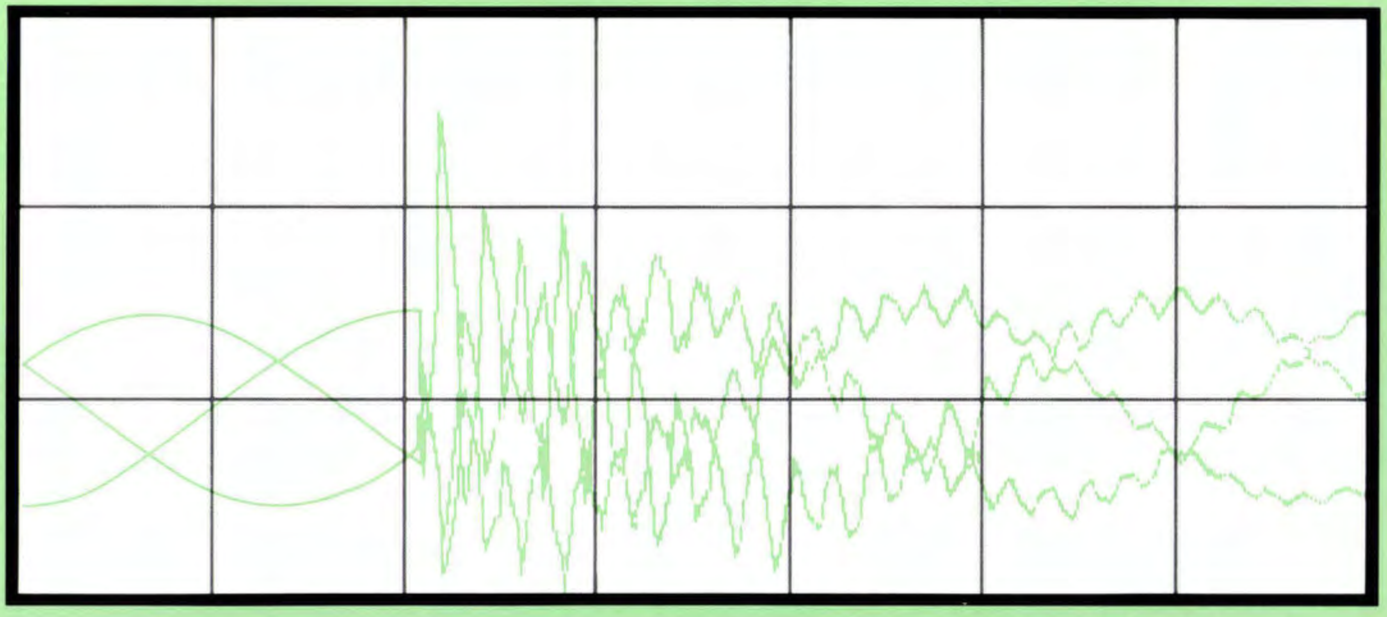
EPRI EL-4651, Volume 3

Electromagnetic Transients Program (EMTP)

WORKBOOK III



ELECTRIC POWER RESEARCH INSTITUTE

EMTP DEVELOPMENT COORDINATION GROUP

REPORT SUMMARY

SUBJECTS	Power system planning and engineering / Power system operations
TOPICS	Transients Computer simulation Power systems Substations Transmission EMTP code
AUDIENCE	Power system planners / Electrical engineers

Electromagnetic Transients Program (EMTP)
Volumes 2–4

The complex and versatile EMTP computer program can help utilities analyze electromagnetic transients, which affect the design and operation of power systems. A workbook published in 1986 introduced basic EMTP concepts. To guide advanced users, EPRI and the EMTP Development Coordination Group cosponsored the preparation of three workbooks on complicated program applications.

BACKGROUND Studies of electromagnetic transients were traditionally performed with special analog computer models known as transient network analyzers (TNAs). In the late 1960s, the electromagnetic transient program (EMTP) for digital computers, developed at Bonneville Power Administration (BPA), replaced TNAs. This versatile program can be very complex. Workbook I, published in 1986, presented basic concepts about these transients and the use of the EMTP code, but did not address all program applications. EPRI cosponsored an effort to enhance the EMTP code and its documentation with the EMTP Development Coordination Group (DCG)—composed of BPA, the Canadian Electric Association, Hydro Quebec, Ontario Hydro, the U.S. Bureau of Reclamation, and the Western Area Power Administration. Key to this effort was the development of reference and tutorial material.

OBJECTIVES To provide utilities with tutorial materials on electromagnetic transients; to illustrate analysis of such transients with the EMTP computer code.

APPROACH To create EMTP workbooks, the project team developed a series of case studies that gradually introduce more-sophisticated modeling of the power system. They documented steps for obtaining reasonable values for input parameters and prepared templates to facilitate data entry. They also formulated problems to increase user proficiency and provided tutorial information on transients. Participants and instructors from an annual course on the EMTP code at the University of Wisconsin helped develop and test the workbooks, providing suggestions that were incorporated into the final documents.

RESULTS Building on the information in the first workbook (volume 1 of this series), workbooks II–IV will enable EMTP users to increase their competence in this complicated program. Workbook II presents data preparation and modeling for cables, electromagnetic induction, and frequency-dependent lines. Other covered topics include statistical studies using the EMTP code, circuit breaker models, frequency-dependent source representation, and insulation coordination. Workbook III discusses modeling for transformers, synchronous machines, and induction motors and describes subsynchronous resonance. Workbook IV introduces the use of a model in the EMTP code that simulates the interaction of power system transients and control systems, the transient analysis control systems (TACS) model. It outlines basic TACS concepts and discusses TACS applications such as variable load problems, static VAR systems, thyristor models, and basic and detailed HVDC models.

EPRI PERSPECTIVE

The EMTP workbook series explains the theoretical basis of transient analysis, as well as the practical applications of one of the most frequently used and powerful software packages within the utility industry. These workbooks fulfill several crucial roles. First, they provide an important guideline for preparing and presenting courses about the EMTP code. They also help utility technical staff implement the EMTP code. Finally, they form an excellent reference on electromagnetic transients.

These workbooks are part of a larger effort to improve the EMTP code and its documentation. EPRI initiated this effort in response to a survey of more than 70 utilities, which indicated that EMTP users considered expansion of this documentation a high priority. The program included revision of the rulebook (report EL-4541), the source code documentation (report EL-4652), and the application guide (report EL-4650). Other contributors included EPRI associate members American Electric Power Company and Electricité de France and DCG associate members Central Research Institute of the Electric Power Industry of Japan and ASEA Brown Boveri.

PROJECT

RP2149-6
EPRI Project Manager: Mark G. Lauby
Electrical Systems Division
Contractor: The University of Wisconsin at Madison

For further information on EPRI research programs, call
EPRI Technical Information Specialists (415) 855-2411.

Electromagnetic Transients Program (EMTP)
Volume 3: Workbook III

EL-4651, Volume 3
Research Project 2149-6

Final Report, June 1989

Prepared by

THE UNIVERSITY OF WISCONSIN AT MADISON
Department of Electrical and Computer Engineering
Madison, Wisconsin 53706

Author
F. L. Alvarado

With contributions from

H. Dommel
THE UNIVERSITY OF BRITISH COLUMBIA

V. Brandwajn
SYSTEMS CONTROL

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
M. G. Lauby

Power System Planning and Operations Program
Electrical Systems Division

ORDERING INFORMATION

Requests for copies of this report should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.

NOTICE

Prepared by
The University of Wisconsin at Madison
Madison, Wisconsin

ABSTRACT

This workbook is the third in a series of books intended to introduce the EMTP to users. It assumes that the user is familiar with elementary uses of the EMTP and presents more advanced modeling techniques. The workbook uses a case-study approach, where gradually more sophisticated models of the same system are introduced. This book covers mainly transformers, synchronous machines and induction motors. It includes a description of SSR (SubSynchronous Resonance).

