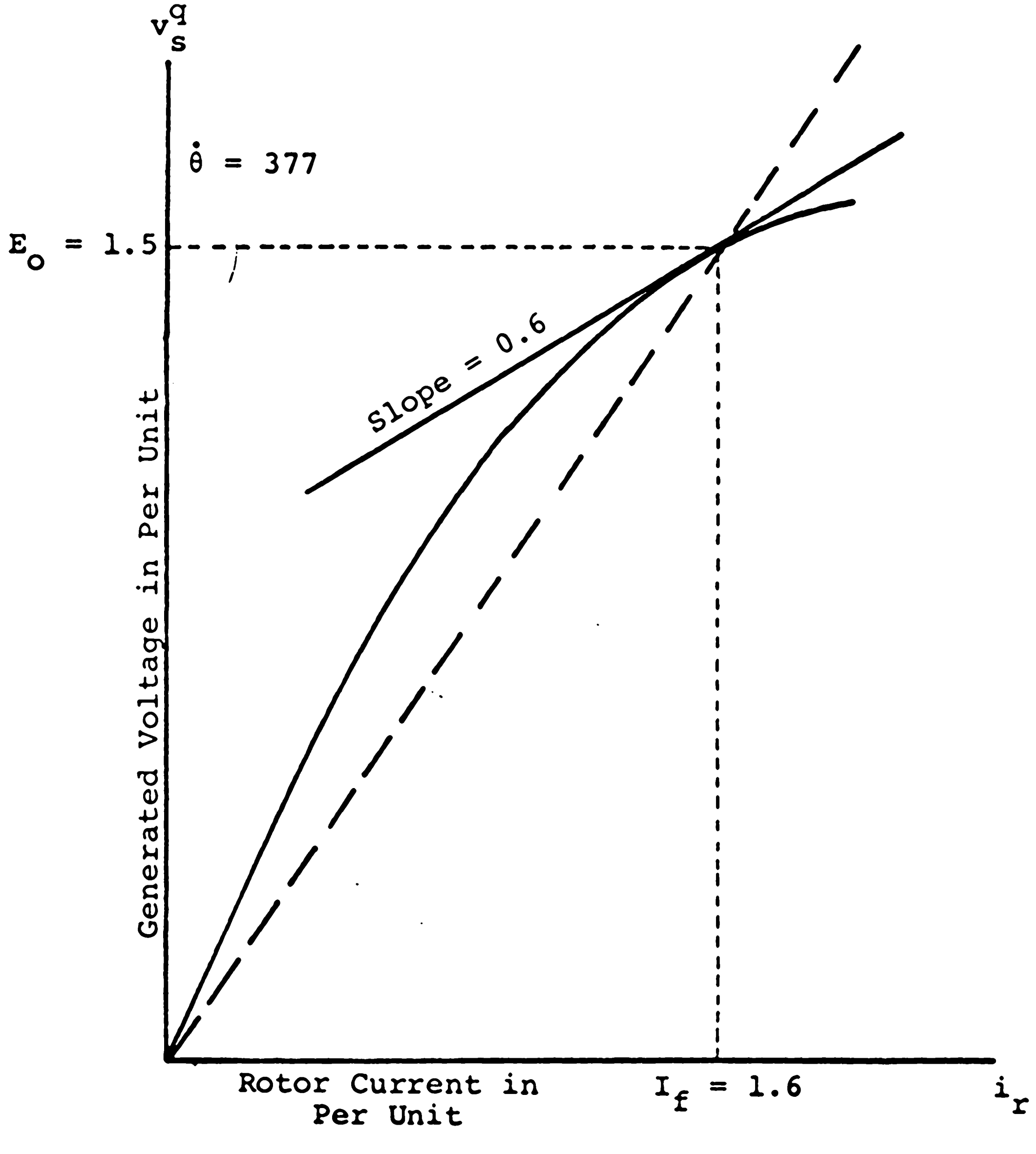


Figure 3.3-2. Generator Saturation Curve for Sample Problems

In order to solve the equations of the system, some additional transcendental equations are needed. Under balanced conditions, the stator voltages are given by

$$\begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = V_s(t) \begin{bmatrix} \cos\ (\omega_s t) \\ \cos\ (\omega_s t - 120°) \\ \cos\ (\omega_s t + 120°) \end{bmatrix} \tag{3.3-3}$$

Application of the transformation

$$\begin{bmatrix} v_s^o \\ v_s^d \\ v_s^q \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & e^{j\theta} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \frac{1}{\sqrt{3}} \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \tag{3.3-4}$$

results in the direct- and quadrature-axis transcendental voltage equations

$$\begin{bmatrix} v_s^d \\ v_s^q \end{bmatrix} = V \begin{bmatrix} \sin\alpha \\ -\cos\alpha \end{bmatrix} \tag{3.3-5}$$

where $\alpha = \theta - \omega t - \pi/2$ (3.3-6)

Initial conditions are specified from steady-state conditions existing immediately before the fault and are as follows:

$i_s^d(o+) = -0.4833$ units $\qquad \theta(o+) = 1.98$ radian

$i_s^q(o+) = 0.333$ units $\qquad \dot{\theta}(o+) = 377$ rad/sec

$i_r'(o+) = 0$ $\qquad v_s^d(o+) = v_s^q(o+) = 0$

The complete mathematical model for the system under study is then

$$\frac{d}{dt}\begin{bmatrix} i_s{}^d \\ i_s{}^q \\ i'_r \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 314v_s{}^d - 1.57i_s{}^d + \dot{\theta}i_s{}^q + 0.0834i'_r \\ 314v_s{}^q - 1.25\dot{\theta} - \dot{\theta}i_s{}^d - 1.57i_s{}^q - 0.5\dot{\theta}i'_r \\ -314v_s{}^d + 1.57i_s{}^d - \dot{\theta}i_s{}^q - 0.1667i'_r \\ \dot{\theta} \\ 31.4 + (78.6 + 0.1i'_r)\, i_s{}^q \end{bmatrix} \quad (3.3\text{-}7)$$

$$\begin{bmatrix} v_s{}^d \\ v_s{}^q \end{bmatrix} = V \begin{bmatrix} \sin\alpha \\ -\cos\alpha \end{bmatrix} \quad (3.3\text{-}5)$$

where $\alpha = \theta - \omega t - \pi/2$ (3.3-6)

The solution was obtained by programming Equations 3.3-7, 3.3-5, and 3.3-6. To place the fault on the system, V in Equation 3.3-5 was set to zero. To clear the fault, it was set to unity. The program is given in the appendix. In actual practice, the raw equations were programmed and the computer was allowed to calculate the coefficients. Figure 3.3-3 illustrates the swing curves for this type of fault. Note that the machine remains in synchronism with the system for a clearing time of 0.25 seconds, but goes out of synchronism for a clearing time of 0.275 seconds, although the torque angle does not increase without bound until the clearing time reaches 0.3 seconds, which is clearly

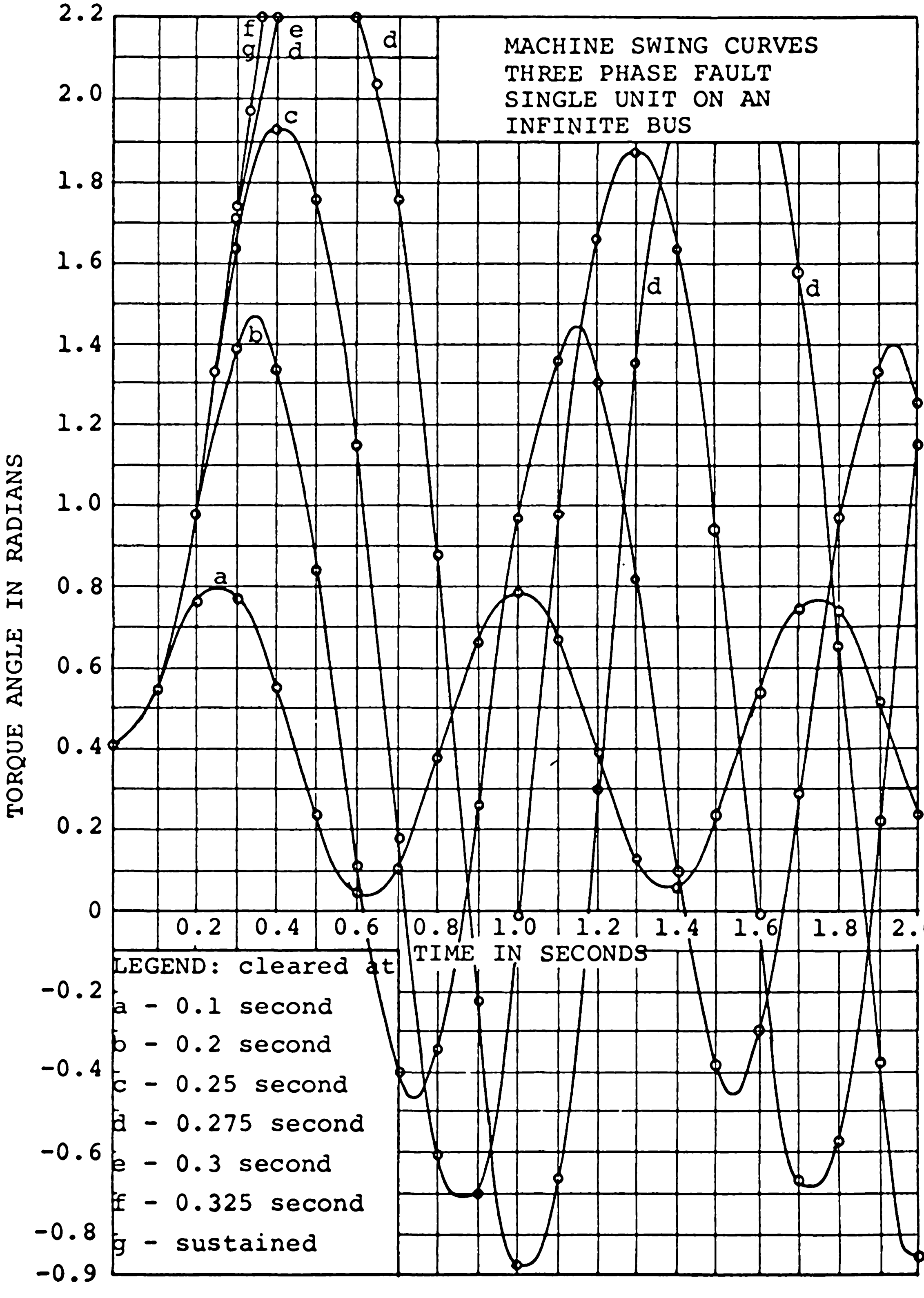


Figure 3.3-3. Sample Problem Swing Curves: Three-Phase Fault

illustrated in the speed curves, Figure 3.3-4. Note also that its maximum swing is 1.92 radians on the 0.25 second curve which corresponds to about 110 degrees. This exceeds the allowable swing of most power systems, and is certainly running very close to the stability limit. These results agree with those of previous researchers (1, 2).

In Figure 3.3-4, note that even on the curves for clearing times of 0.3 and 0.325 seconds, when the machine is completely out of synchronism, the speed starts to drop back and then swings upward. These curves also indicate the stability limits of the system.

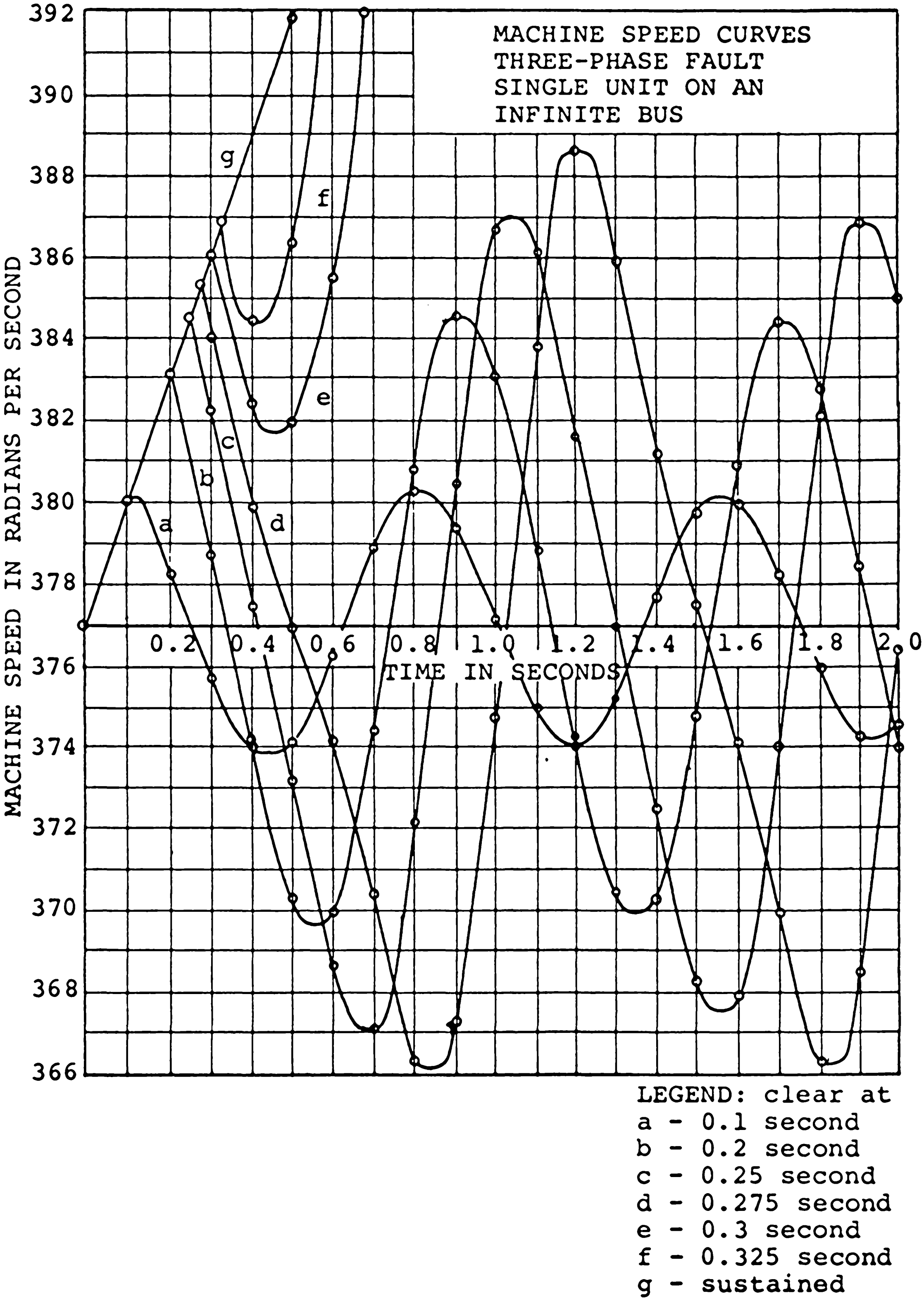


Figure 3.3-4. Sample Problem Speed Curves: Three-Phase Fault

CHAPTER 4

THE DERIVATION OF THE EQUATIONS FOR A SINGLE-LINE-TO-GROUND FAULT: ILLUSTRATION OF THE METHOD

4.1 Introduction

Since all previous work in this area deals with balanced three-phase conditions, and since the single-phase-to-ground fault is the most common type, it was decided to attempt to use the method outlined in a problem involving an unbalanced condition of the latter type. In a single-phase-to-ground fault, synchronizing power is still provided to the machine through two of the phases, so that this fault type is not as severe from a stability standpoint as the previously discussed three-phase fault. However, fault currents for this type can be quite large, and efforts must be made to clear the faulted phase and restore service. In some systems, the fault is severe enough to cause instability.

4.2 Derivation of the Equations

For the case of the system shown in Figure 2.1-1, this type of fault will result in the conditions that $v_A(t) = 0$, while $v_B(t)$ and $v_C(t)$ retain their pre-fault relationship, i.e., they remain equal in magnitude and 120° apart. These conditions are realized because of the presence of the infinite bus in the system. Under these conditions, if the pre-fault voltages are given by

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_s(t) \begin{bmatrix} \cos\ (\omega t) \\ \cos\ (\omega t - 120°) \\ \cos\ (\omega t + 120°) \end{bmatrix} \qquad (4.2\text{-}1)$$

then the fault voltages will be given by

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = V_s(t) \begin{bmatrix} 0 \\ \cos\ (\omega t - 120°) \\ \cos\ (\omega t + 120°) \end{bmatrix} \qquad (4.2\text{-}2)$$

Application of the transformations, Equation 3.3-4 is then

$$\begin{bmatrix} v_s^{o}(t) \\ v_s^{d}(t) \\ v_s^{q}(t) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & 0^{j\theta} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

$$\cdot \frac{V_s(t)}{\sqrt{3}} \begin{bmatrix} 0 \\ \cos\ (\omega t - 120°) \\ \cos\ (\omega t + 120°) \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & e^{j\theta} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

$$\cdot \begin{bmatrix} 0 \\ e^{j(\omega t - 120°)} + e^{-j(\omega t - 120°)} \\ e^{j(\omega t + 120°)} + e^{-j(\omega t + 120°)} \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & e^{j\theta} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ a^2e^{j\omega t} + ae^{-j\omega t} \\ ae^{j\omega t} + a^2e^{-j\omega t} \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & e^{j\theta} \end{bmatrix} \begin{bmatrix} (a^2 + a)(e^{j\omega t} + e^{j\omega t}) \\ 2e^{j\omega t} + (a + a^2)e^{-j\omega t} \\ 2e^{-j\omega t} + (a + a^2)e^{j\omega t} \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j\theta} & 0 \\ 0 & 0 & e^{j\theta} \end{bmatrix} \begin{bmatrix} -2\cos\omega t \\ 2e^{j\omega t} - e^{j\omega t} \\ 2e^{-j\omega t} - e^{j\omega t} \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & -1 & -1 \\ 0 & -j & j \end{bmatrix} \begin{bmatrix} -2\cos\omega t \\ 2e^{-j(\theta-\omega t)} - e^{-j(\theta+\omega t)} \\ 2e^{j(\theta-\omega t)} - e^{j(\theta+\omega t)} \end{bmatrix}$$

$$= \frac{V_s(t)}{2\sqrt{2}\sqrt{3}} \begin{bmatrix} -2\sqrt{2}\cos\omega t \\ -2[e^{j(\theta-\omega t)} + e^{-j(\theta-\omega t)}] + e^{-j(\theta+\omega t)} + e^{j(\theta+\omega t)} \\ -2j[e^{-j(\theta-\omega t)} - e^{j(\theta-\omega t)}] + je^{-j(\theta+\omega t)} - je^{j(\theta+\omega t)} \end{bmatrix}$$

Now $\theta-\omega t = \alpha + \pi/2$, $\theta+\omega t = 2\omega t + \alpha + \pi/2 = \gamma + \pi/2$

where $\gamma = 2\omega t + \alpha$

Then $$v_s^{o}(t) = \frac{-V_s(t)}{\sqrt{3}} \cos\omega t \qquad (4.2\text{-}3)$$

$$\begin{bmatrix} v_s^{d}(t) \\ v_s^{q}(t) \end{bmatrix} = \frac{V_s(t)}{\sqrt{2}\sqrt{3}} \begin{bmatrix} -2\cos(\alpha + \pi/2) + \cos(\gamma + \pi/2) \\ -2\sin(\alpha + \pi/2) + \sin(\gamma + \pi/2) \end{bmatrix}$$

$$= \frac{V_s(t)}{\sqrt{2}\sqrt{3}} \begin{bmatrix} -2(\cos\alpha\cos\pi/2 - \sin\alpha\sin\pi/2) + \cos\gamma\cos\pi/2 - \sin\gamma\sin\pi/2 \\ -2(\sin\alpha\sin\pi/2 + \cos\alpha\cos\pi/2) + \sin\gamma\sin\pi/2 + \cos\gamma\cos\pi/2 \end{bmatrix}$$

$$= \frac{V_s(t)}{\sqrt{2}\sqrt{3}} \begin{bmatrix} 2 \sin \alpha - \sin \gamma \\ -2 \cos \alpha + \cos \gamma \end{bmatrix}$$

From the steady state conditions given by Koenig and Blackwell (1),

$$V = \frac{\sqrt{3}V_s}{\sqrt{2}} \qquad \text{or} \qquad V_s = \frac{\sqrt{2}V}{\sqrt{3}}$$

Then coefficients become

$$\frac{\sqrt{2}V}{\sqrt{2}\sqrt{3}\sqrt{3}} = V/3 \qquad \text{and} \qquad \frac{V_s}{\sqrt{3}} = \frac{V\sqrt{2}}{\sqrt{3}\sqrt{3}} = \frac{\sqrt{2}V}{3}$$

and the transcendental voltages equations are

$$\begin{bmatrix} v_s^{o}(t) \\ v_s^{d}(t) \\ v_s^{q}(t) \end{bmatrix} = \frac{V}{3} \begin{bmatrix} -(1/\sqrt{2}) \cos \omega t \\ 2 \sin \alpha - \sin \gamma \\ -2 \cos \alpha + \cos \gamma \end{bmatrix} \qquad (4.2\text{-}4)$$

for the single-phase-to-ground fault.