TABLE OF CONTENTS

SECTION 1 INTRODUCTION

SECTION 2 REPRESENTATION OF TRANSFORMERS: BACKGROUND

SECTION 3 PREPARATION OF TRANSFORMER DATA

SECTION 4 USING TRANSFORMER MODELS

SECTION 5 SYNCHRONOUS MACHINES: ELECTRICAL REPRESENTATION

SECTION 6 SYNCHRONOUS MACHINES: MECHANICAL REPRESENTATION

SECTION 7 USING SYNCHRONOUS MACHINE MODELS

SECTION 8 SYNCHRONOUS MACHINES: REPRESENTING THE CONTROL SYSTEM

SECTION 9 SUBSYNCHRONOUS RESONANCE

SECTION 10 INDUCTION MOTORS AND OTHER MACHINES

APPENDIX A TEMPLATES

SECTION 1

INTRODUCTION

This volume of the workbook series deals with applications of the EMTP to the simulation of power system transient involving machines and transformers. The reader is assumed to be familiar with the basics of EMTP simulations, including simple models for the representation of machines and transformers. For these basics, refer to Volume I of the workbooks.

As in previous workbooks, the emphasis will be on an understanding of the basic questions that the EMTP is capable of answering, any inherent limitations of the program, where to obtain data and how to perform reasonable simulations with incomplete information. Understanding the limitations of digital simulation will be a priority.

This workbook is intended to complement the other materials in the series of EMTP documentation and information published by EPRI for use with the EMTP. Other items relevant to the EMTP include the Rule Book, the Theory Book, the Applications Guide and the Primer. This workbook will not replace any of these publications. It has been designed primarily to be part of course material (either self-taught or formally taught). It is a means for users to gradually gain working familiarity with the EMTP by a progression of problems and examples.

Figure 1-1 illustrates the one line diagram of the 13 bus system of interest. This system and its components will be used for most of the examples in this workbook.

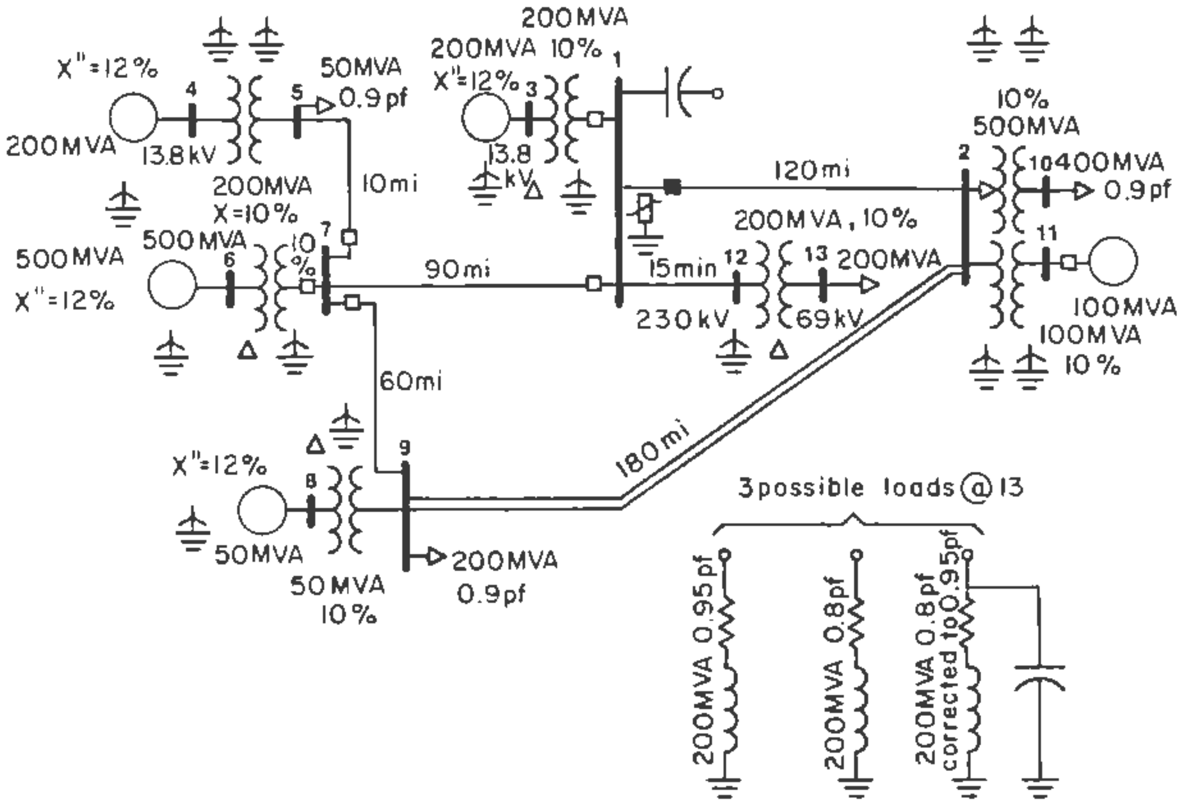


Figure 1-1: Sample 13 bus system.

SECTION 2

REPRESENTATION OF TRANSFORMERS: BACKGROUND

Transformers can be represented in several ways. Three fundamentally different types of transformer models exist in the EMTP. These are: ideal transformer models, built-in "saturable" tranformer models, and models based on mutually coupled coils. Ideal transformers ignore all leakage (assume that all flux is confined to the magnetic core) and in addition they neglect all magnetization currents (that is, they assume no reluctance in the magnetic material). The saturable transformer eliminates both these restrictions and considers leakage as well as the reluctance of the magnetic material. The model assumes that a finite reluctance magnetic path exists, and that around each individual coil a separate possible magnetic leakage path exists. The model does not consider other possible forms of mutual coupling among the coils, and for this reason it is not adequate for complex coil configurations. However, the model is quite easy to use and has proven valuable for single phase transformers. Finally, models based on matrices of mutual couplings are able to consider quite complex coil arrangements but are somewhat harder to use.

In addition to explicit representation of transformers, sometimes a user only needs to represent the effect of the presence of transformers on the rest of the system, without the need for any details about the transformer itself. In these situations it is sufficient to use Thevenin equivalents of transformers. Thevenin equivalent connections of transformers in the sequence domain (positive, negative and zero) are quite well known. In this section we describe how to use these models in actual three phase representations of the system.

Only the built-in saturable transformer model has saturation built-in directly into the model. In this section we also consider how saturation in transformers is represented in the EMTP. In most cases, this can be done externally to the coil model of the transformer. Two other effects that are described in this section include the effect of eddy currents and the effect of capacitances on high frequency behavior. Eddy current models currently do not exist in the EMTP, but we describe the characteristics of the eddy current phenomena and give a simple model capable of accounting for the theoretical effects of eddy currents. Finally, high frequency effects are described and a generic model for inclusion of high frequency effects is described.

2.1 The Ideal Transformer

The main purpose for presenting the ideal transformer equations is to give you a ready intuitive feeling for what to expect of complex winding and core configurations, to verify solutions for reasonableness and to perform quick checks of EMTP solutions.

The simplest transformer model from the mathematical viewpoint is the ideal transformer. The equations that control the behavior of ideal transformers are well known. Consider first a simple two winding transformer as illustrated if Figure 2-1-1.

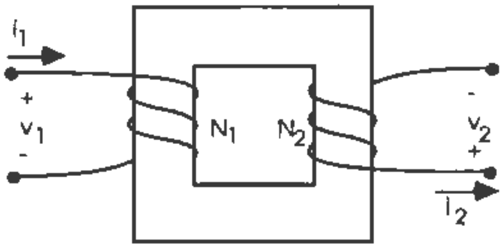


Figure 2-1-1: A two winding ideal transformer.