CHAPTER 5

THE SINGLE-LINE-TO-GROUND FAULT: A SAMPLE PROBLEM

5.1 The Sustained Fault

This sample problem utilizes Equations 3.2-1, 3.3-7, 3.3-6, and 4.2-4 with the coefficient V equal to unity. Since the zero-sequence components are of no consequence in a stability sense, the values of R_s^o and L_s^o in Equation 3.2-1 were taken arbitrarily as 0.005 and 0.0001 per unit, respectively. These components affect neither $\dot{\theta}$ nor α, and the zero-sequence equations are independent of the other system equations (1). However, they are necessary for a fault study, in that v_s^o and i_s^o affect the total fault voltages and currents. Utilizing the values given above yields

$$\frac{d}{dt} i_s^o = 10^4 v_s^o - 50 i_s^o \tag{5.1-1}$$

5.2 Faulting and Clearing the System

The three-phase fault was inserted or removed by the simple expedient of specifying the parameter V to be either zero or one. However, to insert or remove the single-phase-to-ground fault requires the choice of either Equation 3.3-5 or 4.2-4, respectively. The complete mathematical model for the system is then

$$\frac{d}{dt} i_s{}^o = 10^4 v_s{}^o - 50 i_s{}^o \qquad (5.1\text{-}1)$$

$$\frac{d}{dt}\begin{bmatrix} i_s{}^d \\ i_s{}^q \\ i_r' \\ \theta \\ \dot\theta \end{bmatrix} = \begin{bmatrix} 314 v_s{}^d - 1.57 i_s{}^d + \dot\theta i_s{}^q + 0.0834 i_r' \\ 314 v_s{}^q - 1.25\dot\theta - \dot\theta i_s{}^d - 1.57 i_s{}^q - 0.5\dot\theta i_r' \\ -314 v_s{}^d + 1.57 i_s{}^d - \dot\theta i_s{}^q - \\ \dot\theta \\ 31.4 + (78.6 + 0.1 i_r')\ \dot\theta i_s{}^q \end{bmatrix} \qquad (3.3\text{-}7)$$

$\gamma = 2\omega t + \alpha$

where $\alpha = \theta - \omega t - \pi/2$ (3.3-6)

$$\begin{bmatrix} v_s{}^o(t) \\ v_s{}^d(t) \\ v_s{}^q(t) \end{bmatrix} = \frac{V}{3}\begin{bmatrix} -(1/\sqrt{2})\cos\omega t \\ 2\sin\alpha - \sin\gamma \\ -2\cos\alpha + \cos\gamma \end{bmatrix} \qquad (4.2\text{-}4)$$

$$\begin{bmatrix} v_s{}^d \\ v_s{}^q \end{bmatrix} = V\begin{bmatrix} \sin\alpha \\ -\cos\alpha \end{bmatrix} \qquad (3.3\text{-}5)$$

with a choice being made between Equation 4.2-4 for a faulted condition or Equation 3.3-5 for a cleared condition. A program for this problem is given in the appendix.

5.3 Results

The swing curves for this type of fault are presented in Figure 5.3-1. It will be noted that the general shape of

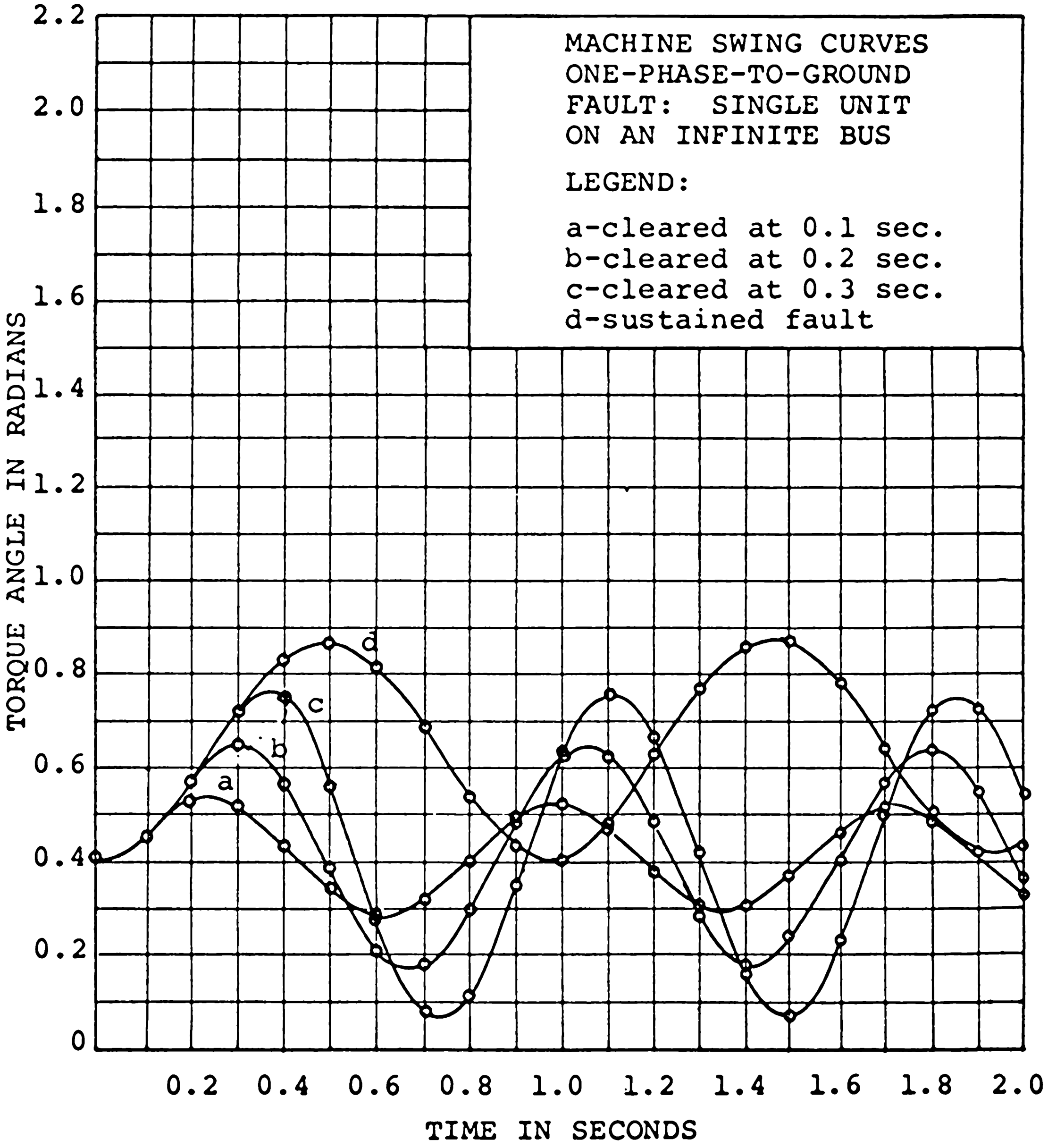


Figure 5.3-1. Sample Problem Swing Curves: Single-Phase-to-Ground Fault.

the curves is the same as that of the curves of the three-phase fault, but the machine did not lose synchronism even under sustained fault conditions. The largest value attained for α was slightly over 0.85 radians.

Figure 5.3-2 shows the machine speed curves for this type of fault. It should be noted that the highest speed attained by the machine was 380 radians per second, or an increase of only 0.796 per cent. This clearly illustrates the fact that this fault type is much less severe from a stability standpoint than the three-phase fault.

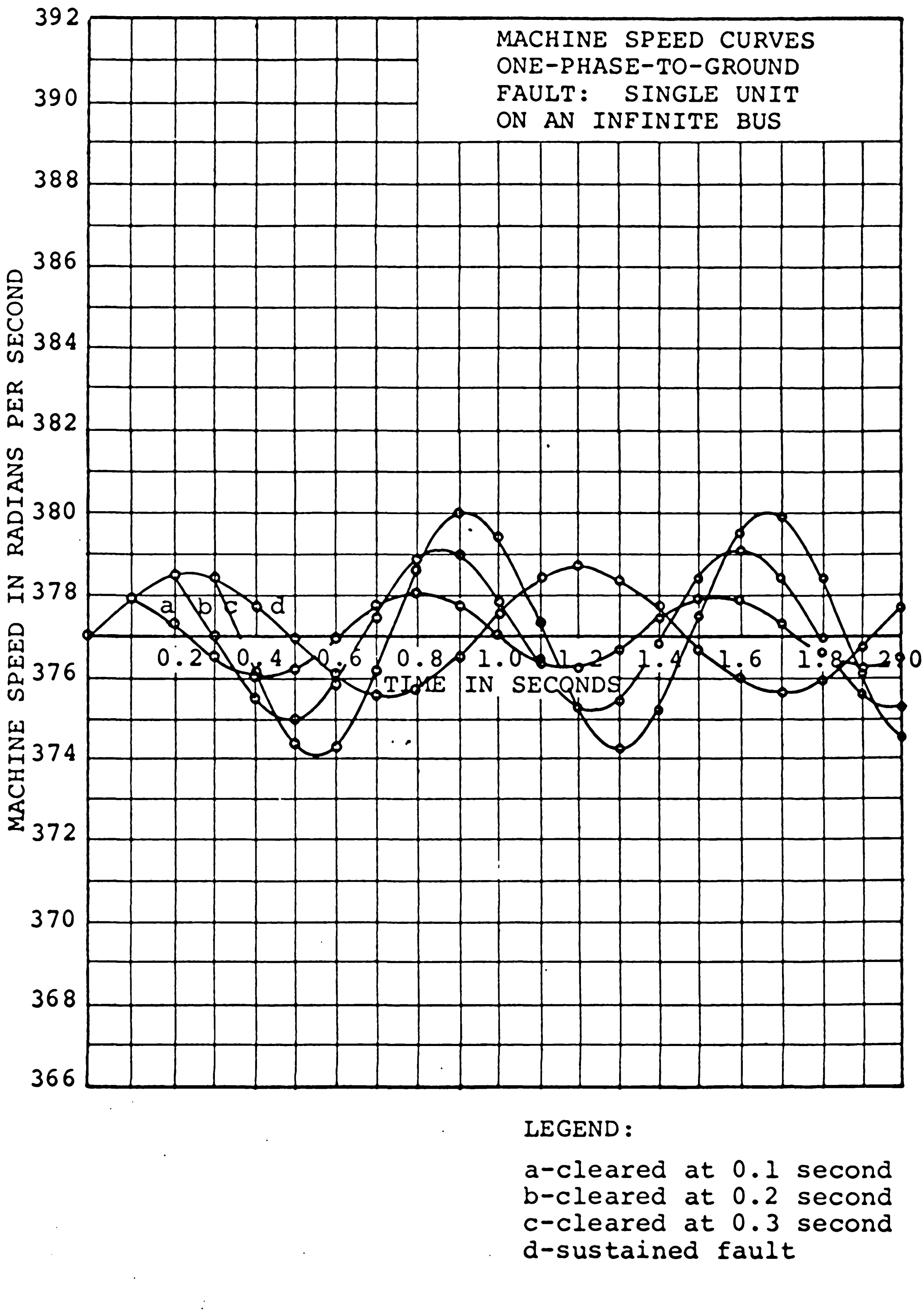


Figure 5.3-2. Sample Problem Speed Curves: Single-Phase-to-Ground Fault

CHAPTER 6

THE LINE-TO-LINE FAULT: THE EQUATIONS

6.1 The Equations

Wagner and Evans (4) and Clarke (13) have shown that the conditions necessary for this type of fault are

$$v_B(t) = v_C(t)$$
$$\bar{V}_s^+ = \bar{V}_s^-$$
$$v_A(t) = -2v_B(t)$$

Letting $v_A(t) = 2V_s \cos \omega t$ implies that $v_C(t) = v_B(t) = -V_s \cos \omega t$, which indicates that during the fault the system voltages will be given by

$$\begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = V_s(t) \begin{bmatrix} 2 \cos \omega t \\ - \cos \omega t \\ - \cos \omega t \end{bmatrix} \qquad (6.1\text{-}1)$$

Applying the transformations, Equation 3.3-4, to Equation 6.1-1 yields the transcendental voltage equations

$$\begin{bmatrix} v_s^o \\ v_s^d \\ v_s^q \end{bmatrix} = \frac{V}{2} \begin{bmatrix} 0 \\ \sin \alpha + \sin \gamma \\ -\cos \alpha - \cos \gamma \end{bmatrix} \qquad (6.1\text{-}2)$$

where $\gamma = 2\omega t + \alpha$

It will be noted that the zero-sequence equations become unnecessary, since ground is not involved in the fault.

6.2 Sample Problem

This sample problem utilizes Equations 3.3-5, 3.3-7, 3.3-6, and 6.1-2. The complete mathematical model for this problem then becomes

$$\begin{bmatrix} v_s{}^d \\ v_s{}^q \end{bmatrix} = V \begin{bmatrix} \sin\alpha \\ -\cos\alpha \end{bmatrix} \qquad (3.3\text{-}5)$$

where $\alpha = \theta - \omega t - \pi/2$ (3.3-6)

$$\frac{d}{dt}\begin{bmatrix} i_s{}^d \\ i_s{}^q \\ i_r' \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 314v_s{}^d - 1.57i_s{}^d + \dot{\theta}i_s{}^q + 0.0834i_r' \\ 314v_s{}^q - 1.25\dot{\theta} - \dot{\theta}i_s{}^d - 1.57i_s{}^q - 0.5\dot{\theta}i_r' \\ -314v_s{}^d + 1.57i_s{}^d - \dot{\theta}i_s{}^q - 0.1667i_r' \\ \dot{\theta} \\ 31.4 + (78.6 + 0.1i_r')\dot{\theta}i_s{}^q \end{bmatrix} \qquad (3.3\text{-}7)$$

$$\begin{bmatrix} v_s{}^o \\ v_s{}^d \\ v_s{}^q \end{bmatrix} = \frac{V}{2}\begin{bmatrix} 0 \\ \sin\alpha + \sin\gamma \\ -\cos\alpha - \cos\gamma \end{bmatrix} \qquad (6.1\text{-}2)$$

where $\gamma = 2\omega t + \alpha$

with a choice between Equation 6.1-2 for a faulted condition or Equation 3.3-5 for a cleared condition. A program for this type of fault is given in the appendix.

The swing curves are given in Figure 6.2-1 for this problem. This fault type is less severe than a three-phase fault, but more severe than a single-phase-to-ground fault. The machine did not lose synchronism under this fault, but swung much further than under a single-phase fault. This is to be expected, both from experience and from the fact that only single-phase synchronizing power is now being supplied to the machine.

In Figure 6.2-2, the machine speed curves, it should be noted that the highest speed attained was 382 radians per second, or an increase of 1.33 per cent.

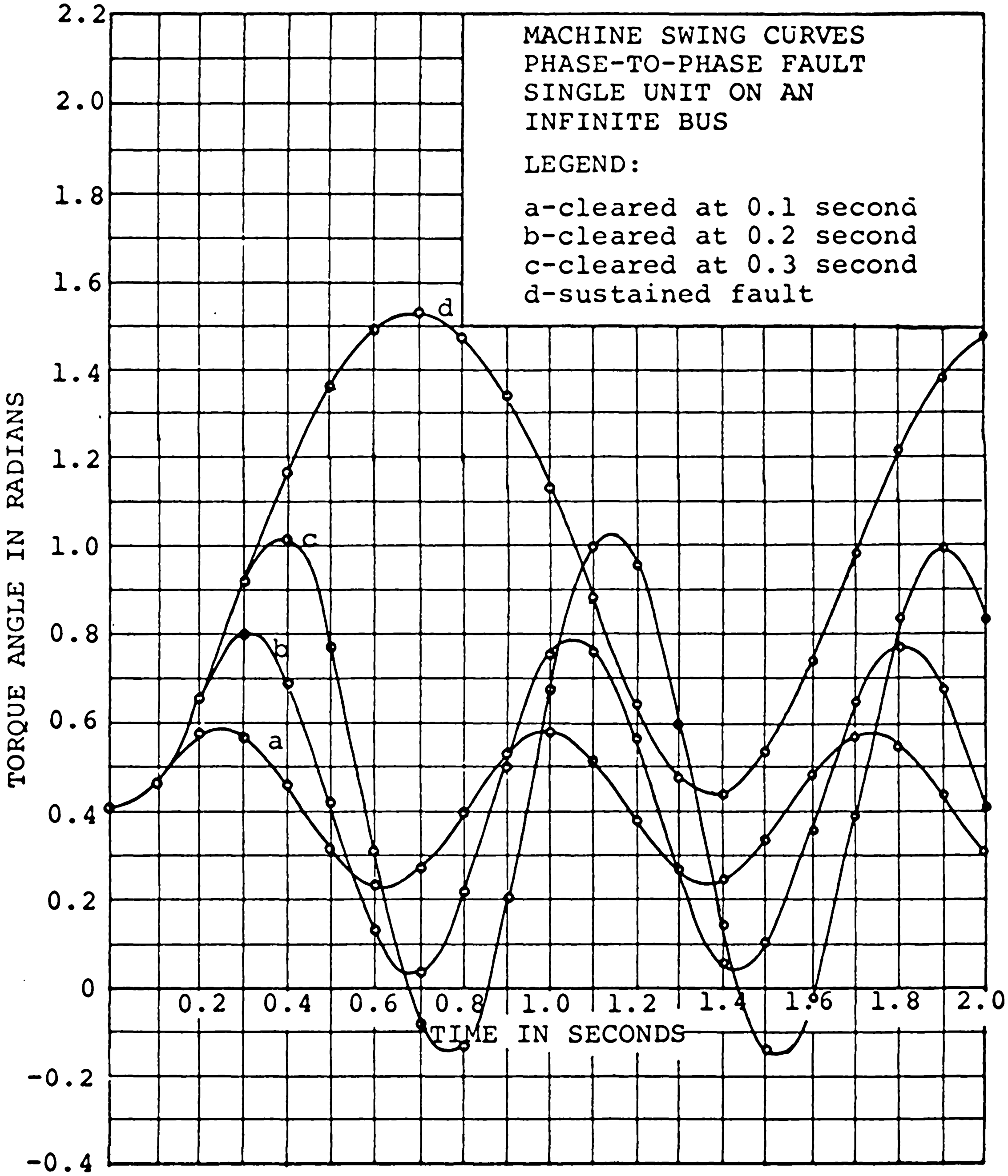
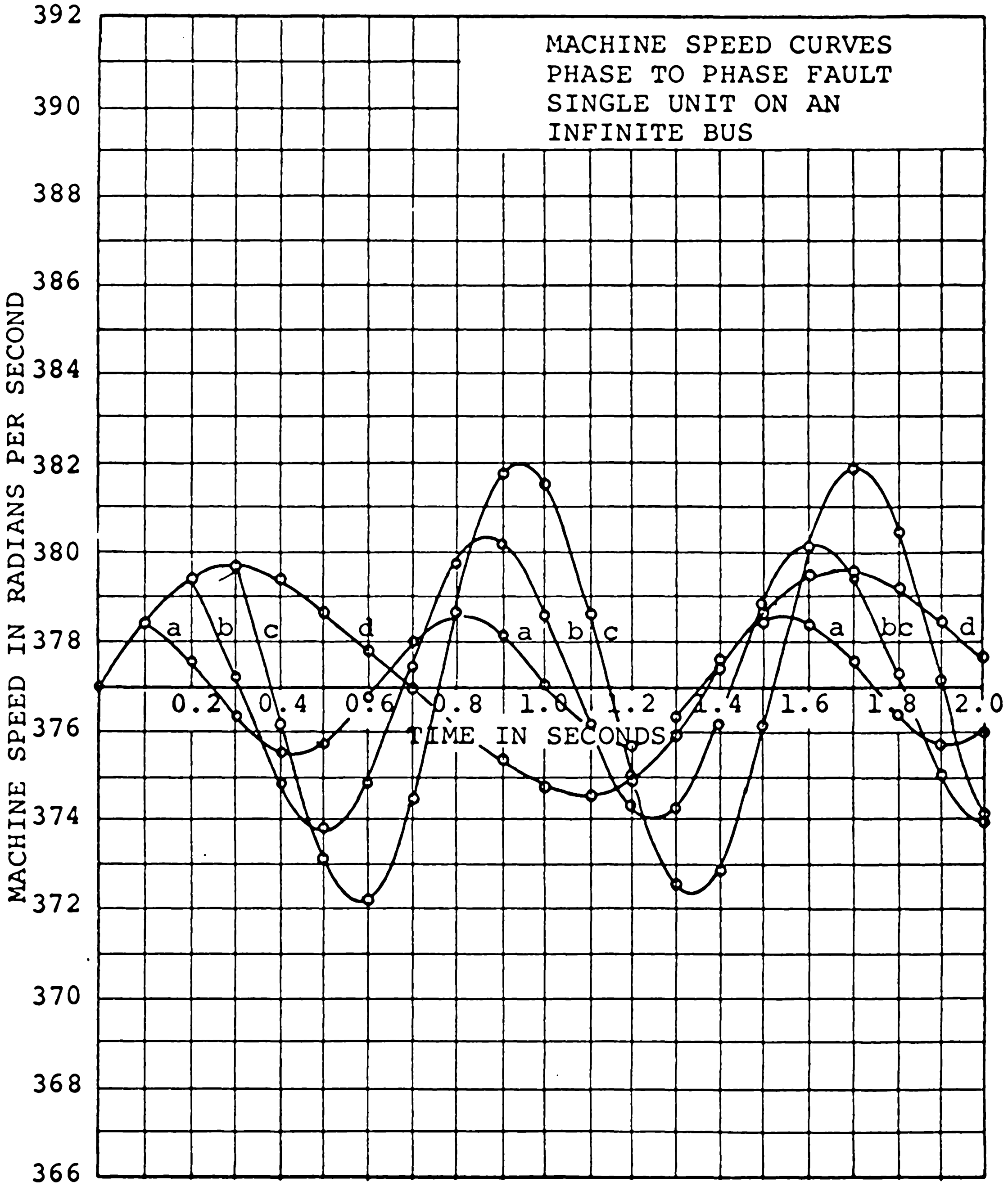


Figure 6.2-1. Sample Problem Swing Curves: Phase-to-Phase Fault



LEGEND:

a-cleared at 0.1 second
b-cleared at 0.2 second
c-cleared at 0.3 second
d-sustained fault

Figure 6.2-2. Sample Problem Speed Curves: Phase-to-Phase Fault

CHAPTER 7

THE TWO-LINE-TO-GROUND FAULT: THE EQUATIONS AND A SAMPLE PROBLEM

7.1 The Equations

References (4) and (13) show that the conditions necessary for this type of fault are

$$\begin{aligned} \bar{v}_s^{+}(t) &= \bar{v}_s^{-}(t) = v_s^{o}(t) \\ v_A(t) &= 3\bar{v}_s^{-}(t) \\ v_B(t) &= v_C(t) = 0 \end{aligned}$$

Then if $v_A(t)$ is of the form $V_s \cos \omega t$, the system voltages will be

$$\begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} = V_s \begin{bmatrix} \cos \omega t \\ 0 \\ 0 \end{bmatrix} \qquad (7.1\text{-}1)$$

Application of the transformation, Equation 3.3-4 to Equation 7.1-1 yields the transcendental voltage equations.

$$\begin{bmatrix} v_s^{o} \\ v_s^{d} \\ v_s^{q} \end{bmatrix} = \frac{V}{3} \begin{bmatrix} (1/\sqrt{2})\cos \omega t \\ \sin \alpha + \sin \gamma \\ -\cos \alpha - \cos \gamma \end{bmatrix} \qquad (7.1\text{-}2)$$

where $\gamma = 2\omega t + \alpha$

The zero-sequence equations must be utilized in this problem if the proper values of fault currents and voltages are to be realized. Again, the presence or absence of the zero-sequence equations has no effect on the stability of the system.

7.2 Sample Problem

This sample problem utilizes Equations 3.3-5, 3.3-6, 3.3-7, 5.1-1, and 7.1-2, which are repeated here for the sake of clarity.

$$\frac{d}{dt} i_s^o = 10^4 v_s^o - 50 i_s^o \tag{5.1-1}$$

$$\frac{d}{dt}\begin{bmatrix} i_s^d \\ i_s^q \\ i_r' \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 314 v_s^d - 1.57 i_s^d + \dot{\theta} i_s^q + 0.0834 i_r' \\ 314 v_s^q - 1.25\dot{\theta} - \dot{\theta} i_s^d - 1.57 i_s^q - 0.5\dot{\theta} i_r' \\ -314 v_s^d + 1.57 i_s^d - \dot{\theta} i_s^q - 0.1667 i_r' \\ \dot{\theta} \\ 31.4 + (78.6 + 0.1 i_r')\dot{\theta} i_s^q \end{bmatrix} \tag{3.3-7}$$

$$\begin{bmatrix} v_s^d \\ v_s^q \end{bmatrix} = V \begin{bmatrix} \sin\alpha \\ -\cos\alpha \end{bmatrix} \tag{3.3-5}$$

$$\begin{bmatrix} v_s^o \\ v_s^d \\ v_s^q \end{bmatrix} = \frac{V}{3} \begin{bmatrix} (1/\sqrt{2})\cos\omega t \\ \sin\alpha + \sin\gamma \\ -\cos\alpha - \cos\gamma \end{bmatrix} \tag{7.1-2}$$

where $\alpha = \theta - \omega t - \pi/2$ (3.3-6)

and $\gamma = 2\omega t + \alpha$

Again, a choice is made between Equation 3.3-5 for a cleared condition or Equation 7.1-2 for a faulted condition. A CSMP program for this fault type is given in the appendix.

The swing curves given in Figure 7.2-1 show that the machine will go out of synchronism under these conditions, but not as quickly as with a three-phase fault. This is due to the presence of one line and ground to supply a small amount of synchronizing power to the machine during the fault. It will also be noted that the machine will stay in synchronism if the fault is cleared within 0.3 seconds, which, when compared with the same clearing time for a three-phase fault shows the stability problem to be less severe for this type. Therefore, this fault type lies between the phase-to-phase and the three-phase in terms of stability.

The machine speed curves, Figure 7.2-2, also indicates that stability is lost for this system under a sustained fault of this type.

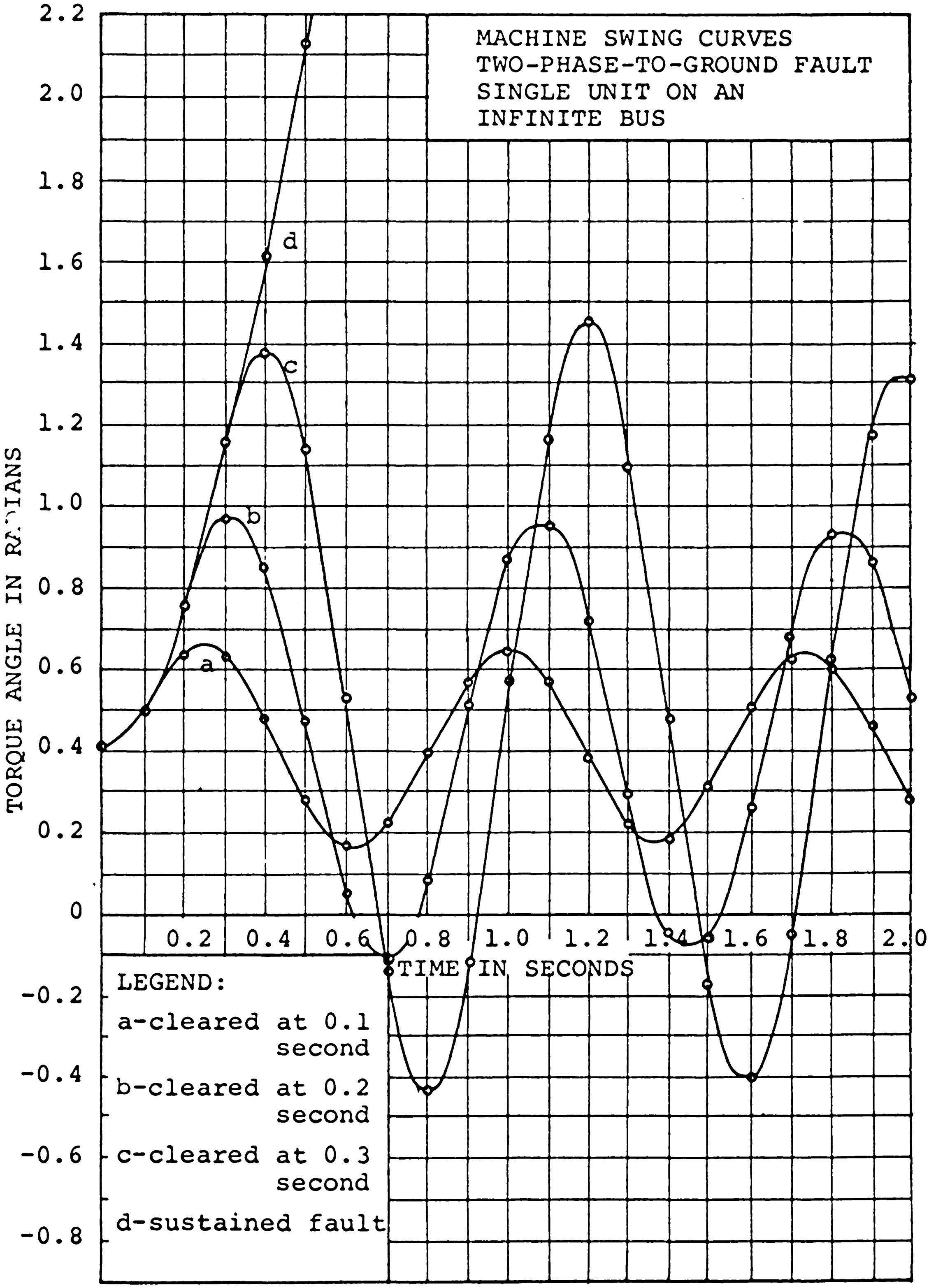
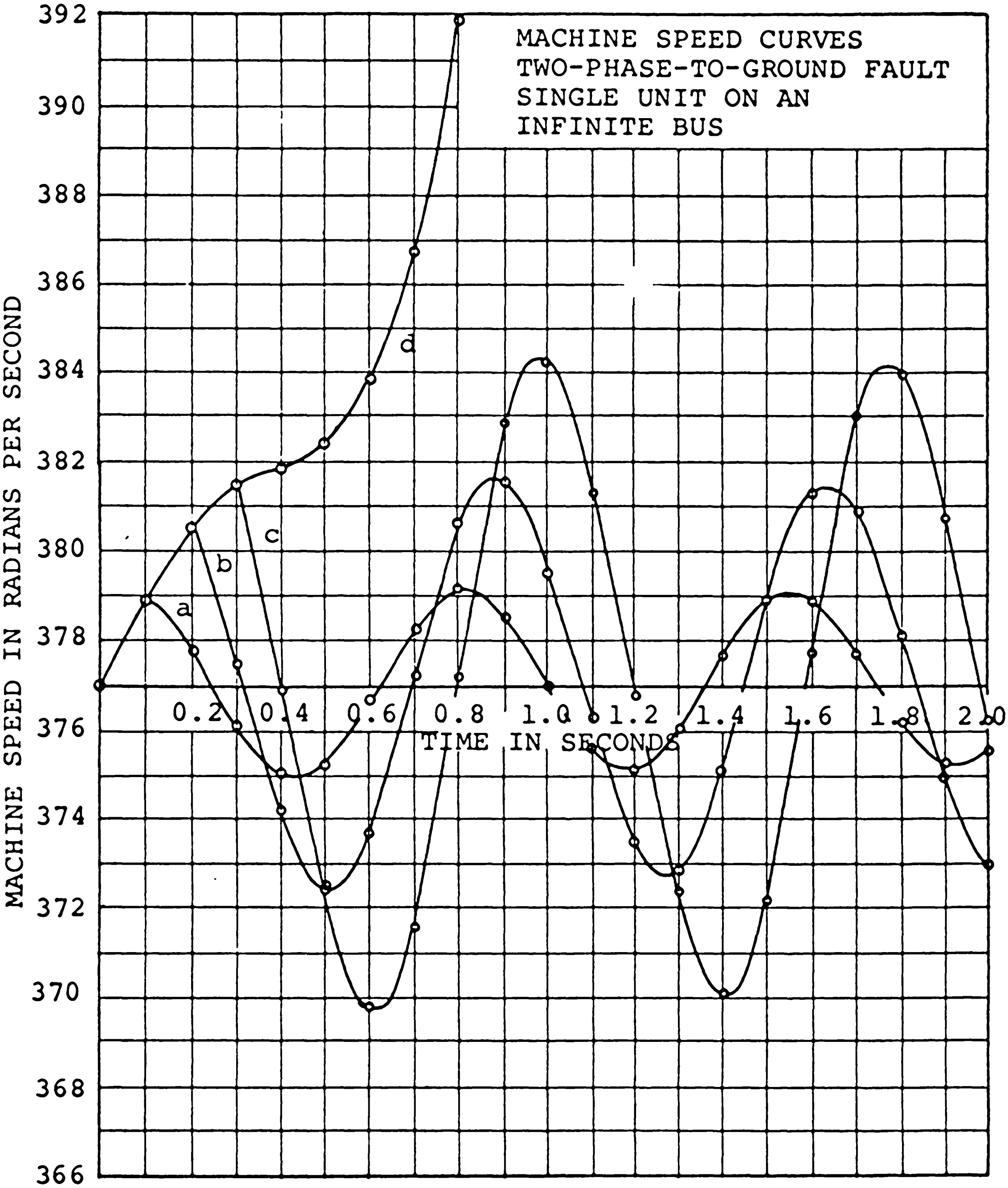


Figure 7.2-1. Sample Problem Swing Curves: Two-Phase-to-Ground Fault



LEGEND:

a-cleared at 0.1 second
b-cleared at 0.2 second
c-cleared at 0.3 second
d-sustained fault

Figure 7.2-2. Sample Problem Speed Curves: Two-Phase-to-Ground Fault

CHAPTER 8

COMPARISON OF RESULTS

8.1 Swing Curves

Since the same system was studied under each type of fault, it was felt that a plot of the swing curves caused by each fault type for a given clearing time would prove to be enlightening. Such a plot is shown as Figure 8.1-1. It should be noted that all the peaks occur approximately 0.1 seconds after the fault is cleared at 0.2 seconds, with the peak value of the single-phase-to-ground fault being 0.65 radian, while that of the three-phase fault is 1.39 radians. These results are as expected, and serve to indicate the validity of the method.

8.2 Currents

Figure 8.2-1 shows a comparison of both direct- and quadrature-axis currents for various types of faults on the same system, all cleared at 0.2 seconds. It is interesting to note that the largest magnitudes of both currents occurred in the most severe faults, but that the single-phase-to-ground fault had a higher magnitude of quadrature-axis current on the first swing than did the phase-to-phase fault. This phenomena could possibly be explained in a future study.

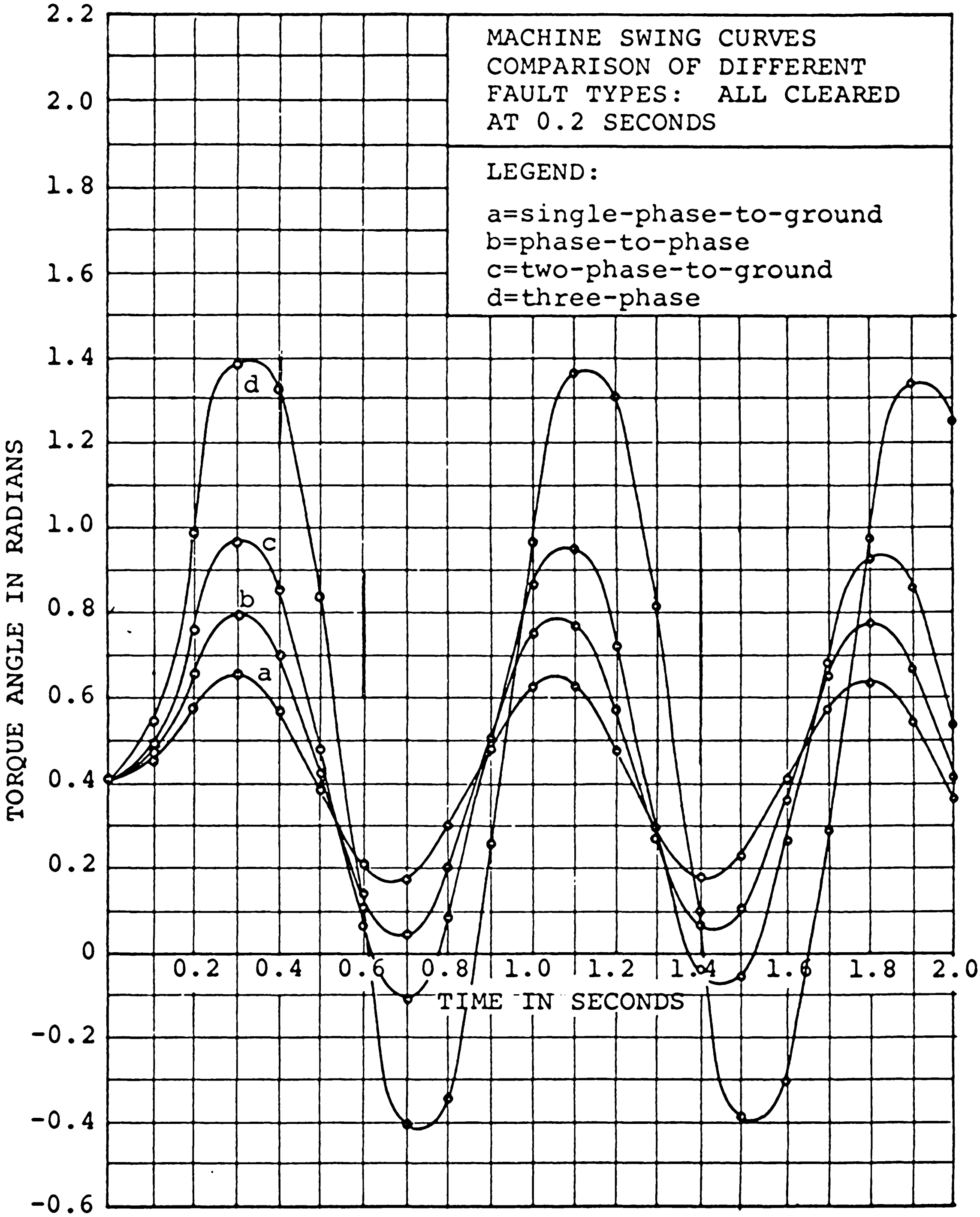
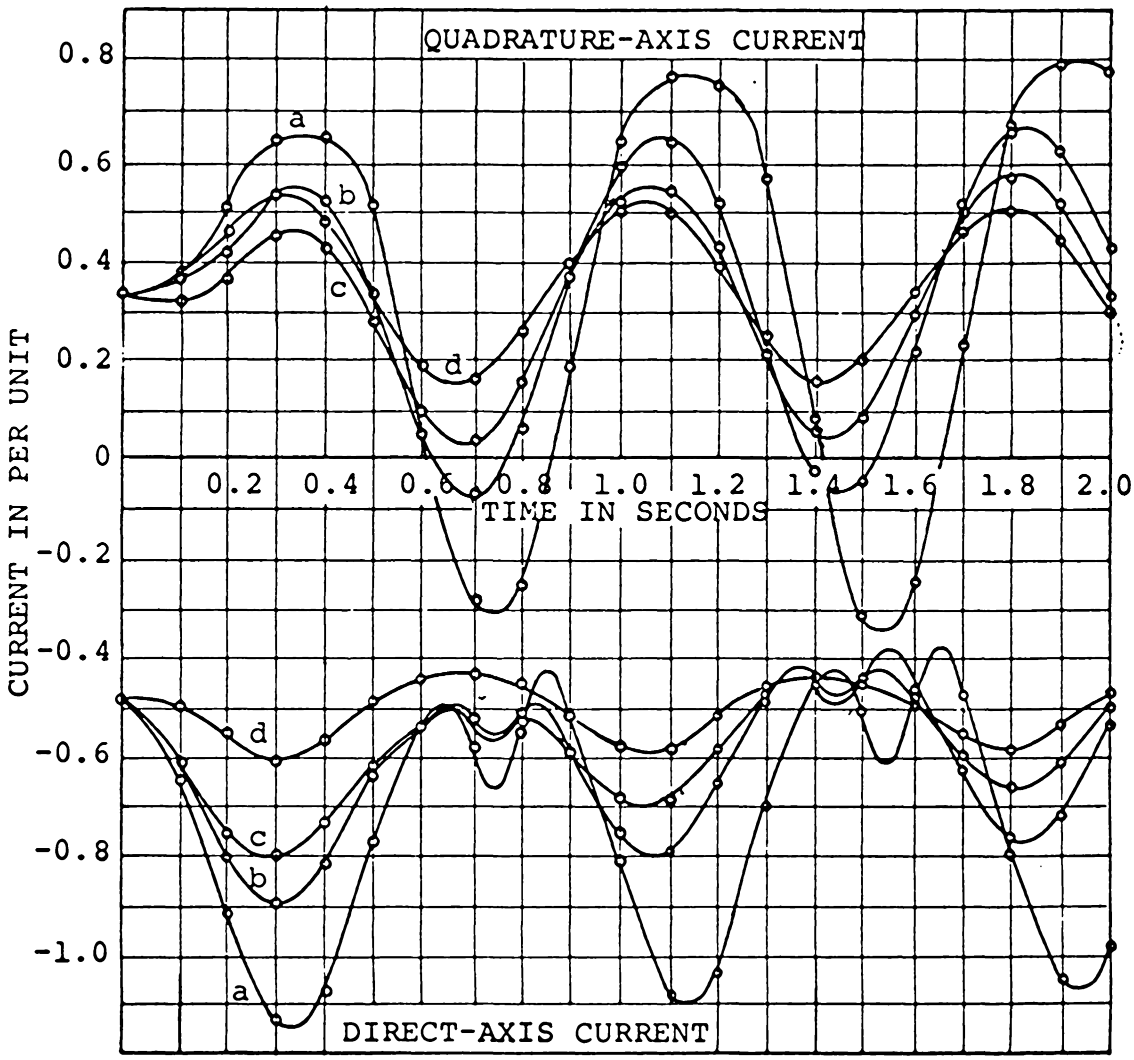


Figure 8.1-1. Sample Problem Swing Curves: Comparison of Fault Types



LEGEND:

a=three-phase
b=two-phase-to-ground
c=phase-to-phase
d=single-phase-to-ground
All faults cleared at t = 0.2 second

Figure 8.2-1. Sample Problem Direct- and Quadrature-Axis Currents Comparison of Fault Types

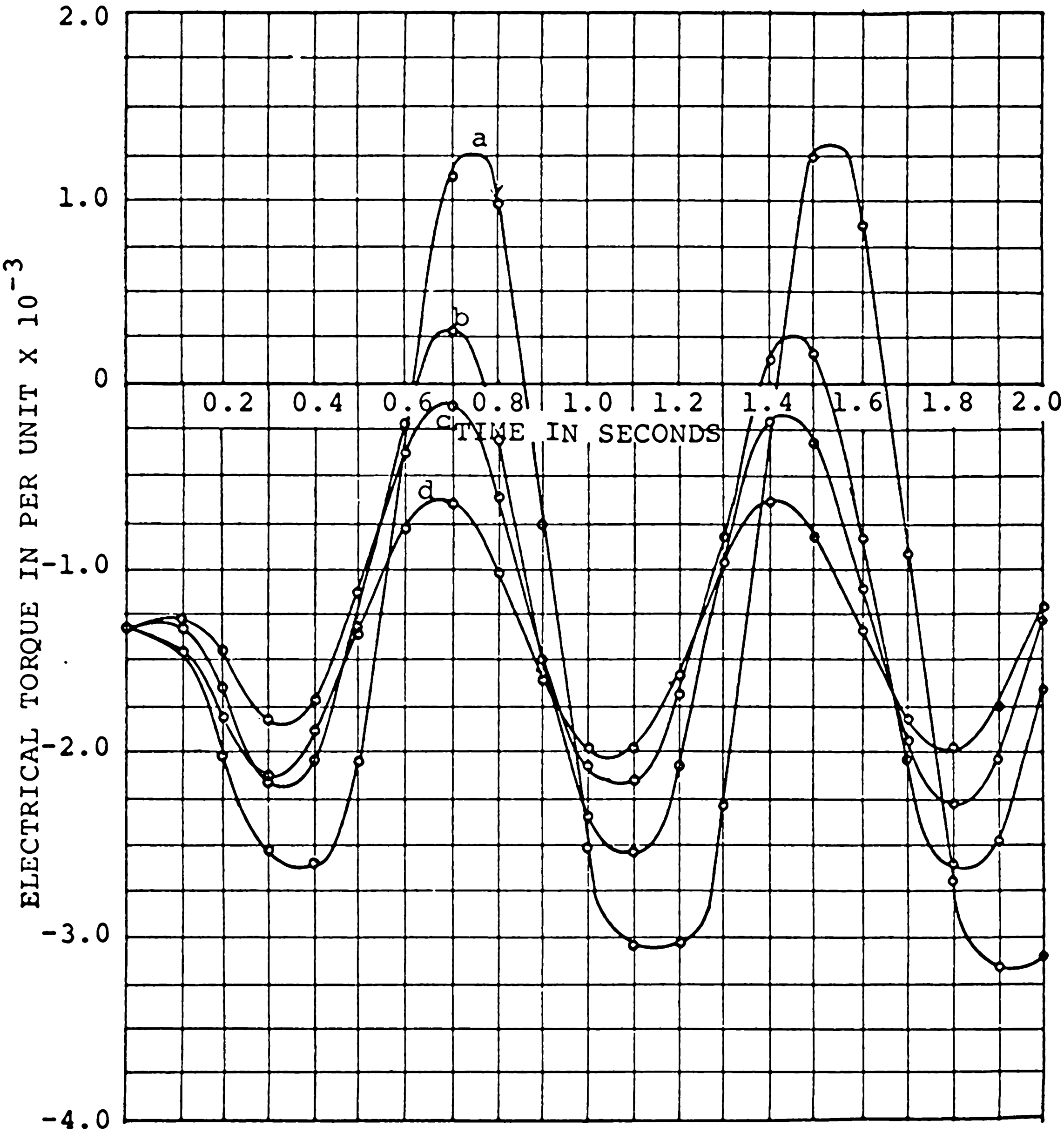
The expression for electrical torque is

$$-(1.5/\omega + \sqrt{2}L_{sr}^{+}i_r')\,i_s^q \qquad (8.2\text{-}1)$$

which reduces to $-(1.5/\omega)i_s^q$ since i_r' is small enough to be neglected, as will be shown below. A plot of electrical torque, as shown in Figure 8.2-2, is then directly proportional to i_s^q.