The equations that describe the behavior of this transformer are:

$$\frac{v_2}{v_1} = n$$

$$\frac{i_2}{i_1} = \frac{1}{n^*}$$

where

$$n = \frac{N_2}{N_1}$$

In a general case, when voltages and currents may be phasors, n may be a complex number. In this case we need to use n^* in the current equations.

A single-core multi-winding transformer is illustrated in Figure 2-1-2. The equations that describe the behavior of this type of transformer are:

$$N_1 \ i_1 + N_2 \ i_2 + \ldots + N_n \ i_n = 0$$

$$\frac{v_1}{N_1} = \frac{v_2}{N_2} = \ldots = \frac{v_n}{N_n}$$

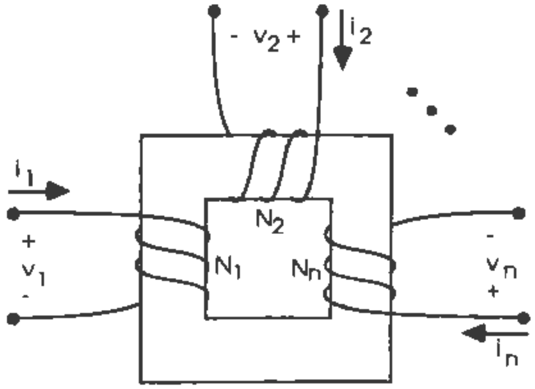


Figure 2-1-2: A single-core multi-winding transformer. Notice the polarity of the currents.

An even more general case is the multi-core multi-winding transformer. Figure 2-1-3 illustrates this type of transformer.

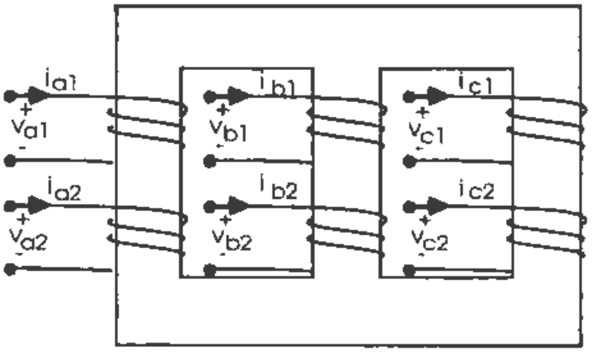


Figure 2-1-3: A multi-core multi-winding transformer.

The equations that describe the behavior of this multi-core multi-winding ideal transformer are:

$$\frac{v_{a1}}{N_{a1}} = \frac{v_{a2}}{N_{a2}}$$

$$\frac{v_{b1}}{N_{b1}} = \frac{v_{b2}}{N_{b2}}$$

$$\frac{v_{c1}}{N_{c1}} = \frac{v_{c2}}{N_{c2}}$$

$$\frac{v_{a1}}{N_{a1}} + \frac{v_{b1}}{N_{b1}} + \frac{v_{c1}}{N_{c1}} = \frac{v_{a2}}{N_{a2}} + \frac{v_{b2}}{N_{b2}} + \frac{v_{c2}}{N_{c2}} = 0$$

$$N_{a1}\, i_{a1} + N_{a2}\, i_{a2} = N_{b1}\, i_{b1} + N_{b2}\, i_{b2} = N_{c1}\, i_{c1} + N_{c2}\, i_{c2}$$

It is only quite recently that the EMTP has been able to represent ideal transformers correctly, and the work was done in connection with the ideal voltage source between arbitrary nodes. The EMTP ideal transformer (a type 18 source) is actually a simple two winding ideal transformer with an ideal voltage source in series with its secondary. Figure 2-1-4 illustrates this type 18 source. For detail input format, refers to the template in Appendix A.

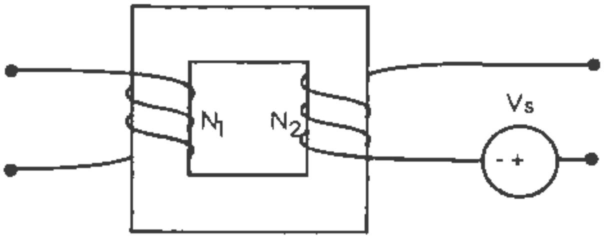


Figure 2-1-4: The EMTP ideal transformer model is a type 18 source. The transformer is linked to the ideal voltage source between nodes. To set up an ideal transformer, set the voltage source to zero.

2.2 Low Frequency Models

This section describes increasingly complex and detailed transformer models for use at relatively low frequencies (up to a few kHz). In this subsection we begin with models that do not require a magnetization current, then move to models that *must* have a non-zero magnetization current. Finally we discuss the topics of saturation and hysteresis

2.2.1 Transformers as Part of the Network Thevenin Equivalent

Transformers, particularly Δ-Y connected transformers, drastically affects the zero sequence impedance of a network. Consider the network one line diagram in Figure 2-2-1.

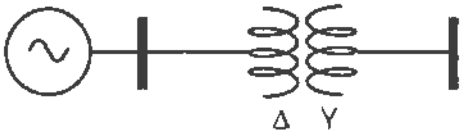


Figure 2-2-1: One line diagram of a Δ-Y transformer connected to ideal voltage source.

The sequence domain equivalent circuits of this network as seen from the secondary of the transformer is shown in Figure 2-2-2.

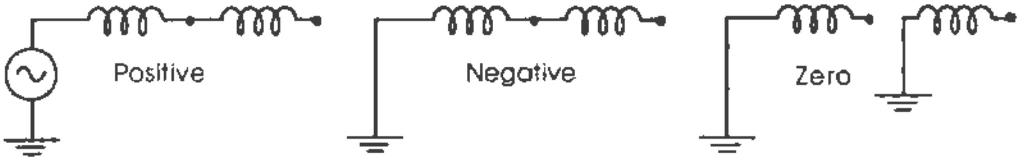


Figure 2-2-2: Sequence domain equivalent circuit of the Δ-Y connected transformer in Figure 2-2-1.

Notice that only the positive sequence has a source, and that the primary and secondary of the transformer zero sequence are disconnected, while the secondary is connected to ground through the transformer impedance (assuming the secondary Y is grounded).

The magnetization branch is sometimes ignored, particularily in fault type studies. Three phase transformers (as opposed to banks of three single phase transformers) generally have quite different zero sequence parameters for the zero sequence, with zero sequence reactances between 20 and 100 times the magnetization current. The magnetization branch is unimportant for delta connected transformers.

Other transformer connections lead to other types of and zero sequence impedances.

2.2.2 Simple Admittance Representation

The use of Thevenin equivalents of transformers considers the effect of the transformer on the network, but the transformer itself is no longer explicitly available. For example, it is not possible to determine circulating currents in the delta-connected winding of the transformer.

In order to do that, we need slightly more detailed models of the transformer. This section describes transformer models based on admittance equivalent circuit representations of the transformer. These models remain quite simple as long as the zero sequence leakage reactance, X_0, equals to the positive sequence leakage reactance, X_1, as is the case for three phase transformer banks consisting of three single phase units, or in three phase transformers with 5-legged core or limb design. These models can be extended to three phase transformers where X_0 is between 0.7 to 1.0 X_1, as is often the case for three phase transformers with three leg cores.

From load flow type studies, we know that the two-port admittance matrix that describes a non-ideal transformer as seen from the primary side is given by the following matrix:

$$[Y] = [\omega L]^{-1} = \begin{bmatrix} Y & -t\ Y \\ -t^{*}\ Y & |t|^{2}\ Y \end{bmatrix}$$

In this matrix,

$$Y = \frac{S_{rating}}{X_{pu}\ V_H^{2}}, \quad t = \frac{V_H}{V_L}$$

This admittance matrix is nothing more than a linear relationship between the primary and the secondary side voltages and currents:

$$\begin{bmatrix} i_L \\ i_H \end{bmatrix} = [Y] \begin{bmatrix} v_L \\ v_H \end{bmatrix}$$

We also know that *any* admittance matrix has an equivalent circuit consisting of pure admittances that behaves exactly as described by the admittance matrix equation. This circuit may bear little resemblance to the original circuit, but its behavior is identical to any other circuit described by the same admittance matrix. In the case of load flow studies, this matrix can be interpreted as originating from the network in Figure 2-2-3.