The comparison of field incremental currents given in Figure 8.2-3 shown that the maximum variation of field current is of the order of 2.7×10^{-4} units, even for the most severe type of fault. By comparing this to the assumed operating point of 1.6 unit of rotor current, it will be seen that the maximum variation is of an order of 1.69×10^{-4} unit, or $(1.69 \times 10^{-4} \times 100)/1.6 = 0.0106\%$. At a slope of 0.6 for the operating point on Figure 3.3-2, it will be seen that the variation incurred in the generated voltage will be approximately $0.6 \times 1.69 \times 10^{-4}$ per unit, or 1.01×10^{-4} away from a starting point of 1.5 units, which results in an overall change of only $(1.01 \times 10^{-4}/1.5) \times 100 = 0.00673\%$, which is negligible. Therefore, the portion of the program which deals with the variations of field current can be removed with no perceptible disturbance to the results, thus greatly simplifying the programs.

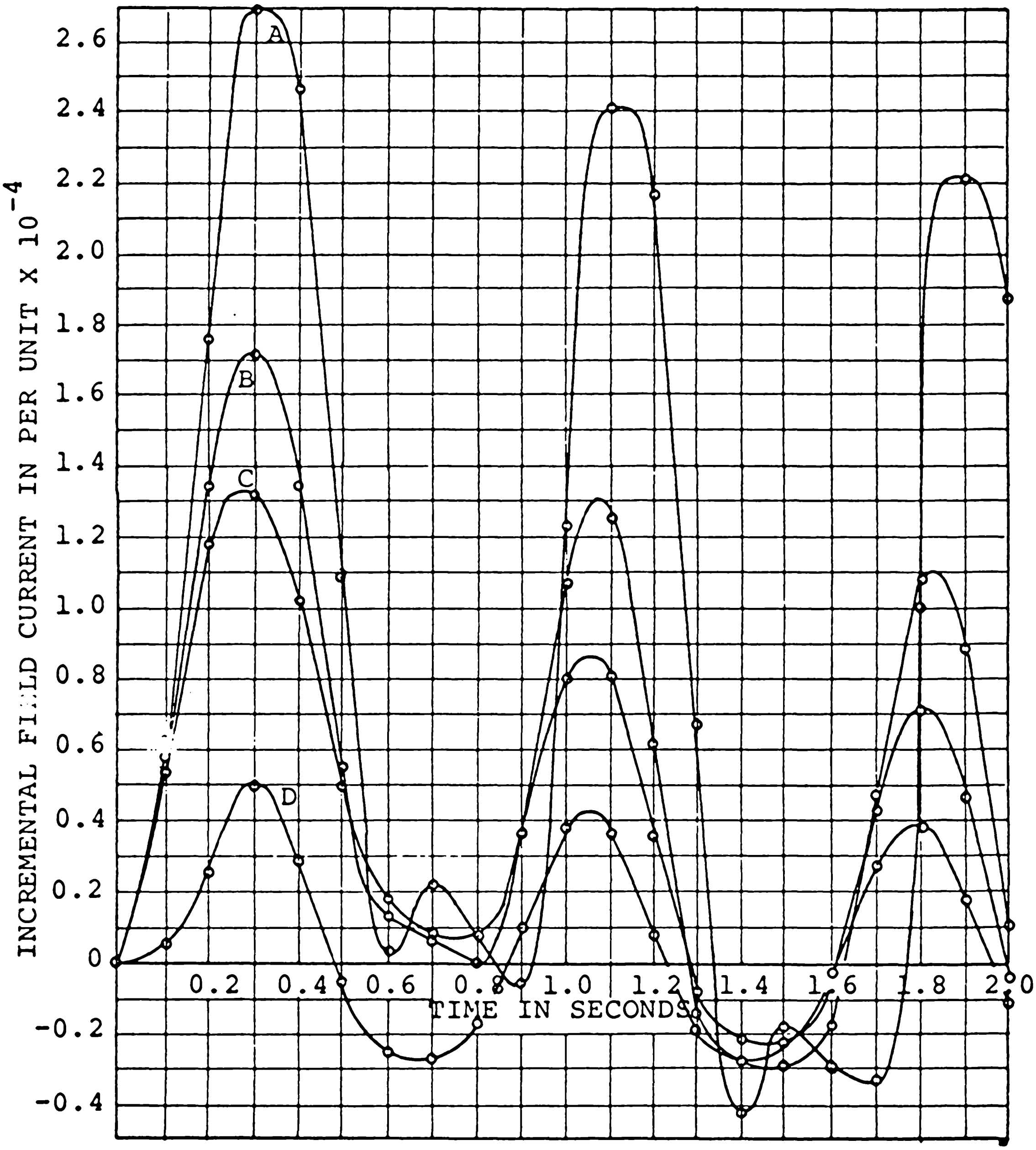
Figure 8.2-4 shows both the zero-sequence currents and voltages for two types of faults which involved ground.



LEGEND:

a=three-phase fault
b=two-phase-to-ground fault
c=phase-to-phase fault
d=one-phase-to-ground fault
cleared at 0.2 second

Figure 8.2-2. Sample Problem Electromagentic Torques Comparison of Fault Types



LEGEND:

A = three-phase fault
B = two-phase-to-ground fault
C = phase-to-phase fault
D = single-phase-to-ground fault
All faults cleared at t = 0.2 second

Figure 8.2-3. Sample Problem Incremental Field Currents Comparison of Fault Types

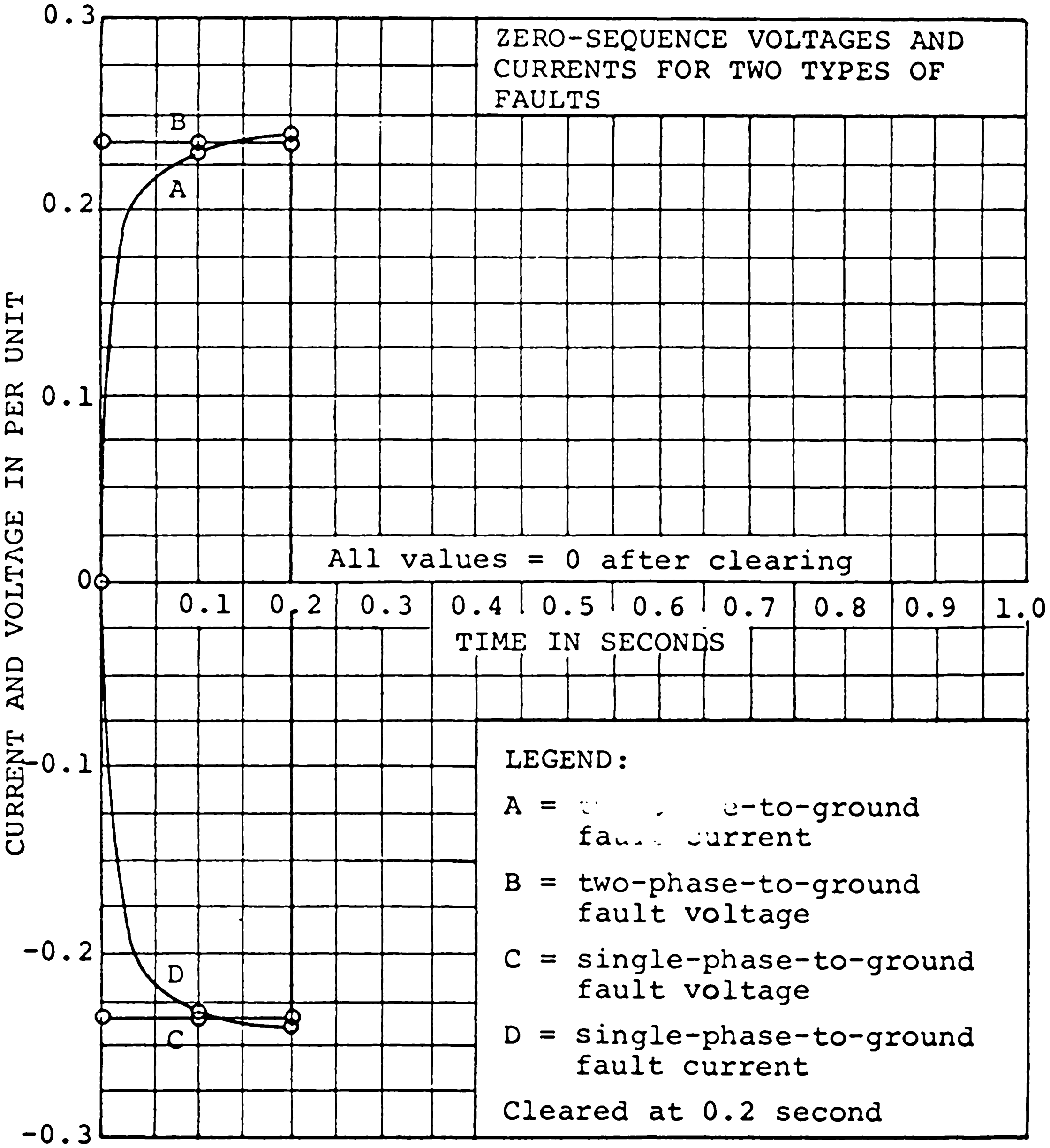


Figure 8.2-4. Sample Problem Zero-Sequence Currents and Voltages Comparison of Fault Types

These curves are of no great importance for a stability study, but are necessary to determine the total fault currents and voltages involved.

Figures 8.2-5, 8.2-6, 8.2-7, and 8.2-8 show the magnitudes of line currents for the various types of faults. These curves were obtained by recombining the direct-axis, quadrature-axis, and zero-sequence currents into line currents. Since line currents are phasor quantities, the absolute values were plotted.

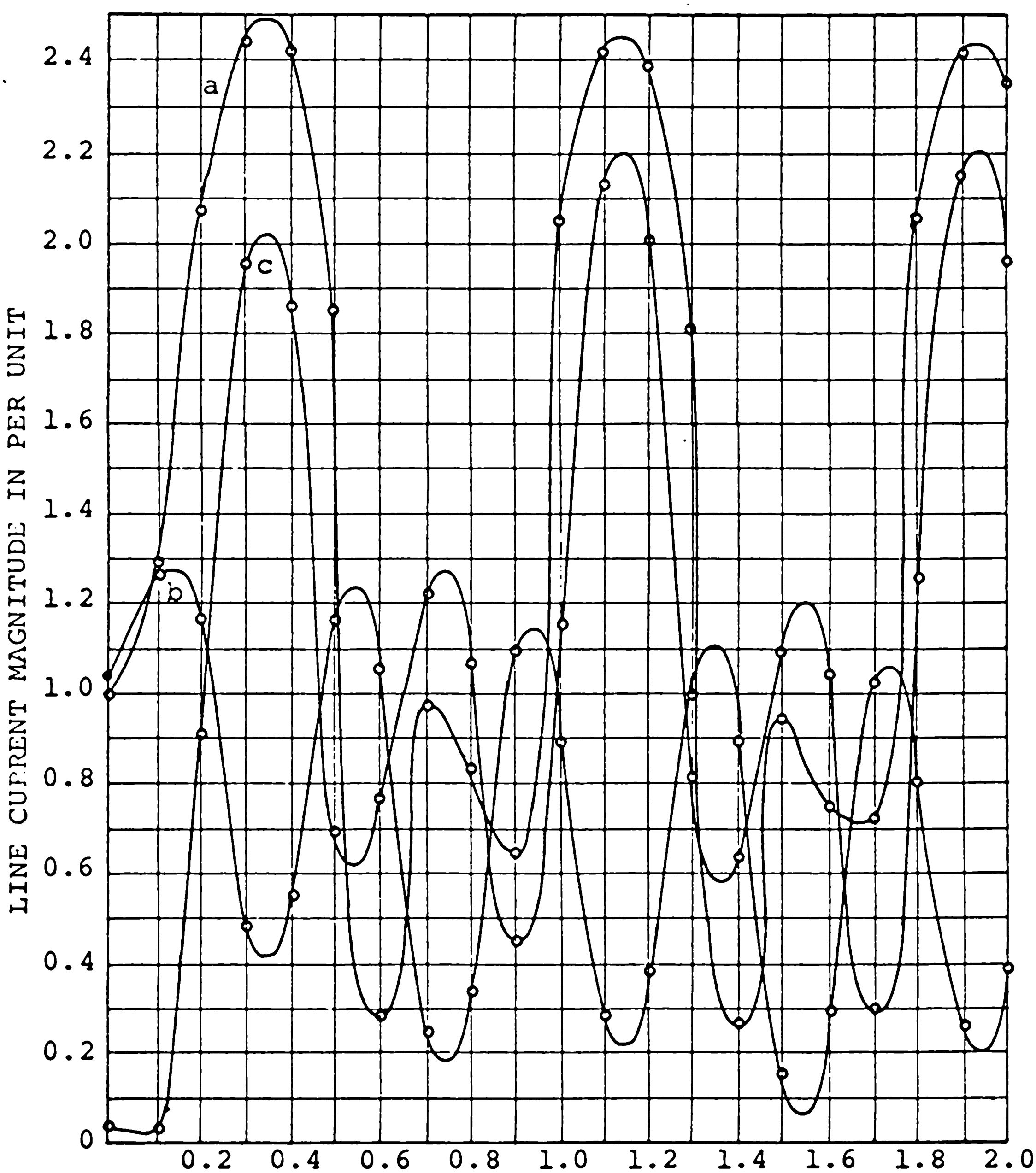
8.3 Voltages

The zero-sequence voltages are shown in Figure 8.2-4, along with the currents.

Figure 8.3-1 shows a comparison of direct-axis and quadrature-axis voltages. Note that the clearance of the fault resulted in an offset of the voltages. This was to be expected, since the fault voltages will show such a disturbance during oscillographic records when a system is faulted. This offset occurred due to a change in the voltage equations when the system is cleared.

8.4 Machine Speeds

The curves shown in Figure 8.4-1 show that the machine under study tends to oscillate about synchronous speed when the fault is removed, but that the oscillation is damped. They also indicate that the more severe the fault type, the



LEGEND:

a = phase a
b = phase b
c = phase c
cleared at 0.2 second

Figure 8.2-5. Sample Problem Line Current Magnitudes: Three-Phase Fault

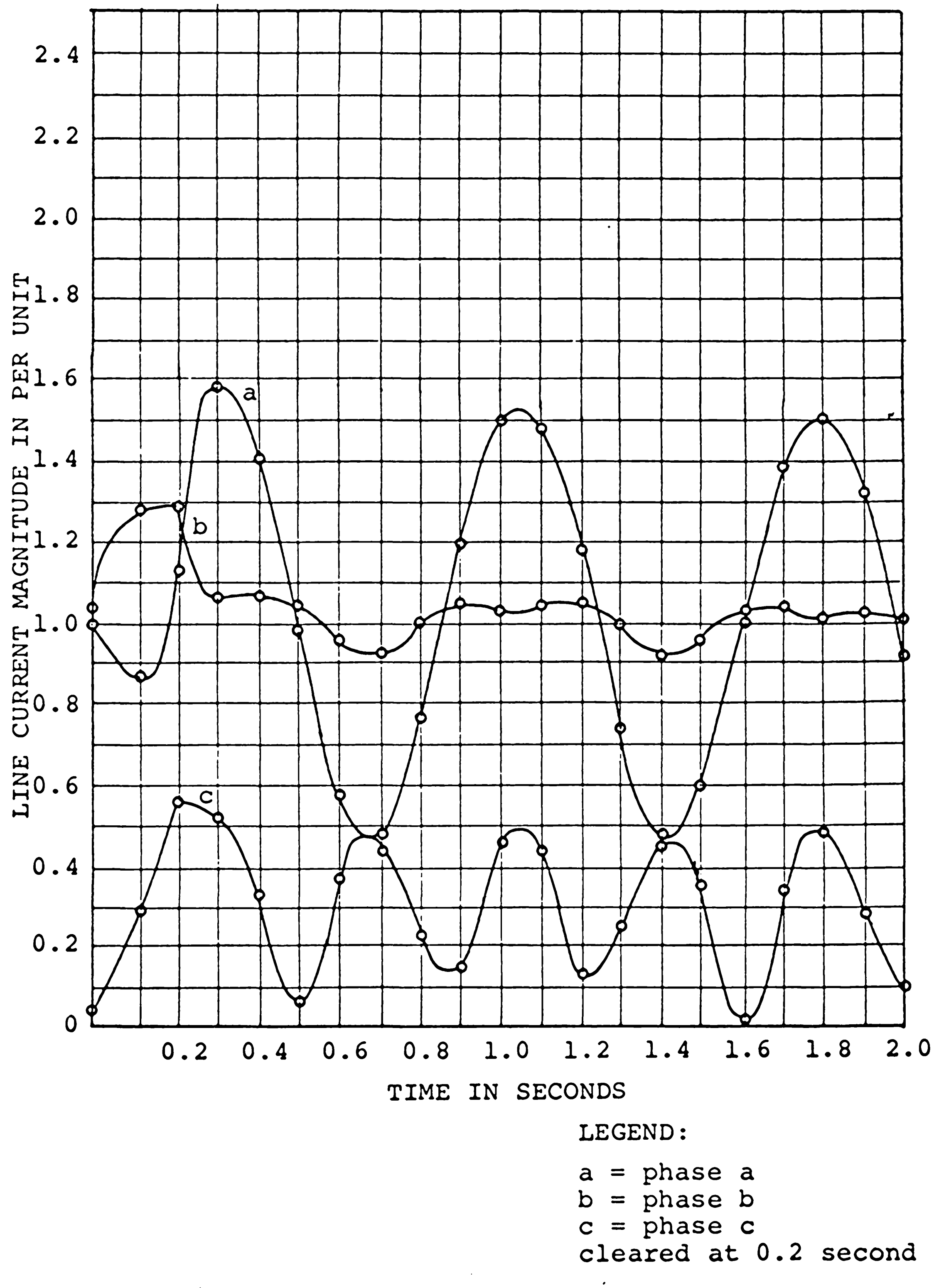


Figure 8.2-6. Sample Problem Line Current Magnitudes Single-Phase-to-Ground Fault