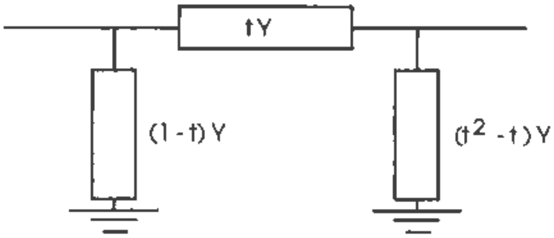


Figure 2-2-3: A π-circuit equivalent of a non-ideal transformer describable by the admittance matrix equation in load flow studies.

For use in transient studies, it is better to use the concept of a "primitive admittance matrix," see [1]. A primitive admittance matrix contains entries for all nodes and makes no assumptions about node grounding. The primitive admittance matrix for the ordinary transformer is given by:

$$[\omega L]^{-1} = \begin{bmatrix} Y & -t\ Y & -Y & t\ Y \\ t^{*}\ Y & -|t|^{2}\ Y & -t^{*}\ Y & |t|^{2}\ Y \\ -Y & t\ Y & Y & -t\ Y \\ -t^{*}\ Y & |t|^{2}\ Y & t^{*}\ Y & -|t|^{2}\ Y \end{bmatrix}$$

It is still possible to come up with a network interpretation of this matrix. The network now looks just a bit more complex, but every node retains its identity. Figure 2-2-4 illustrates this equivalent network.

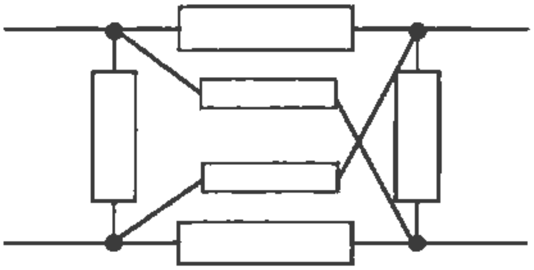


Figure 2-2-4: A circuit equivalent of a non-ideal transformer using primitive admittance matrix representation.

Thus, we can say that the circuit in Figure 2-2-4 is an equivalent representation of the transformer in Figure 2-2-5.

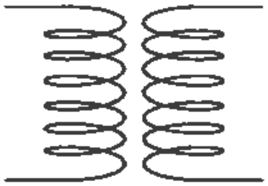


Figure 2-2-5: A simple transformer representation.

An advantage of using the primitive admittance concept is that we retain full flexibility for winding interconnections, whereas the ordinary admittance matrix models assume a certain pattern of node grounding. A disadvantage of the primitive admittance matrix is that it may be singular if there are no connections to ground, or ill conditioned if the only connection to ground is through a very high impedance.

If we were dealing with admittances the problem would end here. However, it is more proper to speak of "inverse inductances." What we really compute is an inverse inductance matrix, and the resistances of the winding are considered externally and in series with these inductances. Thus, we must separate resistances from inverse inductances. We therefore specify not $[Y]$ but $[L]^{-1}$ and $[R]$ as separate matrices. Starting with Version 2 of the EMTP you will be able to specify these two matrices directly. In prior versions of the EMTP the use of this particular model is not recommended unless $[R]$ equals to zero. These models can be obtained using the BCTRAN auxiliary program.

2.2.3 Equivalent Circuit Models

Up to reasonable frequencies (to about 2 kHz) the transformer is representable as an ideal transformer with some series and shunt branches. The traditional low frequency model for two winding transformers including the magnetization current branch is shown in Figure 2-2-6.

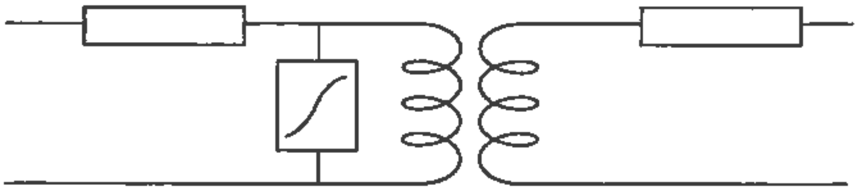


Figure 2-2-6: The traditional low frequency equivalent of a two winding transformer.

Single-core multi-winding transformers have also had a traditional equivalent circuit. This circuit is illustrated in Figure 2-2-7.

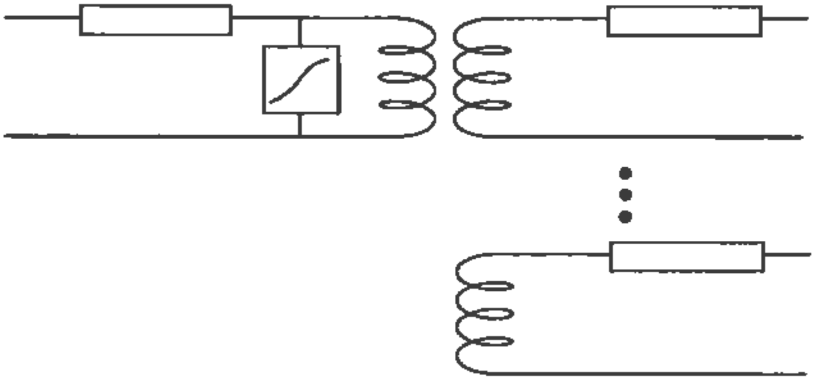


Figure 2-2-7: The traditional equivalent circuit for a single-core multi-winding transformer.

All of these models can be reduced to the admittance matrix models of the previous section.

There is some reason to question the validity of all of these traditional models, particularly for multi-winding transformers. In particular, much debate has centered around the location of the shunt magnetization branch, and how to split the series transformer impedances among the various windings. Part of the problem is that transformer parameters are almost invariably determined from a sequence of tests, and the models above make certain explicit or implicit assumptions about the magnetic circuit of the transformer. The main objective of this discussion is merely to point out that the traditional model may not be as accurate as once thought, and that there are good reasons for much of the recent effort in coming up with better models for the transformer in the EMTP.

There is one EMTP model that is very closely associated with the traditional equivalent circuit. This is the built-in `TRANSFORMER` (saturable transformer model) within the EMTP that was described in Workbook I. Details of construction for this model is included in templates.

2.2.4 Coupled RL Models and Impedance Models

There are two alternate detailed coupled-coil matrix representations of the transformer. These are the mutually coupled branches and the impedance matrix models. The impedance matrix and mutually coupled models are only feasible when at least some portion of the magnetization branch of the transformer is represented, otherwise the corresponding `[Y]` matrix on which these models are based is singular and the `[Z]` matrix does not exist.

In the mutually coupled branches model, a transformer is represented as a set of mutually coupled impedances. Using the EMTP, this corresponds to the use of type `51`, 52, etc mutually coupled RL branches (or type 1, 2, 3 RLC branches with C equals to zero). Figure 2-2-8 illustrates the representation of this model for a two winding transformer. Figure 2-2-9 illustrates the equivalent interpretation of the same transformers using an equivalent without mutual couplings.

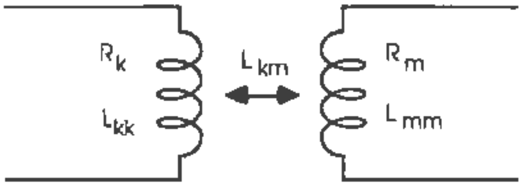


Figure 2-2-8: Representation of a two winding transformer by mutually coupled impedances.