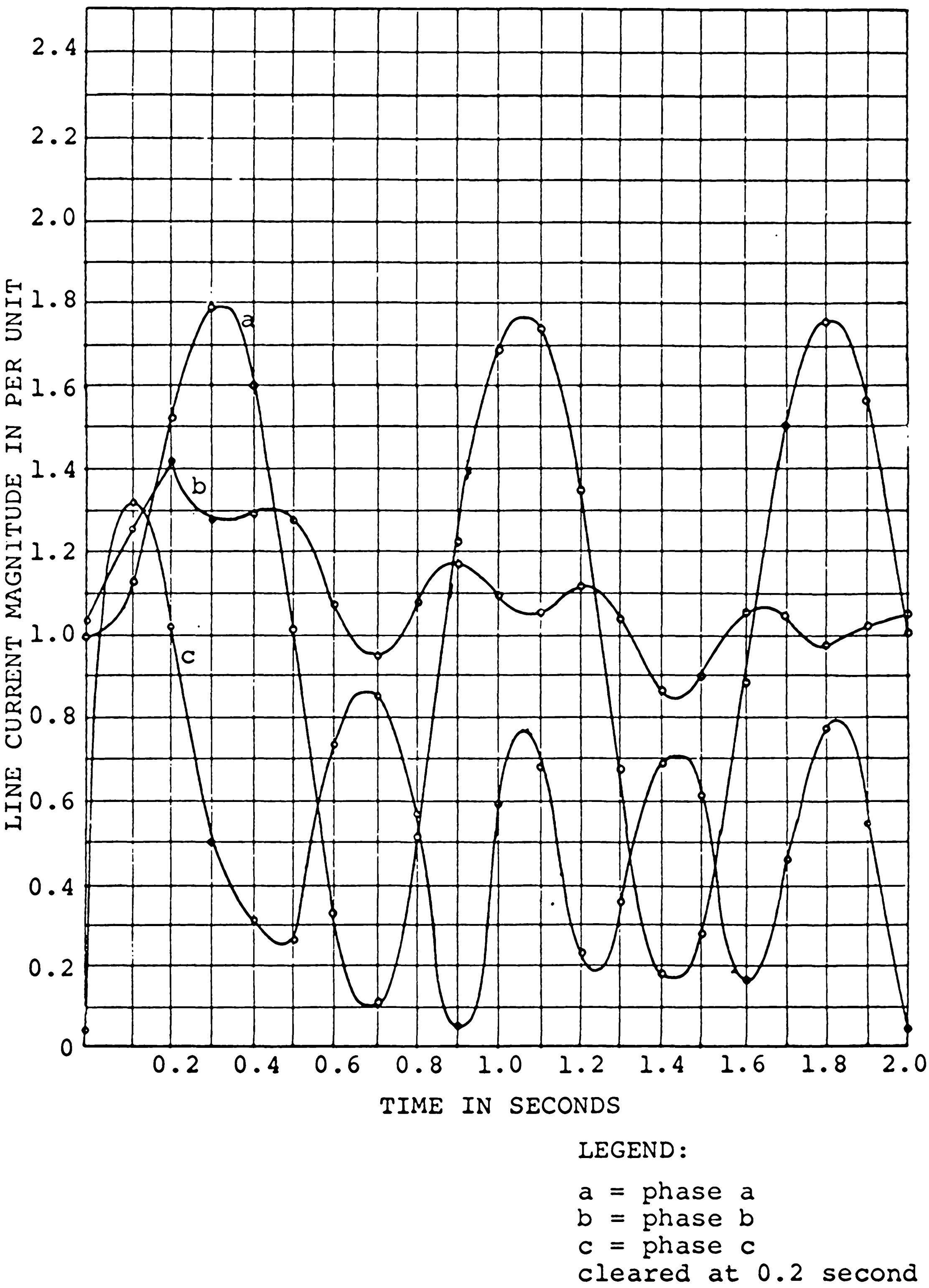


Figure 8.2-7. Sample Problem Line Current Magnitudes: Phase-to-Phase Fault

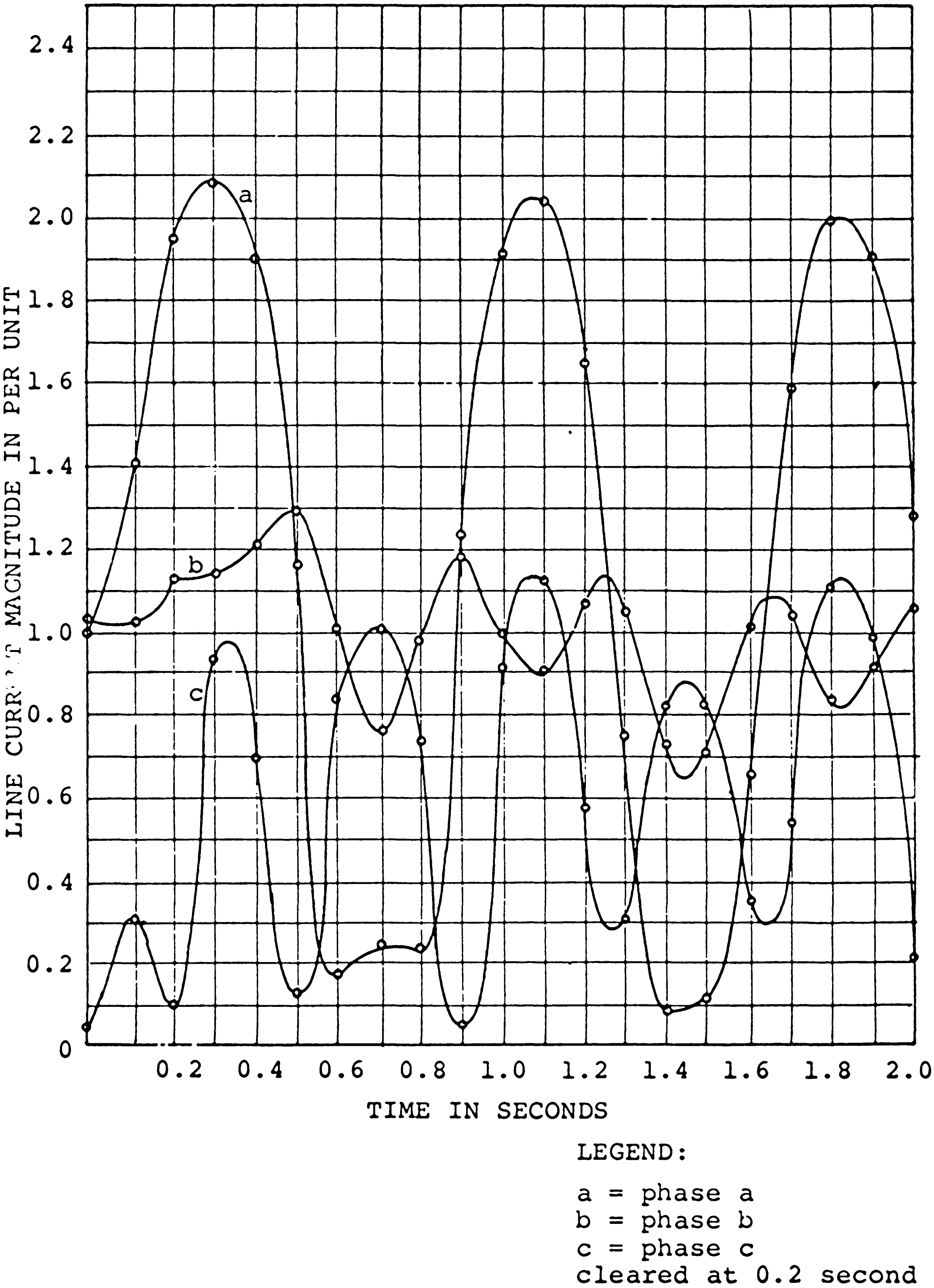
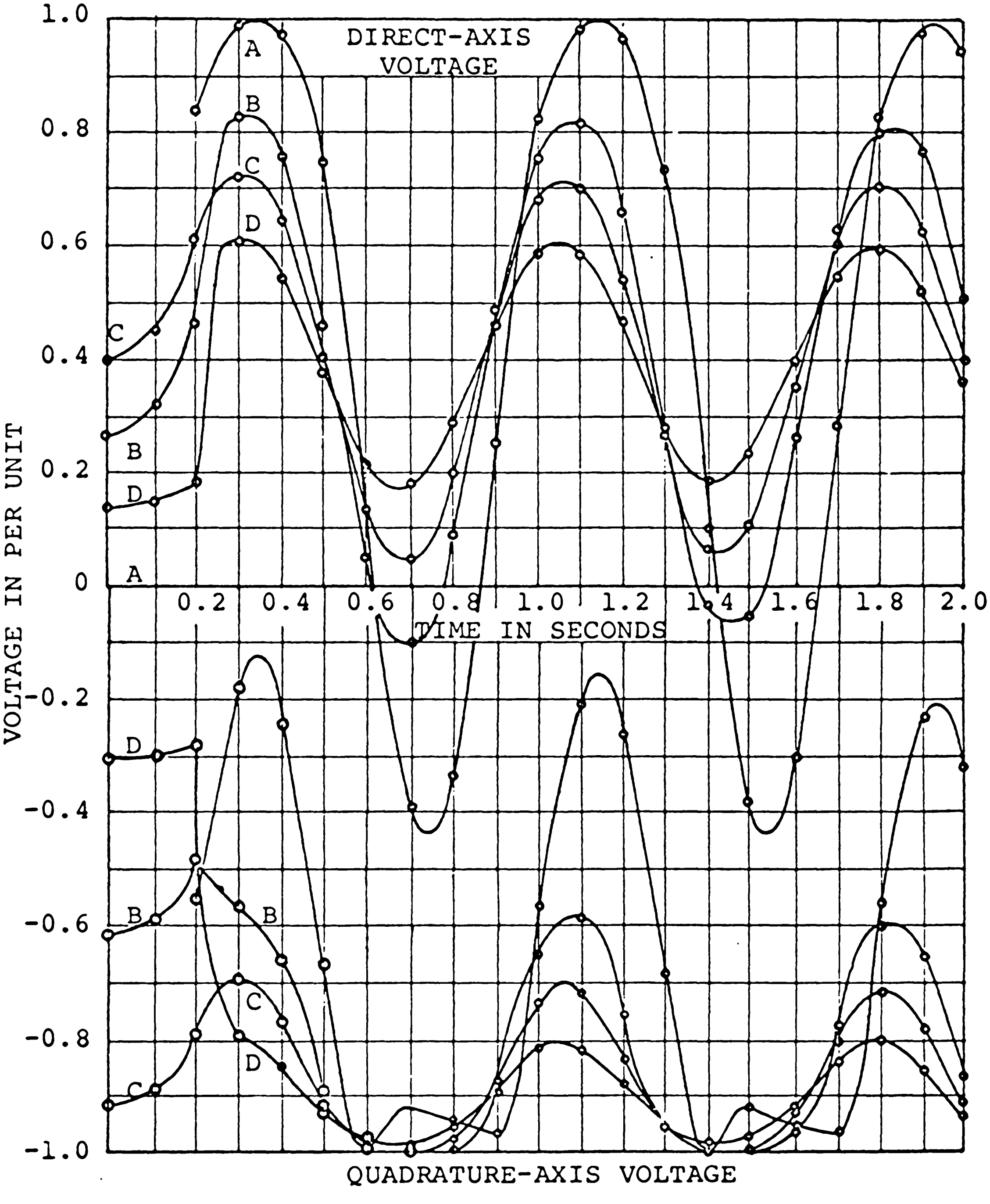


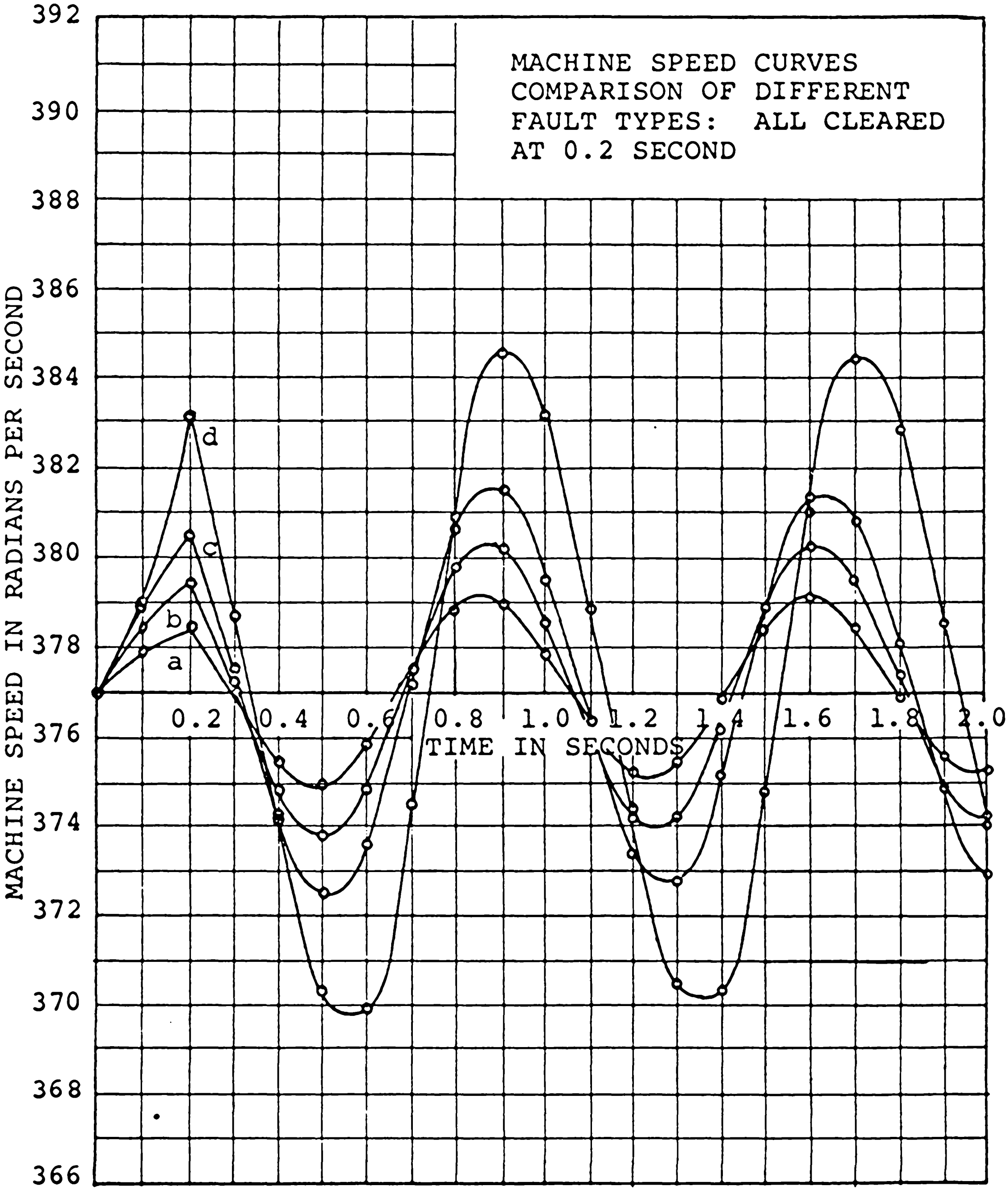
Figure 8.2-8. Sample Problem Line Current Magnitudes: Two-Phase-to-Ground Fault



LEGEND:

A = three-phase fault
B = two-phase-to-ground fault
C = phase-to-phase fault
D = single phase-to-ground fault
All faults cleared at t = 0.2 second

Figure 8.3-1. Sample Problem Direct- and Quadrature-Axis Voltages: Comparison of Fault Types



LEGEND:

a = one-phase-to-ground
b = phase-to-phase
c = two-phase-to-ground
d = three-phase

Figure 8.4-1. Sample Problem Speed Curves: Comparison of Fault Types larger the magnitude of this oscillation. It must be remembered that no provision was made for either governor action or for the effects of saliency in this study, and that these effects would tend to damp the oscillations more rapidly than shown by the curves. It should be noted that the oscillations caused by the three lesser faults are all in phase with each other, but that there is a definite phase shift in the curve for the three-phase fault. This is due to the machine having no synchronizing power available during the fault, which in turn led to a much larger swing, thereby causing the machine to approach much closer to instability. These results again agree with theory and practice, and tend to show the validity of the method. There are many other curves which may be plotted from these studies, but these are considered to be the ones of greatest significance.

CHAPTER 9

INTRODUCTION TO PARADISE

9.1 Introduction

It was the author's privilege to participate in some staged fault tests performed by the Tennessee Valley Authority on their 500 KV system during the summer of 1969. The system is shown in Figure 9.1-1, and consists of a 1278 MVA cross-compound machine located in Paradise, Kentucky, tied to the TVA system through a 90-mile 500 KV radial line which terminates at the Davidson substation in Nashville, Tennessee. The line is compensated for capacitance by shunt reactors at Davidson. During the staged fault tests, the change in the unfaulted phase voltages at Davidson was undetectable on an oscillographic record. Under these conditions, the system at Davidson simulated the action of an infinite bus, and the fault and stability studies became almost the classic textbook case of a single machine on an infinite bus.

9.2 The Paradise Machine

The one deviation from the classic textbook system lay in the type of machine at the Paradise plant. This machine, Paradise Unit 3, is a 1278 MVA, cross-compound unit, but it is peculiar in that the two units which form the machine

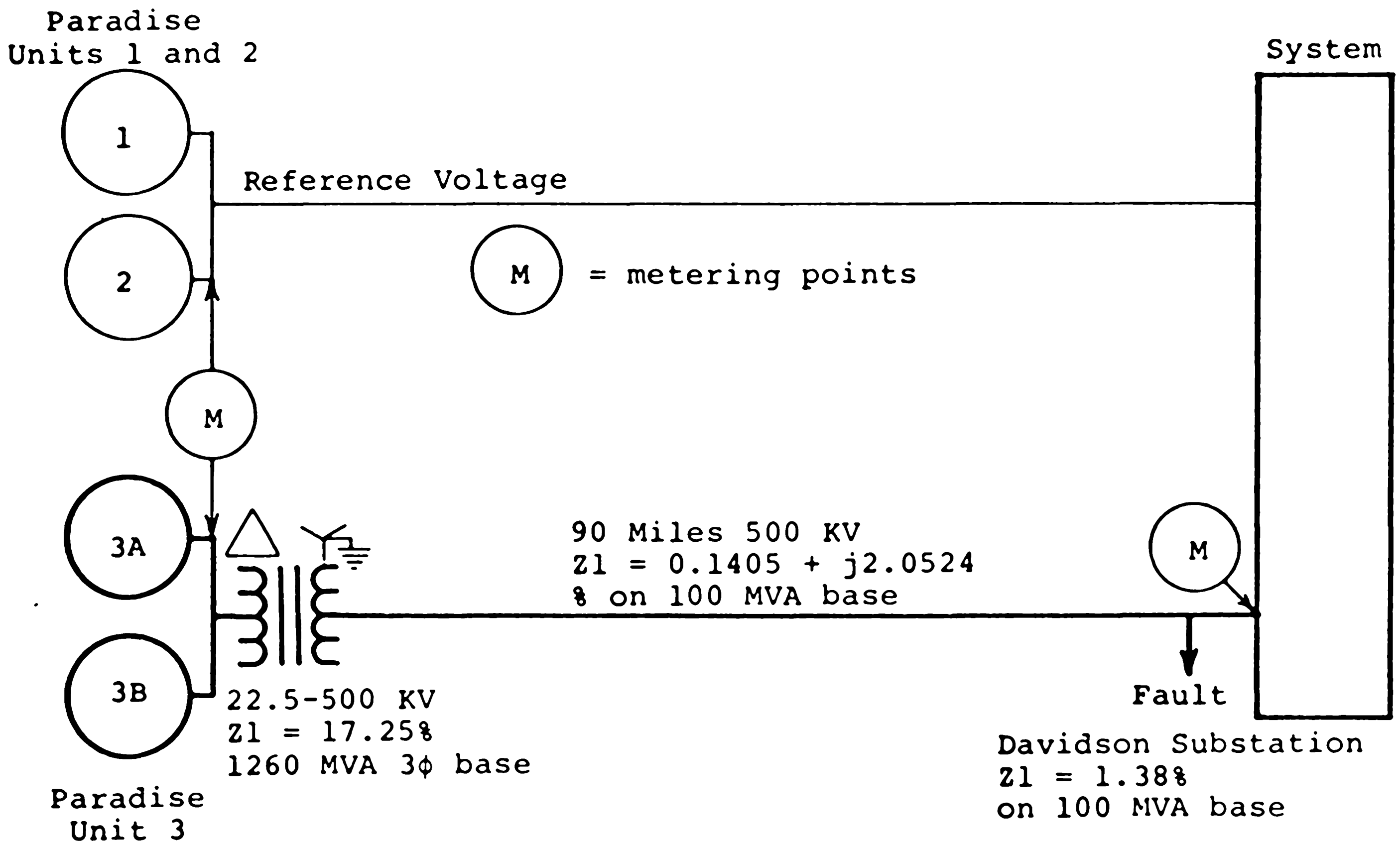


Figure 9.1-1. System for Field and Computer Studies

operate at two different speeds, and have widely differing moments of inertia. The values that are of interest in this study are given in Figures 9.2-1 through 9.2-3 which were taken from the manufacturer's specifications. Figure 9.2-4 shows a diagram of such an alternator, and it will be noted that the units are very closely coupled electrically while being separated mechanically. This means that the equations had to be written using two separate machines, but with a common voltage, which had to be taken at the fault. Since the only fault test which could be used in this study was at Davidson, the line impedance had to be inserted in the equations. It will also be noted that while both units may swing about the system, the lighter unit may also swing about the heavier unit, which leads to rather unique performance.