Mathematically, the representation of these coupled impedances as a set of *time domain* matrix equations is:

$$\begin{bmatrix} L_{kk} & L_{km} \\ L_{km} & L_{mm} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_k \\ i_m \end{bmatrix} = \begin{bmatrix} v_k \\ v_m \end{bmatrix} - \begin{bmatrix} R_{kk} & 0 \\ 0 & R_{mm} \end{bmatrix} \begin{bmatrix} i_k \\ i_m \end{bmatrix}$$

A problem with these equivalents is that if there is no magnetization branch in the transformer (that is, if the magnetization current is negligible) this model results in singular matrices. If the magnetization current is small (as it usually is) the inductance matrix is ill-conditioned, requiring great precision in its representation. They are, nevertheless, of value and recommended by some.

To obtain the actual inductance matrix, we first obtain a per unit impedance matrix using the expression:

$$\begin{bmatrix} \frac{1}{2} X_{short\ pu} + X_{mag\ pu} & X_{mag\ pu} \\ X_{mag\ pu} & \frac{1}{2} X_{short\ pu} + X_{mag\ pu} \end{bmatrix}$$

This matrix can then be converted to an actual ohms impedance matrix, and subsequently to an inductance matrix. *All calculations must be done in high precision.*

In reality, these models can be obtained for arbitrary transformers with the help of the `TRELEG` auxiliary program.

The mutually coupled branches model is intimately related to the mutual inductance matrix of the element. The inductance matrix can be obtained as the inverse of the $[L]^{-1}$ matrix described earlier. Once this matrix is obtained, it is possible to interpret it in terms of a T- or star-circuit *provided we do not have more than three windings.* For situations with more windings, it is no longer possible to expect a star-circuit equivalent.

Obtaining T-circuit equivalents from test is quite simple. Put half of the per unit short-circuit reactance on each side of the T, and calculate the inductance of the T-branch from:

$$X_{mag\ pu} = \frac{1}{I_{exc\ pu}} - \frac{1}{2} X_{short\ pu}$$

Once again, calculations must be done in high precision.

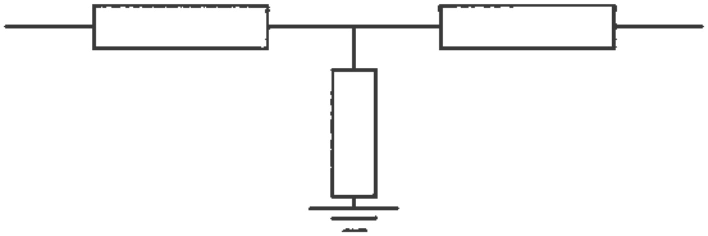


Figure 2-2-9: A T-circuit equivalent of a two winding transformer.

2.3 Transformer Saturation

This subsection and the next two discuss the generalities of some model extensions useful in representing transformers more accurately. In all three subsections, the methodology is not actually built into the EMTP. Nevertheless, we hope to give those attempting to obtain more accurate models an understanding of the nature of the physical phenomena as well as a repertoire of tools that can be used within the existing framework of the EMTP. In all these cases, good engineering judgement will be required about the validity of the models and results.

Conventional wisdom represents transformers as equivalent circuits. As we say in section 2.2, these equivalent circuits often have as many branches as there are windings in the transformer. In a transformer with more than three windings it is, however, not possible to come up with a correct equivalent circuit based on leakage impedances and ideal transformers. In fact, the leakage impedances that one calculates for two- and three-winding transformers are simply numeric values capable of reproducing the short circuit test results. The so-called internal node in this equivalent is an entirely fictitious or equivalent node. Nevertheless, it has been customary to place the magnetization branch of the transformer across this node. In a simple two-winding configuration there is some basis for this: the magnetization branch is associated with the reluctance of the magnetic material. Placing the magnetization branch between the two leakage reactances is equivalent to assuming that all the reluctance of the magnetic circuit (including any losses and saturation) occurs outside the path linked by the leakage reactances. However, for three or more branches there is no basis for this location. In fact, it has been established that a better location for the magnetization branch is at the terminals of the innermost winding.

Representation of the magnetization branch can be quite important. In tbe equivalent circuit representations using the TRANSFORMER (saturable transformer model) the saturable magnetization current branch is an integral part of the model, and is placed internally within the transformer model. In the impedance and admittance matrix models, the saturable branch must be placed at the transformer terminals. The exact location of the saturable branch does affect the behavior. It is recommended that the branch be placed at the terminals of the winding that physically corresponds to the innermost winding in the transformer, usually one of the lower voltage windings.

What location of the magnetization branch is the correct one? This is a question that is not well posed, as there is no actual "magnetization branch" in a transformer. The only correct way to model the magnetization current in a transformer would be to *represent the magnetic circuit in detail*. In the limit this would require laborious finite element methods. Thus, we, like others before us, accept the need for a "magnetization branch" in the representation of transformers, and include saturation effects entirely within this magnetization branch.

The EMTP offers some assistance in the calculation of the magnetization branch saturation parameters. This is done using the "Saturation" auxiliary program. All that is needed to use this program is a few RMS values of voltage and current from open circuit tests at various voltages. The reader is referred to Workbook I and to the Users Manual for further details. We do not replicate these example here. Here we simply suggest that judgement should be used in locating the branch so obtained within the equivalent circuit, keeping in mind that any choice is an approximation because there is no exact location for this branch.

A second concern of saturation is its interaction with eddy currents and flux penetration. As described in the next section, eddy currents generally delay the penetration of magnetic flux into magnetic material. Thus, the nature of saturation will be affected by the frequency of interest. To date there are no reliable computationally efficient and accurate ways of accounting for saturation effects at higher frequencies.

2.4 Eddy Currents

Modelling of transients effects in transformer shares many features with modelling of transients in lines and cables. The problem of eddy currents for lines is usually referred to as the "frequency dependence of parameters" problem. In transformers, frequency dependence effects caused by eddy currents also play an important role. Saturation, hysteresis and eddy currents effects must also be included in an accurate transformer model. In the following section, we will discuss a model capable of simulating eddy currents effects in the transformer [1]

Eddy currents in the core of a transformer have two major effects: they introduce core losses, and they oppose (delay) flux penetration into the core. Figure 2-4-1 shows the classical plot of the magnetic field intensity within a lamination under a step magnetic field excitation versus the distance from the center of the lamination, with time as a parameter.

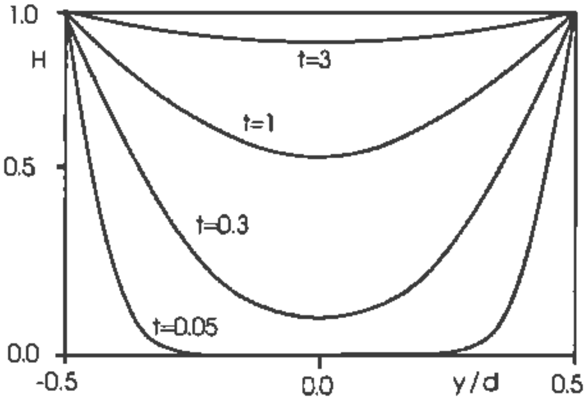


Figure 2-4-1: Magnetic field intensity in a limination under a step magnetic field excitation. y/d is the normalize distance form the center of the limination to the surface.

To model eddy currents effects, we can consider a transformer core with ideal dielectric between laminations. Under this hypothesis, each of the laminations can be studied seperately. We may furthur assume that the conductivity and permeablility of the lamination is constant and the width of the lamination is much larger that the thickness so that end effect may be neglected. From these assumptions, we can derive either impedance or admittance equations.