While at first glance it may seem that the two machines are treated here as a single unit, close attention to the equations given in the next section will show that the units are actually kept separate, but with a common terminal voltage. This models the system as it exists, rather than idealizing it into something which might possibly be easier to handle mathematically but which would not be as exact a model. The two units interact electrically because they are connected to the same machine bus, which accounts for the terms in the equations of each unit which are dependent upon the other unit. The machine bus is connected to the line,

DESCRIPTION AND UNITS	SYMBOL	VALUES FOR UNIT A	UNIT B
Kva, rated		639,000	639,000
kw at rated power factor	P	575,100	575,100
Current, rated amperes		15,372	15,372
Power-factor, rated		0.90	0.90
Machine speed, rpm		3,600	1,800
Number of Phases		3	3
Number of Poles		2	4
Cycles		60	60
Volts, line		24,000	24,000
Mechanical Constant, Lbs. Ft^2	WR^2	296,600	6,262,000
Direct-axis synchronous reactance per unit	X_d	1.74	1.77
Stator leakage reactance saturated per unit	X_1	0.171	0.175
Stator winding resistance, per phase, ohms	R_d	0.00197	0.00183

Taken from TVA Turbogenerator Data Sheets 661C99-35 and 661C99-36.

Figure 9.2-1. Specifications Paradise Generator

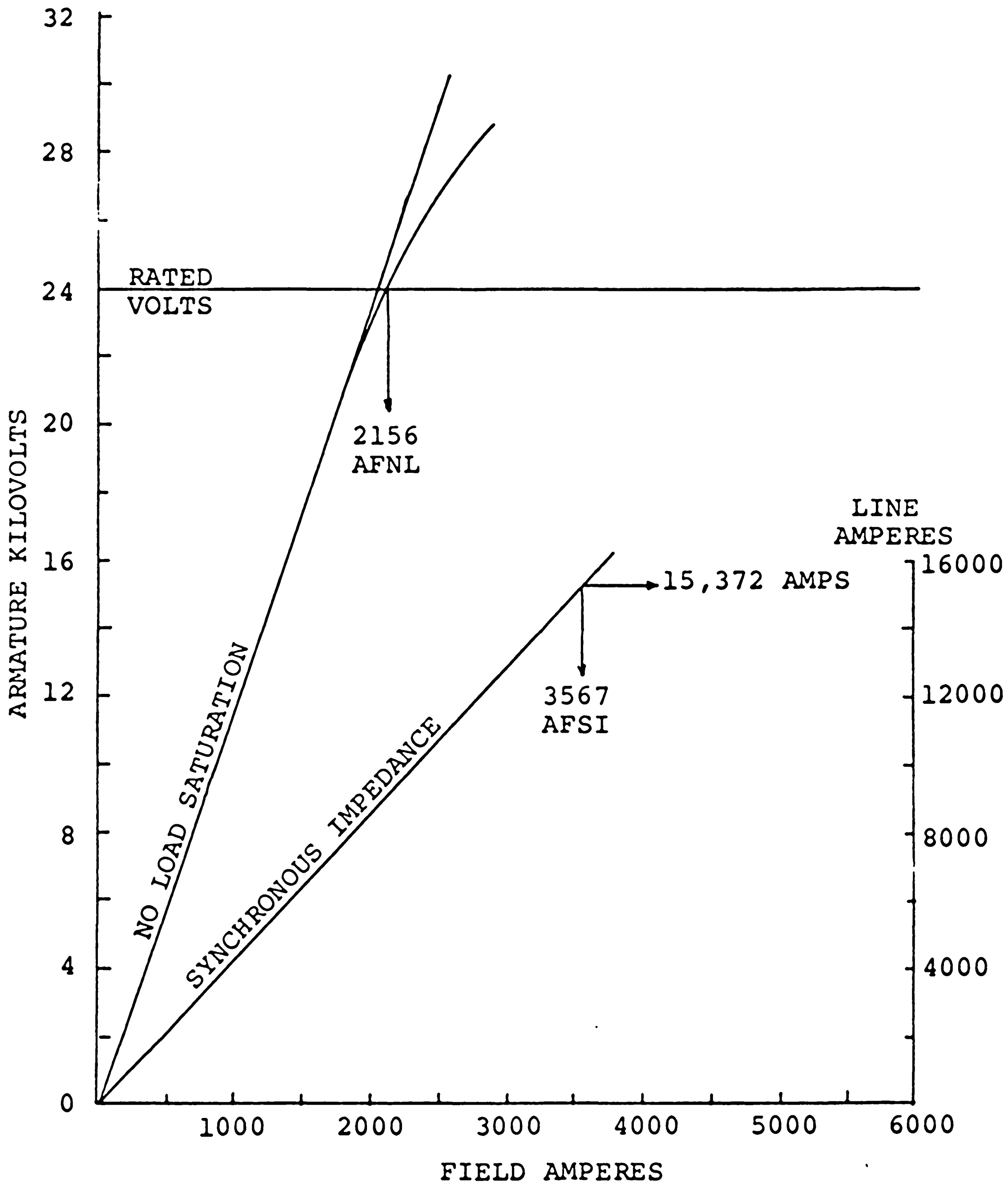


Figure 9.2-2. Saturation Curve for Paradise Unit A

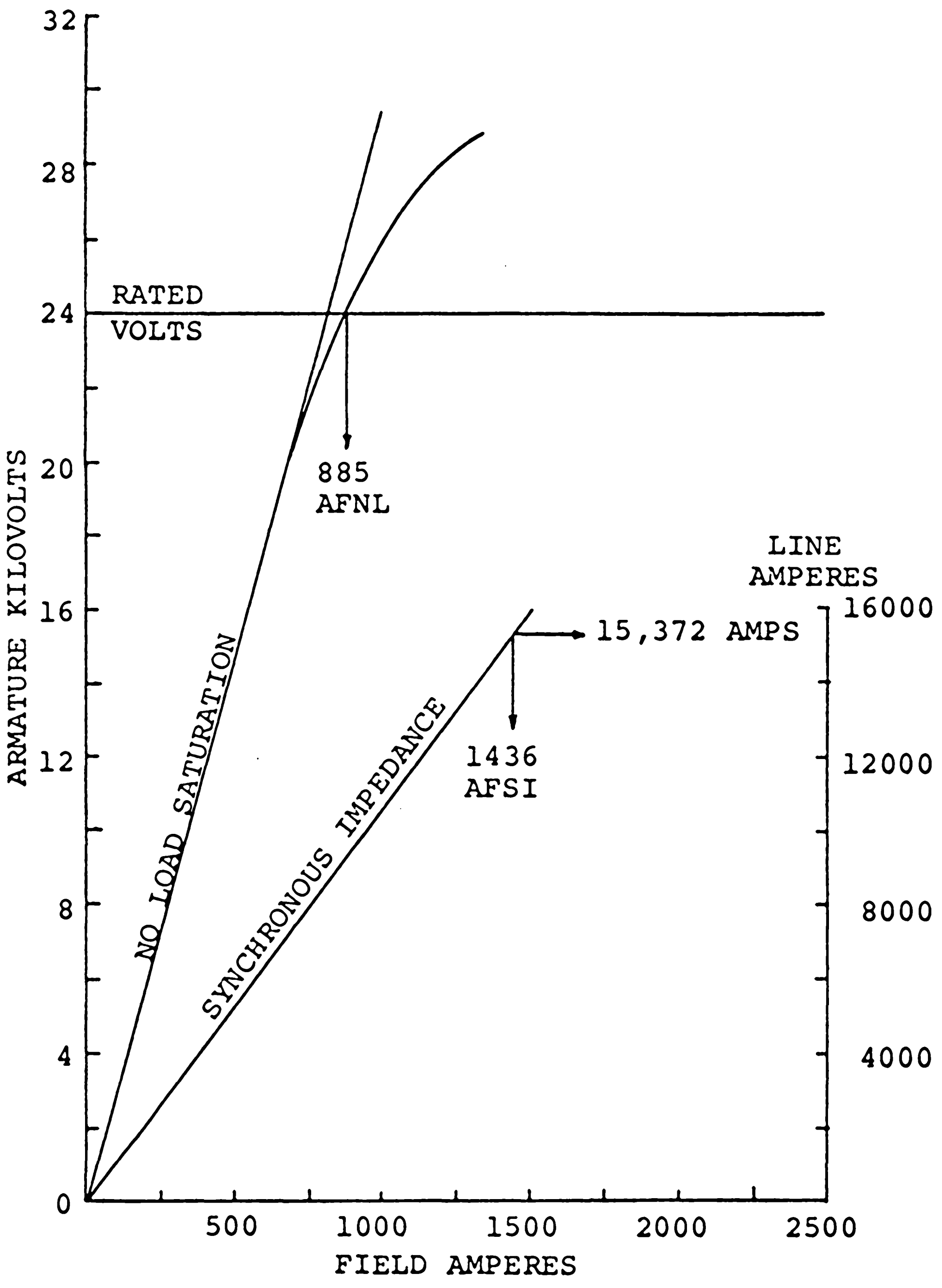


Figure 9.2-3. Saturation Curve for Paradise Unit B

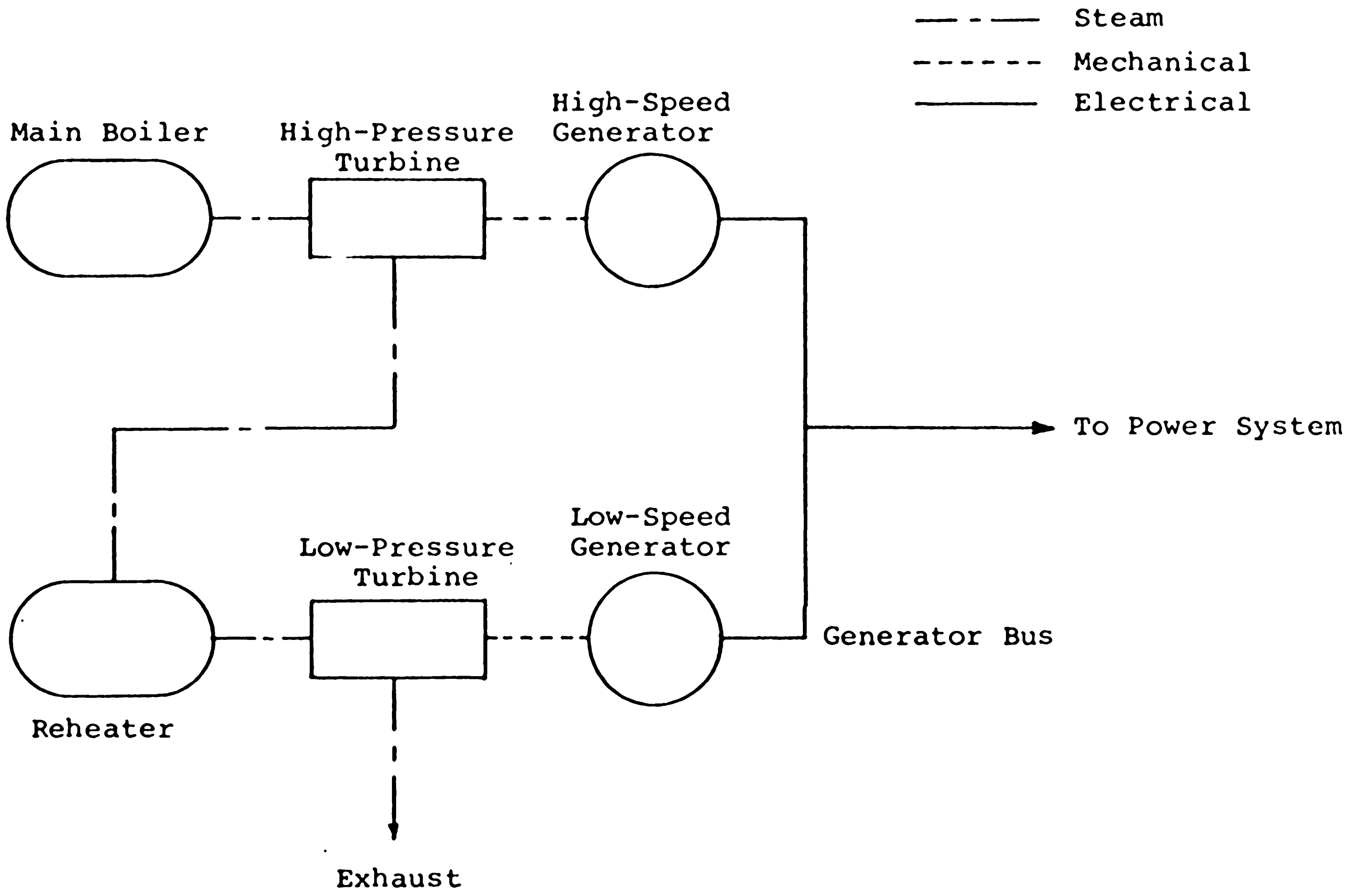


Figure 9.2-4. Diagram of Paradise Cross-Compound Machine

and the fault is placed at the remote end of this line. The terms R_{eq} and L_{eq} refer to the line and transformer, and appear in both equations. The equations referred to here are those of the next section, Equation 9.3-7.

The torque equations, Equations 9.3-10 and 9.3-11, are independent for each unit, and are treated accordingly.

The torque angle referred to in this study is the same as that used in the previous sample problem, as defined in Section 1.7. The voltage equations used here are derived in terms of the average torque angle, since the voltage is common to both machines. It should be noted that the torque angle of the line and transformer is a constant during the fault, and will only serve to offset the reference point by the amount of this constant. The reference used is rather arbitrary, and may be changed by the simple expedient of adding or subtracting a given angle from each value noted. Since the reference is arbitrary, the real consideration is the degree of deviation away from the reference, or the shape of the swing curve. The oscillographic records taken during the field tests are therefore plotted on a different reference than the computer studies.

On the basis of the theoretical studies done previously, it was feasible to omit those portions of the machine equations which deal with the changes in the rotor current, which serves to greatly simplify the equations used here.

9.3 Derivation of the Equations

With the previous comments in mind, the actual derivation of the equations is a straightforward procedure outlined by Koenig and Blackwell (1), who give the terminal equations of a two-machine system as

$$\begin{bmatrix} V^s_{s1}(t) \\ V^s_{s2}(t) \\ v_{r1}(t) \\ v_{r2}(t) \end{bmatrix} = \begin{bmatrix} Z^s_{s1} & 0 & \frac{d}{dt}L^s_{sr1}(\phi) & 0 \\ 0 & Z^s_{s2} & 0 & \frac{d}{dt}L^s_{sr2}(\phi) \\ \frac{d}{dt}L^s_{rs1}(\phi) & 0 & z_{r1} & 0 \\ 0 & \frac{d}{dt}L^s_{rs2}(\phi) & 0 & z_{r2} \end{bmatrix} \begin{bmatrix} I^s_{s1}(t) \\ I^s_{s2}(t) \\ i_{r1}(t) \\ i_{r2}(t) \end{bmatrix} \qquad (9.3\text{-}1)$$

$$T_1(t) = -P_1 L^+_{sr1} i_{r1} \mathrm{IM}(i^+_{s1} e^{-j\theta 1}) \qquad (9.3\text{-}2)$$

$$T_2(t) = -P_2 L^+_{sr2} i_{r2} \mathrm{IM}(i^+_{s2} e^{-j\theta 2}) \qquad (9.3\text{-}3)$$

where

$$\begin{bmatrix} V^s_{s1}(t) \\ V^s_{s2}(t) \end{bmatrix} = \begin{bmatrix} S & 0 \\ 0 & S \end{bmatrix} \begin{bmatrix} V_{s1}(t) \\ V_{s2}(t) \end{bmatrix} \qquad \begin{bmatrix} I^s_{s1}(t) \\ I^s_{s2}(t) \end{bmatrix} = \begin{bmatrix} S & 0 \\ 0 & S \end{bmatrix} \begin{bmatrix} I_{s1}(t) \\ I_{s2}(t) \end{bmatrix} \qquad (9.3\text{-}4)$$

and S represents the symmetrical-component transformation matrix. Submatrix entries are in script.

The fact that the machines are bussed together dictates that

$$V^{s}_{s1}(t) = V^{s}_{s2}(t) = V^{s}_{s}(t) \tag{9.3-5}$$

which allows the addition of the first two equations of (9.2-1) to yield

$$\begin{bmatrix} 2V^{s}_{s}(t) \\ v_{r1}(t) \\ v_{r2}(t) \end{bmatrix} = \begin{bmatrix} Z^{s}_{s1} & Z^{s}_{s2} & \frac{d}{dt}L^{s}_{sr1}(\phi) & \frac{d}{dt}L^{s}_{sr2}(\phi) \\ \frac{d}{dt}L^{s}_{rs1}(\phi) & 0 & Z_{r1} & 0 \\ 0 & \frac{d}{dt}L^{s}_{rs2}(\phi) & 0 & z_{r2} \end{bmatrix} \cdot \begin{bmatrix} I^{s}_{s1}(t) \\ I^{s}_{s2}(t) \\ i_{r1}(t) \\ i_{r2}(t) \end{bmatrix} \tag{9.3-6}$$

From this point on, the derivation follows the procedure given in Reference 1, with the resulting system equations

$$\frac{d}{dt}\begin{bmatrix} i_{sa}^{d} \\ \\ \\ i_{sb}^{d} \\ \\ \\ i_{sa}^{q} \\ \\ \\ \\ i_{sb}^{q} \end{bmatrix} = \begin{bmatrix} \begin{array}{l} \{(L_{eq}^{+} - L_{b}^{+})(2v_{s}^{d} - i_{sa}^{d}) + (L_{b}^{+}L_{a}^{+}\dot{\theta}_{a} \\ \quad - L_{eq}^{+2}\dot{\theta}_{b})i_{sa}^{q} - (R_{b}^{+}L_{eq}^{+} - L_{b}^{+}R_{eq}^{+})i_{sb}^{d} \\ \qquad + L_{eq}^{+}L_{b}^{+}i_{sb}^{q}\dot{\theta}\}/(L_{eq}^{+2} - L_{a}^{+}L_{b}^{+}) \end{array} \\ \\ \begin{array}{l} \{(L_{eq}^{+} - L_{a}^{+})2v_{s}^{d} - (R_{a}^{+}L_{eq}^{+} - L_{a}^{+}R_{eq}^{+})i_{sa}^{d} \\ \quad - L_{eq}^{+}L_{a}^{+}i_{sa}^{q}\dot{\theta} - (R_{eq}^{+}L_{eq}^{+} - R_{b}^{+}L_{a}^{+})i_{sb}^{d} \\ \qquad - (L_{eq}^{+2}\dot{\theta}_{a} - L_{a}^{+}L_{b}^{+}\dot{\theta}_{b})i_{sb}^{q}\}/(L_{eq}^{+2} - L_{a}^{+}L_{b}^{+}) \end{array} \\ \\ \begin{array}{l} \{(L_{eq}^{+} - L_{b}^{+})2v_{s}^{q} - (R_{eq}^{+}L_{eq}^{+} - R_{a}^{+}L_{b}^{+})i_{sa}^{q} \\ \quad - (L_{b}^{+}L_{a}^{+}\dot{\theta}_{a} - L_{eq}^{+2}\dot{\theta}_{b})i_{sa}^{d} - (R_{b}^{+}L_{eq}^{+} \\ \quad - L_{b}^{+}R_{eq}^{+})i_{sb}^{q} - L_{eq}^{+}L_{b}^{+}i_{sb}^{d}\dot{\theta} - \sqrt{2}L_{sra}^{+}L_{b}^{+}\dot{\theta}_{a}i_{ra} \\ \qquad + \sqrt{2}L_{srb}^{+}L_{eq}^{+}\dot{\theta}_{b}i_{rb}\}/(L_{eq}^{+2} - L_{a}^{+}L_{b}^{+}) \end{array} \\ \\ \begin{array}{l} \{(L_{eq}^{+} - L_{a}^{+})2v_{s}^{q} - (R_{a}^{+}L_{eq}^{+} - L_{a}^{+}R_{eq}^{+})i_{sa}^{q} \\ \quad + L_{eq}^{+}L_{a}^{+}i_{sa}^{d}\dot{\theta} - (R_{eq}^{+}L_{eq}^{+} - R_{b}^{+}L_{a}^{+})i_{sb}^{q} \\ \quad + (L_{eq}^{+2}\dot{\theta}_{a} - L_{a}^{+}L_{b}^{+}\dot{\theta}_{b})i_{sb}^{q} + \sqrt{2}L_{sra}^{+}L_{eq}^{+}\dot{\theta}_{a}i_{ra} \\ \qquad - \sqrt{2}L_{srb}^{+}L_{a}^{+}\dot{\theta}_{b}i_{rb}\}/(L_{eq}^{+2} - L_{a}^{+}L_{b}^{+}) \end{array} \end{bmatrix} \tag{9.3-7}$$

where the subscripts a and b refer to units a and b of the machine, the subscript eq refers to the equivalent external system, and

$$\dot{\theta} = (\dot{\theta}_a + \dot{\theta}_b)/2 \tag{9.3-8}$$

It was arbitrarily decided to derive the voltage equations in terms of the average torque angle, and following the procedure given previously yields

$$\begin{bmatrix} v_s{}^d \\ v_s{}^q \end{bmatrix} = \frac{V}{3} \begin{bmatrix} 2 \sin \alpha - \sin \gamma \\ \cos \gamma - 2 \cos \alpha \end{bmatrix} \tag{9.3-9}$$

where $\gamma = (\gamma_a + \gamma_b)/2$ and $\alpha = (\alpha_a + \alpha_b)/2$

The transformation of the torque equations, Equations 9.3-2 and 9.3-3, is perfectly straightforward, since the units are separated mechanically. This transformation yields

$$\frac{d}{dt}\dot{\theta}_a = (P_a - \dot{\theta}_a \sqrt{2} L^+_{sra} i_{ra} i^q_{sa})/M_a \tag{9.3-10}$$

$$\frac{d}{dt}\dot{\theta}_b = (P_b - \dot{\theta}_b \sqrt{2} L^+_{srb} i_{rb} i^q_{sb})/M_b \tag{9.3-11}$$

The zero-sequence equations are not necessary to this study, as the machine transformers are connected wye-delta, which effectively eliminates the zero-sequence components from the machine.