The admittance equation derived for a simple two-port network is:

$$Y(s) = \frac{\ell}{2WN^2}\sqrt{\frac{\sigma}{\mu_0\mu s}}\coth\left(\sqrt{\mu_0\mu s}\,\frac{d}{2}\right)$$

where

ℓ	Length of the magnetic path
W	Width of the lamination
N	Number of turns of the coil
σ	Conductivity of the limination
μ	Permeability of the limination
d	Lamination thickness

The partial fraction of this equation is:

$$Y(s) = \frac{1}{sL_{dc}} + \sum_{n=1}^{\infty} \frac{\frac{2}{L_{dc}}}{s + \frac{n^2}{\tau}}$$

where

$$L_{dc} = \frac{\mu_0 \mu N^2 A_{fe}}{\ell} \qquad \text{(Low-frequency inductance)}$$

$$\tau = \frac{\mu_0 \mu \sigma d^2}{4\pi^2} \qquad \text{(Diffusion time constant)}$$

This equation has a Foster network representation as shown in Figure 2-4-2.

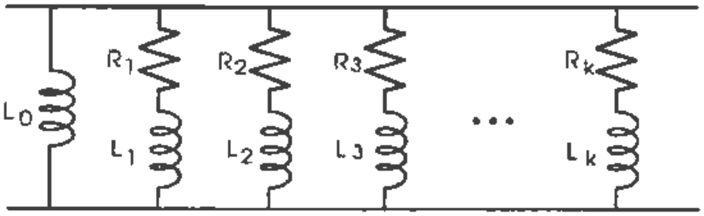


Figure 2-4-2: Equivalent network for the frequency dependence admittance of a transformer.

The values of each of the n parallel Foster branches can be calculated as follow:

$$L_0 = L_{dc}, \quad L_k = \frac{L_{dc}}{2}, \quad R_k = \frac{k^2 L_{dc}}{2\tau} \qquad k=1,\ldots,n$$

The model discussed above takes into account both the effects of core losses and flux penetration. The resistance of the RL branches account for the losses, while the inductances represent the effect of a limited penetration of flux variations into the laminations of the core.

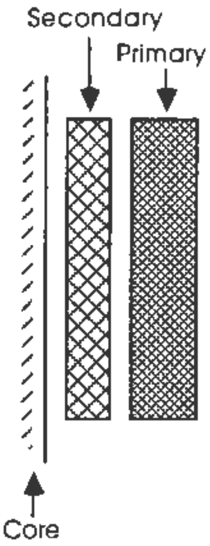
At low frequencies, the value of the resistors is significantly higher than the value of the inductive reactances. Therefore inductances can be neglected, resulting in an equivalent resistance. This resistance represents the eddy current losses in the core when a uniform distribution of electromagnetic field is assumed within the lamination.

At high frequencies, the value of the inductances may become higher than the value of the resistances. At extreme frequencies, the resistances can be neglected. The effect of neglecting resistances means that a very low value of the inductance appears at the port of the circuit. This very low value of inductance means that not much flux penetrates the core. This is due to eddy currents in the core.

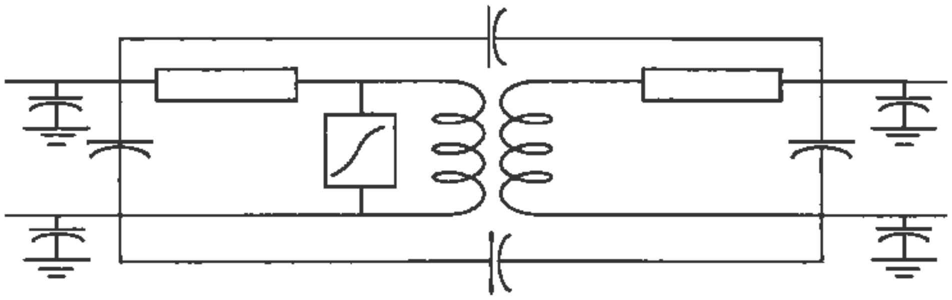
2.5 High Frequency Equivalents

At frequencies above 2 kHz the traditional transformer models begin to break down. Capacitances and capacitive coupling among windings become important. In fact, at sufficiently high frequencies the behavior of the transformer becomes dominated by its capacitances.

For frequencies up to about 30 kHz or so, the simple addition of total capacitances of windings and between windings is sufficient for most purposes. Figure 2-5-1 illustrates a model based on this extension. For even higher frequencies, a more detailed representation of the internal winding arrangement is required and capacitances between and among winding segments must be obtained or estimated. Figure 2-5-2 illustrates a possible single phase tap changing transformer, including the arrangement of windings around the core and its equivalent circuit.

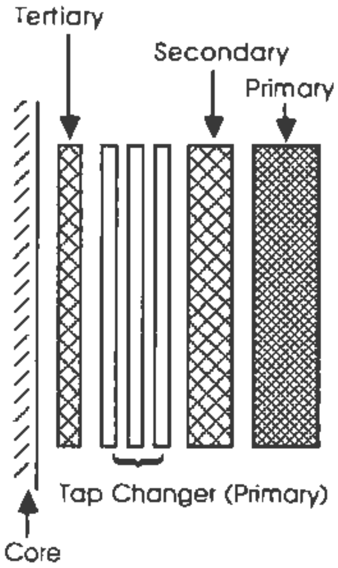


(a) Coil configuration.

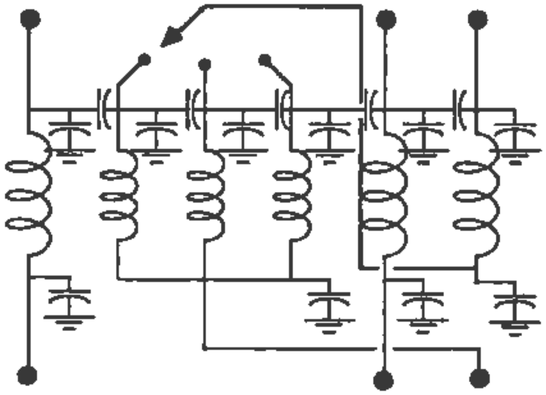


(b) High frequency equivalent circuit.

Figure 2-5-1: A high frequency equivalent for a simple transformer arrangement.



(a) Coil arrangement.



(b) The equivalent circuit including capacitances.

Figure 2-5-2: High frequency model of a single phase tap changing transformer.

2.6 References

[1] F. Alvarado, "Formation of Y-Node Using the Primitive Y-Node Concept," IEEE Transactions on Power Apparatus and Systems, vol. PAS-101, No. 12, pp. 4563-4571, December 1982.

[2] J. Avila-Rosales, F. Alvarado, "Nonlinear Frequency Dependent Transformer Model for Electromagnetic Transient Studies in Power Systems," IEEE Transaction on Power Apparatus and Systems, vol. PAS-101, pp. 4281-4288, Nov. 1982.

SECTION 3

PREPARATION OF TRANSFORMER DATA

The EMTP has a built-in saturable transformer component and three auxiliary programs for transformer parameters calculation. The built-in saturable transformer model, `TRANSFORMER`, is introduced in Workbook I. In this section we discuss this saturable transformer model in more detail. The three auxiliary programs, `XFORMER`, `TRELEG` and `BCTRAN`, derive matrix parameters for modelling transformer windings as mutually coupled branches (`type 51, 52 ... etc`). When these matrix models are used, the core of the transformer is usually represented as a non-linear reactance (`type 98`) or a hysteretic reactance (`type 96`) branch connected externally to the terminals of one of the windings.

The `XFORMER` program is capable of calculating the `[R]` and `[L]` matrices for single-phase transformer banks. Therefore, `XFORMER` can represent only three-phase transformers consist of three single-phase banks. The `TRELEG` program also calculates the `[R]` and `[L]` matrices but it has the capability of representing single-phase as well as three-phase core-type transformers. Unlike the previous two, `BCTRAN` produces the `[R]` and `[L]` as well as $[L]^{-1}$ matrices. Thus, the $[L]^{-1}$ matrix can be used to avoid the ill-condition problems associated with the `[L]` matrix. `BCTRAN` is capable of representing both single-phase and three-phase core-type transformers.

When core saturation is represented in the EMTP, a piecewise linear flux-current magnetization curve must be supplied. This curve is inputted point by point, starting from the point nearest to the origin (origin is assumed an implicit point) and increase monotonically moving away from the origin. Both the saturable transformer and the pseudo-nonlinear reactance (`type 98`) branch uses a flux-current magnetization curve. Since most manufacturers do not supply this data, an auxiliary program `CONVERT` is designed to preform the conversions from RMS voltage-current or current versus incremental inductance data to flux-current data.

The EMTP is capable of representing the transformer core as a hysteretic reactance. A pseudo-nonlinear hysteretic reactance (`type 96`) branch can be used to replace the pseudo-nonlinear reactance (`type 98`) branch when the matrix models are being used. However, the type 96 branch is harder to initialize than the type 98 branch. As a result, it is not usually used. The piecewise linear element in the type 96 branch is a hysteresis curve which captures the characteristic of the major hysteresis loop. Since the shape of the hysteresis loop depends primarily on the material of the core, the EMTP provides an auxiliary program `HYSDAT` to help obtaining the flux-current curve for designated core materials. In Version 1.0 of the EMTP, only 1 ARMCO M4 oriented silicon steel is supported.

The saturable transformer component is simpler to use than the other matrix models. However, if zero sequence behavior of three-phase core-type transformer must be represented, `TRELEG` or `BCTRAN` should be used. When a three-winding core-type transformer has a closed delta tertiary, it is usually not necessary to model the zero sequence effects because the delta terminal connections will predominate.

As discussed in earlier section, the transformer models described in this section is valid only at moderate frequencies. In general, these models are accurate enough in switching surge studies but they are not adequate for lightning surge studies. Transformer model that is accurate at higher frequencies is being developed and it will be available in future versions the EMTP.

3.1 Simple Two Winding Linear Models

Simple transformer models can be constructed directly from the knowledge of transformer rating, size and perhaps its short circuit tests.

The EMTP has a build in saturable transformer model which can represent single-phase as well as three-phase transformers of some core formation. To use this model, a keyword `TRANSFORMER` must be specified along with a unique transformer name. All other data fields are optional. These option fields can be used to specify the steady-state RMS magnetization flux (in volt-seconds) and current (in amperes) as seen from winding #1, and the magnetization core loss resistance. Core losses are confined to constant linear resistance in parallel with the magnetization branch. Figure 3-1-1 shows the circuit representation of the saturable transformer.

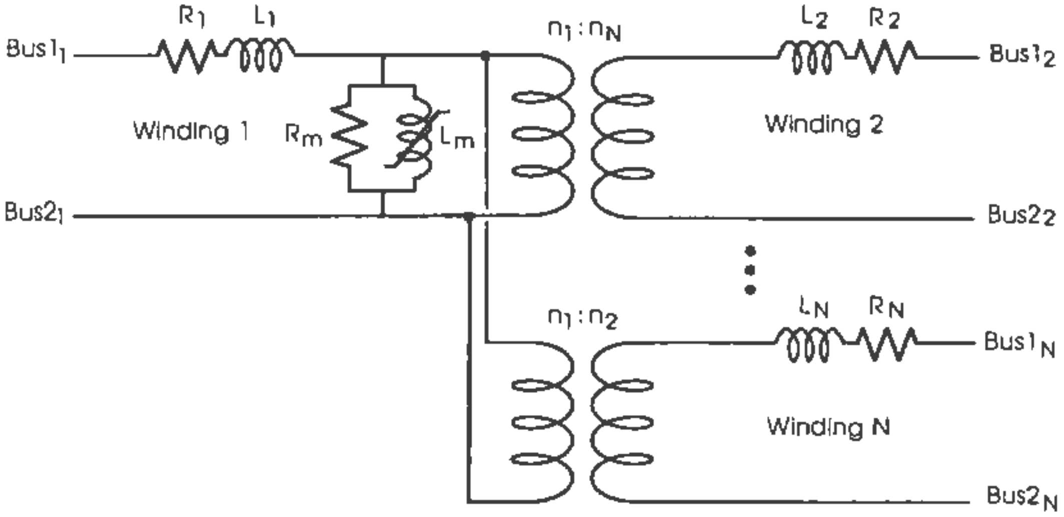


Figure 3-1-1: Star-circuit representation of N-winding transformer.

Following the first data line naming of a transformer are the data lines describing the saturation curve of the transformer as points in a flux-current curve. The magnetization curve data is terminated with a data line containing `9999` in the current field. In case no flux-current data point is specified, the EMTP assumes that the magnetization branch does not exist. In case only one flux-current is specified, the EMTP uses a linear inductance representation of the magnetization branch which results in a linear transformer. In other cases, the saturation and magnetization effects are modelled as a pseudo-nonlinear reactor (`type 98`) branch in winding #1. Normally, the first point in the piecewise linear magnetization curve is set to equal to the steady-state current and flux so that continuity between steady-state and transient solutions at time zero is attained. Nevertheless, this continuity between steady-state and transient solutions is not mandatory. The final point in the magnetization curve defines the slope of the final segment. This final segment is assumed to extended to infinity.

The flux-current magnetization curve is generally not available, however, it can be calculated from most manufacturer's data. The EMTP has an auxiliary program `CONVERT` which performs conversion from a RMS voltage-current curve or current versus incremental inductance curve to a flux-current curve. Refers to section 3.6 for more details in using `CONVERT`.

Following the magnetization data is the winding data. Each winding must be numbered in natural order (i.e. 1, 2, ...). Each winding is connected to two nodes. In each winding data line, specify the winding resistance, leakage reactance and voltage. Zero winding resistances is allowed in all winding but leakage inductances must be non-zero with the exception of winding #1. The inductance L_1 in winding #1 can be zero only if the resistance R_1 is non-zero. Rated winding voltage can be used for each winding. Templates that describe the precise formats and connections of single-phase and three-phase transformers are available in Appendix A.

The saturable transformer has some limitations. It cannot represent more than three windings because the transformer is represented as a star-circuit internally with the saturation branch connected to the internal point of the star circuit. Besides, the saturable transformer can only model single-phase or three-phase bank of single-phase units. For three-phase shell-type transformer, as shown in Figure 3-1-2, we must assume that the magnetic induction of the three-phases is independent for the saturable transformer model to be valid.

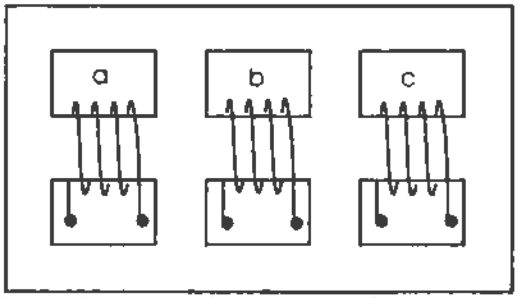


Figure 3-1-2: A three-phase shell-type transformer.

Using the saturable transformer in other core formations is *not recommended.* In core-type transformers where the zero sequence flux is forced to return through the air, the transients behavior is radically different when the zero sequence is excited. Figure 3-1-3 illustrates a three-phase three-legs core-type transformer. The saturable transformer has been extended from single-phase to three-phase units through the addition of zero sequence reluctance parameter. However, its usefulness for core-type units is limited. Three-phase units are better modelled with `[R]` and `[L]` or $[L]^{-1}$ matrices obtained from `TRELEG` or `BCTRAN`. Furthermore, numerically instability has occasionally been observed for three winding saturable transformer.