CHAPTER 10

PARADISE LOST: A FIELD STUDY

10.1 Introduction

The staged fault tests were undertaken by TVA to determine the feasibility of single-pole tripping and reclosing of a radial line for a 500 KV system. Their initial computer studies indicated that the fault would have to be removed, the line cleared, and service restored in a minimum of thirty cycles from the fault inception, or the machine would lose synchronism. These studies proved to be somewhat pessimistic, although on this basis it was decided to set the trip time such that the breakers would open after three cycles, allowing a dead time of twenty-three cycles for clearing, and then reclose. This was found to be a workable scheme, and the tests were successful.

10.2 Discussion

A single-phase-to-ground fault was placed on the Davidson end of the line by the use of an electrically fired cross-bow which placed a 0.004 inch diameter steel wire between one phase of the line and ground. This resulted in immediate vaporization of the wire and an arcing fault, such as would occur due to a lightning strike. The results of one of these tests became usable in this study due to the fact that the relays failed to operate properly, and the fault remained on long enough to allow a meaningful swing curve to be plotted before the circuit breakers at the Davidson end of the line operated and opened all three phases.

The test was made on June 25, 1969, at 10:59 p.m. The machine was loaded to 750 MW, 0.9 power factor, and the field currents were measured immediately before the fault was applied. The reference voltage was taken from the 161 KV station service voltage supplied by the 161 KV ring bus. This voltage is electrically remote from that of Unit 3. Oscillographic records were made at both Paradise and Davidson, and both with reference to the same ring bus voltage. These records recorded line currents, phase voltages, Paradise machine terminal voltage, and the reference voltage, among other quantities. A "pip" was inserted on the records each time the reference voltage went through zero in a positive direction, which allowed the swing of the machine terminal voltage to be measured, as defined in section 1.6. In this particular test, the relays failed to trip the line, and the arc persisted until the line was opened three-phase by the circuit breakers and the machine was shut down.

CHAPTER 11

PARADISE LOST: A COMPUTER STUDY

11.1 Introduction

Since the field study discussed in the previous chapter was available, it was decided that an attempt should be made to correlate the field study results with the results of a program of the type derived in this thesis. In order to do this, the following study was made.

11.2 Program

Equations 9.3-7 through 9.3-11 were programmed, and the data given in Figures 9.1-1 through 9.2-3 were converted to a 639 MVA base and used to evaluate the necessary constants, with additional data from the field tests. This program, given in the appendix, describes the system used in the field tests, with the initial conditions, parameters, and constants either being measured or computed by conventional methods.

11.3 Machine and System Values

The calculations of the values used in the study is rather straightforward in most instances, but sample items will be calculated here in order to show the procedure. The bases chosen were those of one unit, *i.e.*, 639 MVA, 24 KV, which led to a base current of 15.372 KA and a base impedance of 0.902 ohms. From Figure 9.2-1, for Unit A, $X_d = 1.74$, therefore, $L_s^+ = 1.74/377 = 0.00461$, and $R_s^+ =$ $0.00197/0.902 = 0.00218$. The mechanical constants may be found by use of the equations (3, 12).

$$H = \frac{0.231(WR^2)(rpm)^2 10^{-6}}{KVA} \tag{11.3-1}$$

and

$$M = H/\pi f \tag{11.3-2}$$

Using these equations, H = 1.39, and M = 0.00737. Since $\omega\sqrt{2}L_{sr} = 1$, $\sqrt{2}L_{sr} = 1/377 = 0.00265$.

Figure 9.2-2 shows that the field current for rated voltage at no load for Unit A is 2156 amperes. During the staged fault tests, the field current was measured immediately before the fault, and was found to be 2900 amperes. Therefore, $I_r = 2900/2156 = 1.35$. The measured value of I_r for Unit B was 1210 amperes. The power output of the machines was measured prior to the fault and was found to be 750 MW. This was assumed to split equally between units, therefore the power output = 750/1278 = 0.587 for each unit. Similar calculations for Unit B yields the values used in the program, which are all in per unit on the machine bases.

The initial conditions for Unit A were found by noting that Figure 9.2-2 gives a line current of 12,498 amperes or 0.813 p.u. for a field current of 2900 amperes, or 1.35 p.u.

By the torque equations, Equation 9.3-10, $0.587 = 377 \times (0.00265)(1.35) i_s^q$, and $i_s^q = 0.435$ p.u. Then, since $(i_s^d)^2 + (i_s^q)^2 = (0.587/0.9)^2$, $i_s^d = -0.486$. Since $|i| = 0.653$, and the power factor angle, $\beta = \cos^{-1} 0.9 = 25.9°$, and, by Reference 3, $i_s^q = |i| \cos(\delta + \beta)$ where δ is defined as the torque angle measured between the voltage behind transient reactance and the terminal voltage, which corresponds to our definition in Section 1.5, $\delta = 22.3°$ and $\theta = \delta + \pi/2 = 112.3° = 1.96$ radian. A similar procedure is used for the values for Unit B.

The system values present a slightly different problem, in that they are given on different MVA bases. This simply requires the use of the formula (13)

$$Z_{pu\ new} = (Z_{pu\ given})\left(\frac{\text{KV base given}}{\text{KV base new}}\right)^2 \cdot \left(\frac{\text{KVA base new}}{\text{KVA base given}}\right) \qquad (11.3\text{-}3)$$

It should be noted, however, that the only change to be made in voltage bases results from the transformer being 5 per cent overexcited, so that each impedance reflected through the transformer is multiplied by $(22.5/24)^2$ and the ratio of KVA bases. Utilizing the values given in Figure 9.1-1, Equation 11.3-3 yields the system quantities used in the program. For example, $R_{eq} = 0.001405(22.5/24)^2(639/100) = 0.00789$. L for the line $= 0.020524/377 = 5.44 \times 10^{-5}$, and L_{eq} for the line $= 5.44 \times 10^{-5}(22.5/24)^2(639/100) =$

0.000305, L_{eq} for the transformer = $0.1725/377(22.5/24)^2$ $\times$ (639/1260) = 0.000204. Then L_{eq} = 0.000509, the sum of the values for the line and the transformer. Note that the equivalent values are taken looking back from the point of fault toward the machine. All quantities used in the program are tabulated in Table 11.3-1.

Since the voltage across an arc path is normally considered to be 400 volts per foot and independent of current (12), and the arc path involved in this study was twelve feet long, this led to a nominal voltage of 400 $\times$ 12 = 4800 volts at the arc. On a 500 KV system, the phase voltage is $500/\sqrt{3}$ = 289 KV, which implies an arc path voltage of (4.8/289) $\times$ 100 = 1.66 per cent of rated phase voltage at the fault. On this basis, the voltage used in this study was assumed to be zero, since it considerably simplified the mathematics involved while introducing very little error.

Table 11.3-1. Tabulation of Quantities Used in Paradise Study

QUANTITY	SOURCE	EQUATION	VALUE
L^+_{sa}	Fig. 9.2-1	x_d/ω	0.00461
L^+_{sb}	"	"	0.00469
R^+_{sa}	"	R_{ohms}/Base ohms	0.00218
R^+_{sb}	"	"	0.00203
M_a	"	11.3-1 and 11.3-2	0.00737
M_b	"	"	0.0389
$\sqrt{2}L^+_{sra}$	Text	$\omega\sqrt{2}L^+_{sr}/\omega$	0.00265
$\sqrt{2}L^+_{srb}$	"	"	0.00265
P_a, P_b	Field Study	P measured/2	0.587
I_{ra}	Field Study Fig. 9.2-2	I_r measured/I_r base	1.35
I_{rb}	Fig. 1.2-3	"	1.37
i^q_{sa}	Fig. 9.2-2 Eq. 9.3-10	$P = \omega\sqrt{2}L^+_{sr}i_r i^q_s$	0.435
i^q_{sb}	Fig. 9.2-3	"	0.428
i^d_{sa}	Text	$(i^d_s)^2 + (i^q_s)^2 = (P/pf)^2$	-0.486
i^d_{sb}	"	"	-0.492
θ_a	Ref. 3	$i^q_s = \lvert i \rvert \cos(\delta + \beta)$	1.96
θ_b	Definition	$\theta = \delta + \pi/2$	1.98
R_{eq}	Fig. 9.1-1	Eq. 11.3-3	0.00789
L_{eq}	"	Eq. 11.3-3 and $L = X_L/\omega$	0.000509

CHAPTER 12

PARADISE REGAINED: A COMPARISON OF FIELD AND COMPUTER STUDIES

12.1 Comparison of Results

Figure 12.1-1 shows the swing curve obtained from the field tests, VF, compared to some other curves obtained from a TVA computerized transient stability study. The curves labeled EA, EB, and EAV are the swing curves of the Paradise machine, being for Unit A, Unit B, and the average of the two, respectively. The curve labeled V is the terminal voltage swing curve of the machine, plotted to show that there is a close correlation between the terminal voltage swing and the actual swing of the machine. This relationship holds true as long as there is no external disturbance to the system. During switching, such as fault clearing, the terminal voltage offsets, whereas the generated voltage follows a smooth swing curve. This indicates that, for the field test considered here, the terminal voltage swing is a very good indication of the actual machine swing, and the correlation between the shape of the three curves, EAV, V, and VF should be noted. Values plotted for these curves are given in Appendix C, with sources.

When the transient stability study was obtained, it showed that the system voltage used as reference in the

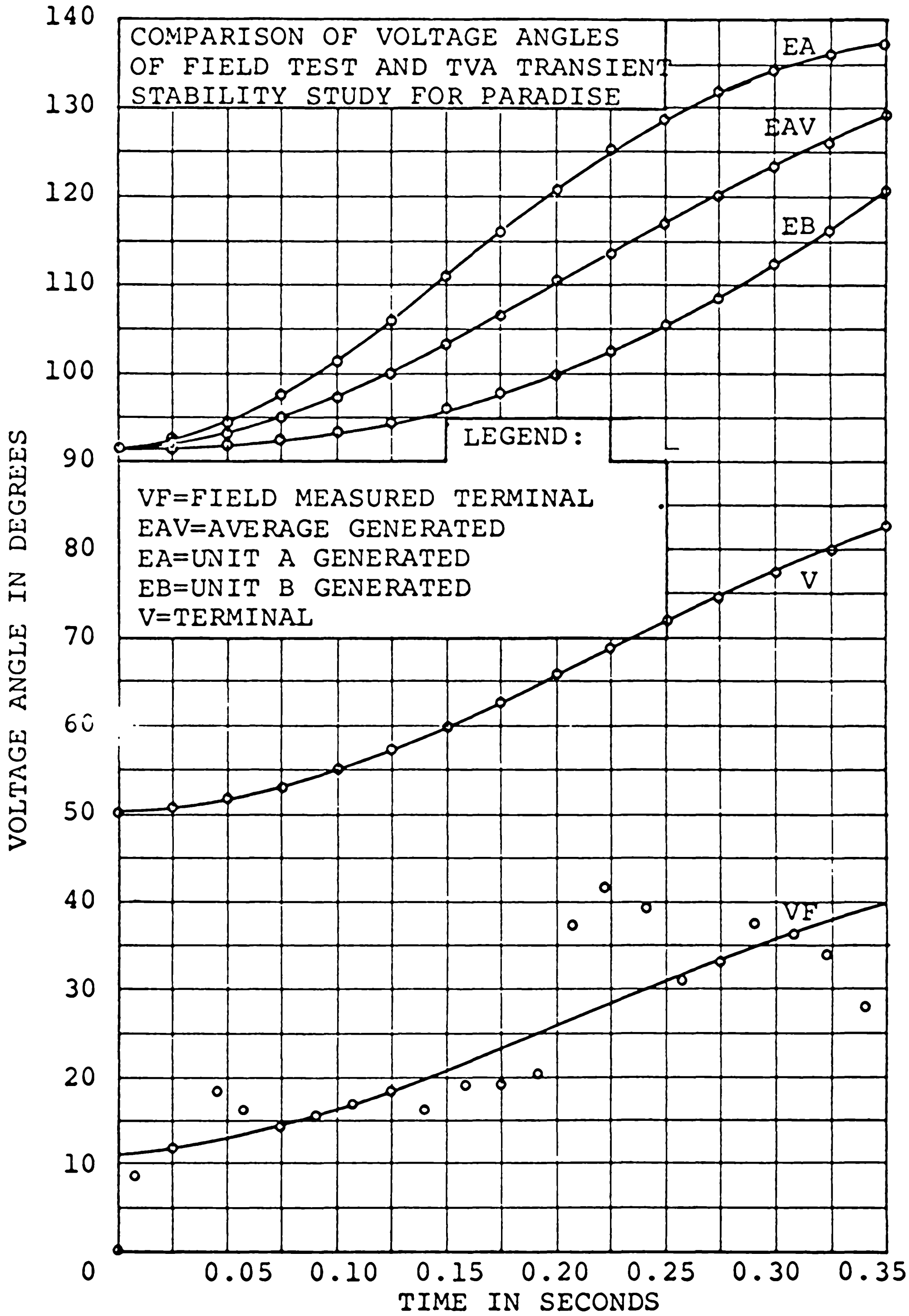


Figure 12.1-1. Comparison of Swing Curves for Paradise from Field Test and TVA Transient Stability Study

field test did swing somewhat, so the curve EAV of Figure 12.1-1 was corrected for this swing, and plotted as EAVC on Figure 12.1-2. This was because the computer study used here assumed the system to act as an infinite bus with no swing. This correction was accomplished by subtracting the angle of the reference voltage used in the field study from the angle of EAV at each plotted point, and was done in order to show the correlation of the swing curve obtained by the thesis method with that of the transient stability study, and thereby also with that of the field study. Admittedly, this is a rather round about method of showing the correlation between the field tests and the program used here, but it seemed to be the only provable method available.

No attempt was made to plot voltages or current as it would have been almost impossible to obtain meaningful data from the oscillograms due to the scales used. The oscillograms were intended to be used to obtain approximations of maximum values, rather than point-by-point variations.

It should be noted that in none of these studies did the machine actually swing out of synchronism. This indicated that the initial studies upon which the field tests were based were rather pessimistic, and the machine would probably remain stable out to one second or longer under a single-phase-to-ground fault, although such a fault would certainly be noticed by the system.

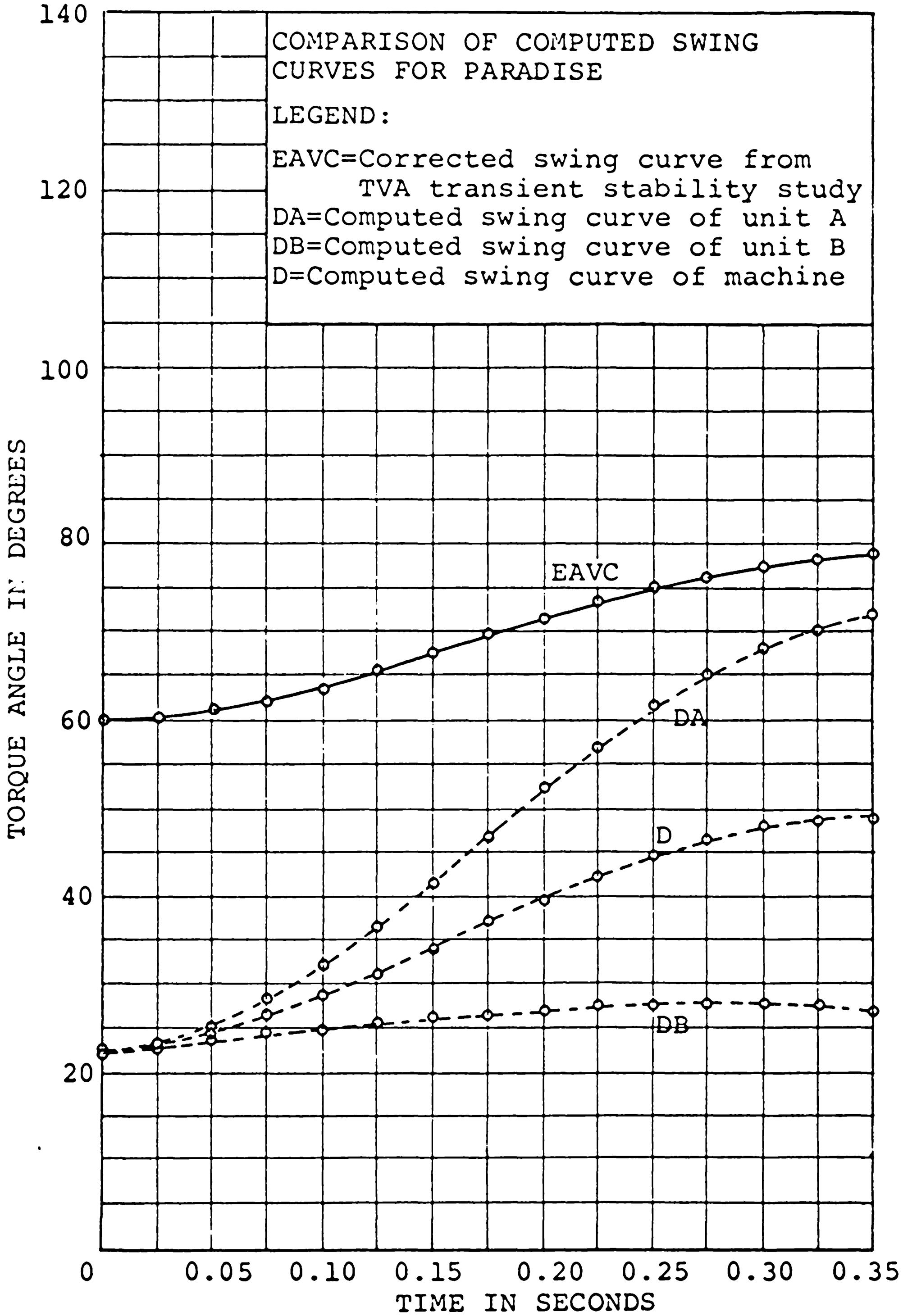


Figure 12.1-2. Comparison of Computed Swing Curves for Paradise

CHAPTER 13

CONCLUSIONS

13.1 Conclusions

While the curves given in Figures 12.1-1 and 12.1-2 cannot be construed to offer positive proof of the entire contents of this thesis, they do indicate that the approach taken here is a reasonable one. The representation of the unbalanced conditions existing during fault conditions on a system are solidly based upon long existing and thoroughly proven theory, and may, therefore, be assumed correct. This assumption is proven sound by the thoroughly predictable swing curves shown in Figure 8.1-1.

During the course of this study, many areas open to further study have presented themselves. For example, representation of a system during the so-called "dead time", when the faulted phases are open-circuited. This becomes of paramount importance with the advent of single-phase tripping and reclosing, made necessary by the use of large machines and radial lines. Another area is the representation of the familiar two-machine system during unbalanced conditions, and the expansion of these basic systems to allow the representation of larger systems. The investigation of other types of faults, and of simultaneous faults, as well as a method of reducing the programs to some easily usable form which may be made to fit any system, such as was done with the symmetrical component networks are other areas in which research should prove worthwhile.

Some additional work may be indicated concerning the action of the governor on the machine speed during fault conditions. No governor action was used in any of the problems discussed in this thesis, and it was not necessary in the Paradise study, since the circuit was opened three-phase by the back-up breakers before the governor could begin to function.

Additional research is also feasible in the area of optimum reclosing conditions for a system, in view of the swing curves plotted previously. Since the method used in this thesis can be used to produce a point-by-point curve, using any necessary interval of integration, and data may be obtained on any quantity which might affect the stability of a machine, i.e., voltage, current, torque angle, field conditions, speed, acceleration, or even the rate of change of acceleration, this method would be very convenient for the study of optimum reclosing conditions for circuit breakers. It could also be used to help design relays and breakers which would sense different values than those currently in use. For example, a system might be made more stable if a relay could reclose a breaker during a voltage zero or a current zero, thereby reducing the shock to the system during reclosure. The method used here would lend itself easily to such studies. Incidentally, some effort is being made along these lines, as breakers are now in use which have a time delay on two phases during reclosure, so that no two phases of a line will reclose at exactly the same instant, thereby reducing the shock to the system.

A recapitulation of what has been accomplished in this study is now in order. It has been shown that a transient stability study can be made for various types of unbalanced fault conditions on a system without having to resort to the traditional linearizing assumptions and their inherent inaccuracies. A method has been developed by which additional types of unbalances can be readily utilized, since it was shown that the only changes necessary are the use of different transcendental voltage equations which serve to categorize the type of unbalance under study. It was shown that the method can be used in studies of any system which can be studied by the traditional methods, since the traditional methods allow a system to be reduced to a single machine on an infinite bus. It was illustrated that the method gives accurate results by correlation between a field test, the method, and a standard transient stability study.

It is believed that the method outlined in this thesis can be utilized to help overcome one of the largest obstacles facing the electric power industry today, that of accurate representation of machines under unbalanced conditions in transient stability studies which are made on the digital computer. Of course, before the method can be used in an existing transient stability program involving several hundred busses and machines, it will have to be simplified further and a great deal more work will be necessary. However, this study has shown that it can be done, and that unbalanced conditions can be handled as easily, and with just as much accuracy, as balanced conditions have been handled previously.

APPENDIX A

TABLE OF SYMBOLS

TABLE OF SYMBOLS

MATH SYMBOL	COMPUTER SYMBOL	DESCRIPTION
VOLTAGES		
ν_s		Nominal System Voltage Matrix
ν_s^s		Symmetrical-Component Voltage Matrix
$V_a V_b V_c$		System Phase Voltage
v_r	VR	Machine Rotor Voltage
v_s^d	VD	Direct-Axis Voltage
v_s^q	VQ	Quadrature-Axis Voltage
v_s^o	VO	Zero-Sequence Voltage
v_s^+		Positive-Sequence Voltage
v_s^-		Negative-Sequence Voltage
CURRENTS		
I_s		System Current Matrix
I_s^s		Symmetrical-Component Current Matrix
i_r		Machine Rotor Current
i_r'	IR	Incremental Rotor Current
i_s^d	ID	Direct-Axis Current
i_s^q	IQ	Quadrature-Axis Current
i_s^o	IO	Zero-Sequence Current

MATH SYMBOL	COMPUTER SYMBOL	DESCRIPTION
i_s^+		Positive-Sequence Current
i_s^-		Negative-Sequence Current

RESISTANCES, INDUCTANCES, AND IMPEDANCES

MATH SYMBOL	COMPUTER SYMBOL	DESCRIPTION
R_s^+	R	Positive-Sequence Resistance
R_s^o	RO	Zero-Sequence Resistance
R_r	RR	Rotor Resistance
R_{eq}	REQ	Equivalent External System Resistance
L_s^+	L	Positive-Sequence Inductance
L_s^o	LO	Zero-Sequence Inductance
$\mathcal{L}_{sr}^s$		Stator to Rotor Leakage Inductance Matrix
L_{eq}	LEQ	Equivalent External System Inductance
$\sqrt{2}L_{sr}^+$	RLSR	$\sqrt{2}$ Times the Stator to Rotor Positive-Sequence Leakage Inductance
L_{rs}	LR	Rotor Inductance
$\mathcal{L}_s^s$		Symmetrical-Component Impedance

MISCELLANEOUS

MATH SYMBOL	COMPUTER SYMBOL	DESCRIPTION
ω	W	Nominal System Frequency in Radians per second
θ	TH	Angular Displacement of Machine Rotor in Radians

MATH SYMBOL	COMPUTER SYMBOL	DESCRIPTION
$\dot{\theta}$	TD	Angular Velocity or Speed of Machine in Radians Per Second
T		Torque Input to Machine from Prime Mover
J		Moment of Inertia of Machine
P	P	Power Output of Machine
$\dot{\phi}$		Rate of Change of Machine Flux
M	M	Momentum of Machine
S		Symmetrical-Component Transformation Matrix
α	A	Torque Angle of Machine
γ	G	$\gamma = 2\omega t + \alpha$

APPENDIX B

CSMP PROGRAMS

CSMP PROGRAMS

Two types of modern nonlinear system simulators were used in this study. The older, and perhaps more widely used is the IBM Pactolus simulator, in which the equations of a system are programmed and solved in a manner similar to that of an analog computer, although the Runge-Kutta method of iterative integration is used within the program. This type of solution requires that the equations of the system be drawn in circuit form utilizing blocks which perform the mathematical operations in their specified order. The circuit is then coded onto punch cards, and the output is returned in column form. A newer and more easily used form is the IBM CSMP, or Continuous Systems Modeling Program. In this simulator, the equations are programmed in much the same way as they would be in normal FORTRAN, although more flexibility is allowed as far as form of the cards is concerned. A knowledge of FORTRAN is not necessary in order to program in CSMP, although such knowledge is certainly helpful. The program is extremely adaptable and flexible, although somewhat slow when compared to Pactolus. However, it is easier to use than Pactolus, and is much less subject to programmer error, while allowing a much greater number of outputs to be obtained per run as well as a choice of integration methods. It is also capable of running a much larger and more complex problem than Pactolus. Although both types of simulators were used in this research, the CSMP programs will be given here due to their relative simplicity.

In the following programs, the INITIAL block is set aside for stating the initial conditions, the parameters, and the constants employed in the program. This block is also used for the purpose of making any initial calculations which do not need to be repeated during each iteration. Due to an internal sort feature, the calculations do not have to be programmed in any specific order, as the program will sort them according to the order in which the outputs are needed.

The DYNAMIC block is the heart of the program. This block is used for the main portion of the calculations in which the iterative procedure is used for integration. The sort feature is also available in this block.

The FINISH statement tells the program to stop if the variables mentioned exceed the limits imposed. The METHOD statement specifies the integration method. The TIMER statement sets the integration interval, the finish time, the output interval, and the print-plot interval. The CONTINUE statement allows the program to continue from the stated finish time to the new finish time with new parameters, while an END statement resets time to zero and allows new parameters to be specified. This allows the fault study to be performed so that only one program need be written to test various clearing times for the fault. This feature is illustrated in the program used for the three-phase fault.

This rather simple use of the CONTINUE and END statements cannot be successfully employed in the other program, since they require modifications of the procedural statements in order to clear the fault during the course of a run. These programs require the use of a PROCED block, which allows some FORTRAN functions to be employed. In this case, the FORTRAN IF statement was utilized to allow fault clearing at the end of a specified time. This means that a separate run must be made for each desired clearing time. Note that the type of fault may be changed by the simple expedient of changing the necessary zero-sequence equations, parameter and initial condition statements, and PROCED block.

CSMP PROGRAM FOR THREE-PHASE FAULT

```
INITIAL
   PARAMETER LR=6.,L=.00318,RLSR=.00265,R=.005,RR=1.,M=.0159,P=.5
   PARAMETER K=.00265
   PARAMETER V=0.
   CONSTANT PI=3.14159,W=377.
   INCON IDIC=-.48330,IQIC=.33332,IRIC=0.,THIC=1.97937,IDIC=377.
          C1=PI/2.
          C2=LR/(LR*L-K**2)
          C3=K/(LR*L-K**2)
          C4=L/(LR*L-K**2)
DYNAMIC
          WT=W*TIME
          A=TH-WT-C1
          VD=V*SIN(A)
          VQ=-V*COS(A)
          DIDDT=(VD-R*ID-TD*L*IQ)*C2+RR*IR*C3
          DIQDT=(VQ+TD*RLSR*1.5+TD*L*ID-R*IQ+TD*K*IR)/L
          DIRDT=-(VD-R*ID-TD*L*IQ)*C3-RR*IR*C4
          DTDDT=(P-TD*IQ*(RLSR*1.5+K*IR))/M
          TD=INTGRL(TDIC,DTDDT)
          TH=INTGRL(THIC,TD)
          IR=INTGRL(IRIC,DIRDT)
          IQ=INTGRL(IQIC,DIQDT)
          ID=INTGRL(IDIC,DIDDT)
          ET=-IQ*(.00398+.00265*IR)
TIMER DELT=.001,FINTIM=.2,PRDEL=.1
METHOD RKSFX
PRINT A,ID,IQ,IR,VD,VQ,TD,ET
END
TIMER FINTIM=.1
CONTINUE
   PARAMETER V=1.
TIMER FINTIM=2.
END
   PARAMETER V=0.
TIMER FINTIM=.2
CONTINUE
   PARAMETER V=1.
TIMER FINTIM=2.
END
   PARAMETER V=0.
TIMER FINTIM=.25
CONTINUE
   PARAMETER V=1.
TIMER FINTIM=2.
END
   PARAMETER V=0.
TIMER FINTIM=.275
CONTINUE
```

```
   PARAMETER V=1.
TIMER FINTIM=2.
END
   PARAMETER V=0.
TIMER FINTIM=.3
CONTINUE
   PARAMETER V=1.
TIMER FINTIM=2.
END
TIMER FINTIM=.325
   PARAMETER V=0.
CONTINUE
TIMER FINTIM=2.
   PARAMETER V=1.
END
STOP
END JOB
```

CSMP PROGRAM FOR SINGLE-PHASE-TO-GROUND FAULT

```
INITIAL
   PARAMETER LR=6.,L=.00318,RLSR=.00265,R=.005,RR=1.,M=.0159,P=.5
   PARAMETER K=.00265
   CONSTANT PI=3.14159,W=377.
INCON IDIC=-.4833,IQIC=.33332,IRIC=0.,THIC=1.97937,TDIC=377.
        C1=PI/2.
        C2=LR/(LR*L-K**2)
        C3=K/(LR*L-K**2)
        C4=L/(LR*L-K**2)
        C5=SQRT(2.)
   PARAMETER LO=.0001,RO=.005
   INCON IOIC=0.
        V=1.
DYNAMIC
        WT=W*TIME
        A=TH-WT-C1
        G=2*WT+A
PROCED IO,DIODT,VO,VQ,VD,=X(A,G,V,TIME,C5,WT,IOIC,RO,LO)
        IF(TIME-.3)1.2.2.
      1 IO=INTGRL(IOIC,DIODT)
        DIODT=(VO-RO*IO)/LO
        VO=-(V/(3.*C5))*COS(WT)
        VQ=(V/3.)*(COS(G)-2.*COS(A))
        VD=(V/3.)*(2.*SIN(A)-SIN(G))
        GO TO 3
      2 IO=0.
        DIODT=0.
        VO=0.
        VQ=-V*COS(A)
        VD=V*SIN(A)
      3 CONTINUE
ENDPRO
        DIDDT=(VD-R*ID-TD*L*IQ)*C2+RR*IR*C3
        DIQDT=(VQ+TD*RLSR*1.5+TD*L*ID-R*IQ+TD*K*IR)/L
        DIRDT=(VD-R*ID-TD*L*IQ)*C3-RR*IR*C4
        DTDDT=(P-TD*IQ*(RLSR*1.5+K*IR))/M
        TD=INTGRL(TDIC,DTDDT)
        TH=INTGRL(THIC,TD)
        IR=INTGRL(IRIC,DIRDT)
        IQ=INTGRL(IQIC,DIQDT)
        ID=INTGRL(IDIC,DIDDT)
        ET=-IQ*(.00398+.00265*IR)
TIMER DELT=.001,FINTIM=2.,PRDEL=.1
METHOD RKSFX
PRINT A,ID,IQ,IO,IR,VD,VQ,VO,TD,ET
END
STOP
```

CSMP PROGRAM FOR PHASE-TO-PHASE FAULT

```
INITIAL
   PARAMETER LR=6.,L=.00318,RLSR=.00265,R=.005,RR=1.,M=.0159,P=.5
   PARAMETER K=.00265
   CONSTANT PI=3.14159,W=377.
INCON IDIC=-.48330,IQIC=.33332,IRIC=0.,THIC=1.97937,IDIC=377.
        C1=PI/2.
        C2=LR/(LR*L-K**2)
        C3=K/(LR*L-K**2)
        C4=L/(LR*L-K**2)
        V=1.
DYNAMIC
        WT=W*TIME
        A=TH-WT-C1
        G=2.*WT+A
PROCED VD,VQ=X1(A,G,V,TIME)
        IF(TIME-.3)1,2,2
      1 VD=(V/2.)*(SIN(A)+SIN(G))
        VQ=-(V/2.)*(COS(A)+COS(G))
        GO TO 3
      2 VQ=-V*COS(A)
        VD=V*SIN(A)
      3 CONTINUE
ENDPRO
        DIDDT=(VD-R*ID-TD*L*IQ)*C2+RR*IR*C3
        DIQDT=(VQ+TD*RLSR*1.5+TD*L*ID-R*IQ+TD*K*IR)/L
        DIRDT=-(VD-R*ID-TD*L*IQ)*C3-RR*IR*C4
        DTDDT=(P-TD*IQ*(RLSR*1.5+K*IR))/M
        TD=INTGRL(TDIC,DTDDT)
        TH=INTGRL(THIC,TD)
        IR=INTGRL(IRIC,DIRDT)
        IQ=INTGRL(IQIC,DIQDT)
        ID=INTGRL(IDIC,DIDDT)
        ET=-IQ*(.00398+.00265*IR)
TIMER DELT=.001,FINTIM=2.,PRDEL=.1
METHOD RKSFX
PRINT A,ID,IQ,IR,VD,VQ,TD,ET
END
STOP
```

CSMP PROGRAM FOR TWO-PHASE-TO-GROUND FAULT

```
INITIAL
   PARAMETER LR=6.,L=.00318,RLSR=.00265,R=.005,RR=1.,M=.0159,P=.5
   PARAMETER K=.00265
   CONSTANT PI=3.14159,W=377.
INCON IDIC=.4833,IQIC=.33332,IRIC=0.,THIC=1.97937,TDIC=377.
   INCON IQIC=0.
   PARAMETER LO=.0001,RO=.005
        C1=PI/2.
        C2=LR/(LR*L-K**2)
        C3=K/(LR*L-K**2)
        C4=L/(LR*L-K**2)
        C5=SQRT(2.)
        V=1.
DYNAMIC
        WT=W*TIME
        A=TH-WT-C1
        G=2.*WT+A
PROCED IO,DIODT,VO,VQ,VD=X(A,G,V,TIME,C5,WT,IOIC,RO,LO)
        IF(TIME-.3)1,2,2
      1 IO=INTGRL(IOIC,DIODT)
        DIODT=(VO-RO*IO)/LO
        VO=(V/(3.*C5))*COS(WT)
        VQ=-(V/3.)*(COS(A)+COS(G))
        VD=(V/3.)*(SIN(A)+SIN(G))
        GO TO 3
      2 IO=0.
        DIODT=0.
        VO=0.
        VQ=-V*COS(A)
        VD=V*SIN(A)
      3 CONTINUE
ENDPRO
        DIDDT=(VD-R*ID-TD*L*IQ)*C2+RR*IR*C3
        DIQDT=(VQ+TD*RLSR*1.5+TD*L*ID-R*IQ+TD*K*IR)/L
        DIRDT=-(VD-R*ID-TD*L*IQ)*C3-RR*IR*C4
        DTDDT=(P-TD*IQ*(RLSR*1.5+K*IR))/M
        TD=INTGRL(TDIC,DTDDT)
        TH=INTGRL(THIC,TD)
        IR=INTGRL(IRIC,DIRDT)
        IQ=INTGRL(IQIC,DIQDT)
        ID=INTGRL(IDIC,DIDDT)
        ET=-IQ*(.00398+.00265*IR)
TIMER DELT=.001,FINTIM=2.,PRDEL=.1
METHOD RKSFX
PRINT A,ID,IQ,IO,IR,VD,VQ,VO,TD,ET
END
STOP
```

CSMP PROGRAM FOR PARADISE STUDY

```
INITIAL
PARAMETER R1=.00218,L1=.00461,R2=.00203,L2=.00469,IRA=1.35,
               IRB=1.37
PARAMETER RLSRA=.00265,RLSRB=.00265
PARAMETER REQ=.00789,LEQ=.000509,PA=.587,PB=.587,MA=.00737,
               MB=.0389,V=1.056
INCON THAIC=1.96,THBIC=1.98,TDAIC=377.,TDBIC=377.
INCON IQAIC=.435,IQBIC=.428,IDAIC=-.486,IDBIC=-.492
        C1=3.14159/2.
        CA=LEQ-L2
        CB=L2*L1
        CC=LEQ**2
        CD=R2*LEQ-L2*REQ
        CE=LEQ*L2
        CF=CC-CB
        CG=(LEQ-L1)*2.
        CH=R1*LEQ-L1*REQ
        CI=LEQ*L1
        CJ=REQ*LEQ-R2*L1
        CK=REQ*LEQ-R1*L2
        CL=180./3.14159
DYNAMIC
        WT=377.TIME
        AA=THA-WT-C1
        AB=THB-WT-C1
        A=(AA+AB)/2.
        GA=2.*WT+AA
        GB=2.*WT+AB
        G=(GA+GB)/2.
        TD=(TDA+TDB)/2.
        X=CB*TDA-CC*TDB
        Y=CC*TDA-CB*TDB
        DIDA=(CA*(2.*VD-IDA)+X*IQA-CD*IDB+CE*IQB*TD)/CF
        DIDB=(CG*VD-CH*IDA-CI*IQA*TD-CJ*IDB-Y*IQB)/CF
        DIQA=(CA*2.*VQ-CK*IQA-X*IDA-CD*IQB-CE*IDB*TD-ZA+ZB)/CF
        DIQB=(CG*VQ-CH*IQA+CI*IDA*TD-CJ*IQB+Y*IDB+ZC-ZD)/CF
        ZA=RLSRA*L2*TDA*IRA
        ZB=RLSRB*LEQ*TDB*IRB
        ZC=RLSRA*LEQ*TDA*IRA
        ZD=RLSRB*L1*TDB*IRB
        DTDA=(PA-TDA*RLSRA*IRA*IQA)/MA
        DTDB=(PB-TDB*RLSRB*IRB*IQB)/MB
        IDA=INTGRL(IDAIC,DIDA)
        IDB=INTGRL(IDBIC,DIDB)
        IQA=INTGRL(IQAIC,DIQA)
        IQB=INTGRL(IQBIC,DIQB)
        TDA=INTGRL(TDAIC,DTDA)
        TDB=INTGRL(TDBIC,DTDB)
```

```
         THA=INTGRL(THAIC,TDA)
         THB=INTGRL(THBIC,TDB)
         ID=IDA+IDB
         IQ=IQA+IQB
         TH=(THA+THB)/2.
         D=A*CL
         DA=AA*CL
         DB=AB*CL
         VQ=(V/3.)*(COS(G)-2.*COS(A))
         VD=(V/3.)*(2.*SIN(A)-SIN(G))
METHOD RKSFX
FINISH A=2.4,A=-2.4
TIMER DELT=.005,FINTIM=.35,PRDEL=.025
PRINT D,DA,DB,IDA,IQA,THA,IDB,DQB,THB,ID,IQ,TH,VD,VQ
END
STOP
```

APPENDIX C

TABULATED DATA FROM TENNESSEE VALLEY AUTHORITY

DATA FROM FIELD TEST OSCILLOGRAM

TIME	DEVIATION	SWING IN DEGREES
0.0	0.0	0.0
0.0083	1.2	8.6
0.025	1.65	11.83
0.042	2.60	18.64
0.058	2.3	16.49
0.075	2.0	14.34
0.091	2.2	15.77
0.108	2.4	17.20
0.125	2.6	18.64
0.141	2.3	16.49
0.158	2.7	19.36
0.174	2.7	19.36
0.191	2.9	20.79
0.207	5.2	37.28
0.223	5.8	41.59
0.240	5.5	39.43
0.257	4.2	30.11
0.274	4.64	33.27
0.290	5.24	37.57
0.307	5.04	36.13
0.324	4.74	33.99

On a scale of 50.2/60 = 180° = 1 cycle

Points obtained from Leo Edwards, TVA Staff Engineer, 8/14/70

DATA FROM TVA TRANSIENT STABILITY PROGRAM

TIME IN SECONDS	ANGLE OF E'_{qA} DEGREES	ANGLE OF E'_{qB} DEGREES	ANGLE OF E'_{qAVE} DEGREES	CORRECTION FACTOR ANGLE OF Vref. DEGREES	ANGLE OF CORRECTED E'_{qAVE} DEGREES	ANGLE OF TERMINAL VOLTAGE DEGREES
0.0	91.84	91.27	91.555	31.37	60.185	50.47
0.025	92.48	91.38	91.93	31.59	60.34	50.84
0.05	94.35	91.75	93.05	32.10	60.95	51.76
0.075	97.34	92.36	94.85	32.74	62.11	53.14
0.10	101.26	93.25	97.255	33.55	63.705	54.97
0.125	105.83	94.43	100.13	34.60	65.53	57.27
0.15	110.77	95.91	103.34	35.74	67.60	59.87
0.175	115.77	97.73	106.75	37.18	69.57	62.83
0.20	120.56	99.89	110.225	38.69	71.535	65.87
0.225	124.92	102.42	113.67	40.32	73.35	68.93
0.25	128.69	105.32	117.005	42.00	75.005	71.91
0.275	131.78	108.59	120.185	43.72	76.465	74.76
0.30	134.18	112.22	123.20	45.56	77.64	77.49
0.325	135.95	116.20	126.075	47.44	78.635	80.08
0.35	137.20	120.49	128.845	49.43	79.415	82.62

$E'_{qAVE} = (E'_{qA} + E'_{qB})/2$

Correction Factor = Angle of terminal voltage of Paradise Machines 1 and 2, used as reference voltage in Field Study.

Corrected $E'_{qAVE} = E'_{qAVE}$ - Correction Factor

Data taken from TVA transient stability study, done on IBM 360 computer using Philadelphia Electric Transient Stability Program, and industry standard.

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A STUDY OF SOME UNBALANCED FAULT CONDITIONS OF POWER SYSTEMS

James Terry Lancaster

Abstract

Much work has been done in applying computer solutions to the problem of power systems fault and stability studies. However, with a few notable exceptions, previous efforts have largely been confined to attempts to solve the problems in the classical manner by having the computer simply take over the tedious portion of the calculations. A few pioneers have succeeded in finding new methods of solving some of the problems by the use of the machine equations, without resorting to the simplifying assumptions necessary for the classical method of solution and their inevitable inaccuracies. These pioneers, however, have only dealt with the balanced condition type of fault, such as a three-phase-fault or a sudden change in load on a machine, and have ignored the far more common although less severe types of fault wherein the system becomes unbalanced due to a fault involving only one or two phases.

In contrast, this thesis deals with the unbalanced type of fault on a system. The necessary equations are derived and simple problems are solved for three major types of faults, *i.e.*, the single-phase-to-ground fault, the phase-to-phase fault, and the two-phase-to-ground fault. In

addition, a program is written to simulate a field study in order that a comparison can be made.

The programs used are written for the single-machine on an infinite bus, and are written so that initial steady conditions and machine and system constants may be entered easily, thus making the thesis method usable by practicing power systems engineers.

The thesis method results in a great variety of useful data, which, since they may be transformed into symmetrical components form allows the use of classical methods of system reduction and re-expansion so that fault currents and voltages may be found at any point in the system. All that is required for a system analysis is the reduction of the system, the choice of program for the type of fault under consideration, and the re-expansion of the system.

It is hoped that the results of this thesis may prove useful not only to those who wish to continue research in this area, but also to those who are practicing engineers concerned with system fault studies and who are in need of an improved method for the study of unbalanced faults.