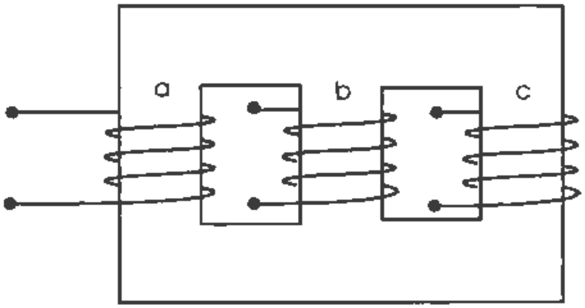


Figure 3-1-3: A three-phase three-legs core-type transformer.

3.2 Using XFORMER

The auxiliary program `XFORMER` derives the `[R]` and `[L]` matrices for representing transformer windings as mutually couple branches (type `51`, `52`, `53`) in the EMTP. The `XFORMER` program is capable of representing up to three windings for single-phase transformers. Thus, the `XFORMER` is useful only for three-phase units consist of single-phase banks.

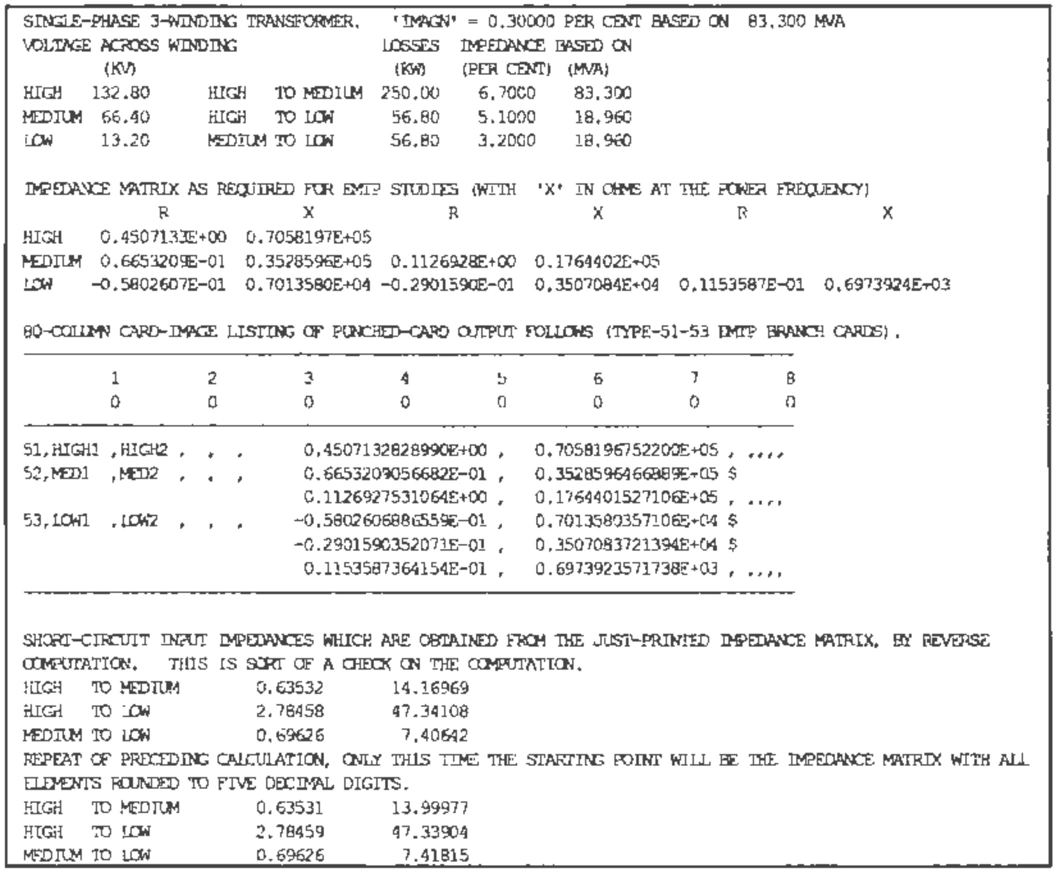
To use the XFORMER program, a XFORMER special request card must be entered at the beginning of a new data case. Then followed by an optional branch card. The branch card is used for naming the terminal nodes of the transformer windings in the output. Since the XFORMER cannot represent more than three windings, there should be no more than six node names appear on this card.

In the data line follows, enter the number of windings (either 1, 2 or 3), the single-phase base power of the transformer (in MVA) and the magnetization current consistent with the base power (in percent). The XFORMER program assumes the existence the finite magnetization impedance. Therefore, if the magnetization current is too small, it can cause admittance matrix to become singular. As a result, inverting the admittance matrix to the desired [R] and [L] matrices becomes impossible.

The electrical parameters of each winding must be specified. One data line is used for each winding. Each data line contains the voltage rating, the power loss, the single-phase power base and the short-circuit impedance. The voltage rating for delta-connected transformer is the RMS line-to-line voltage (in kilovolts) of a winding. For wye-connected transformer, specify $1/\sqrt{3}$ of the line-to-line voltage instead of the line-to-line voltage. The power loss is the load loss (in kilowatts) for a single-phase transformer transmitting rated power between two windings. The short-circuit impedance (in percent of the base power) is measured between two winding. Figure 3-2-1(a) illustrates the XFORMER input for a single-phase three-winding transformer and the output is shown in Figure 3-2-1(b). Templates for one, two and three windings XFORMER input is available in Appendix A.

```
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER
C
C Branch card
C         High (51)  Medium (52)   Low (53)
C ----->Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
BRANCH  HIGH1 HIGH2 MED1  MED2  LOW1  LOW2
C
C Electrical parameters
C ---CMagn<-----PBCur    <-IPunch
3      0.3      83.3          0
C col: (1) NW
C Winding data
C ---Volt1<--PLoss12<-----ZSC12<-----PBZ12
     132.8     250.0       6.7       83.3
C ---Volt2<--PLoss13<-----ZSC13<-----PBZ13
      66.4      56.8       5.1      18.96
C ---Volt3<--PLoss23<-----ZSC23<-----PBZ23
      13.2      56.8       3.2      18.96
BLANK card terminates XFORMER data
BLANK card terminates EMTP solution-mode
```

(a) XFORMER input data.



```
SINGLE-PHASE 3-WINDING TRANSFORMER.   'IMAGN' = 0.30000 PER CENT BASED ON  83.300 MVA
VOLTAGE ACROSS WINDING                 LOSSES  IMPEDANCE BASED ON
       (KV)                             (KW)   (PER CENT)  (MVA)
HIGH   132.80      HIGH   TO MEDIUM  250.00     6.7000     83.300
MEDIUM  66.40      HIGH   TO LOW      56.80     5.1000     18.960
LOW     13.20      MEDIUM TO LOW      56.80     3.2000     18.960

IMPEDANCE MATRIX AS REQUIRED FOR EMTP STUDIES (WITH  'X' IN OHMS AT THE POWER FREQUENCY)
              R            X             R            X             R            X
HIGH    0.4507133E+00  0.7058197E+05
MEDIUM  0.6653209E-01  0.3528596E+05  0.1126928E+00  0.1764402E+05
LOW    -0.5802607E-01  0.7013580E+04 -0.2901590E-01  0.3507084E+04  0.1153587E-01  0.6973924E+03

80-COLUMN CARD-IMAGE LISTING OF PUNCHED-CARD OUTPUT FOLLOWS (TYPE-51-53 EMTP BRANCH CARDS).
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
         0         0         0         0         0         0         0         0
--------------------------------------------------------------------------------
51,HIGH1 ,HIGH2 ,  ,  ,     0.4507132828990E+00 ,   0.7058196752200E+05 , ....,
52,MED1  ,MED2  ,  ,  ,     0.6653209056682E-01 ,   0.3528596466889E+05 $
                            0.1126927531064E+00 ,   0.1764401527106E+05 , ....,
53,LOW1  ,LOW2  ,  ,  ,    -0.5802606886559E-01 ,   0.7013580357106E+04 $
                           -0.2901590352071E-01 ,   0.3507083721394E+04 $
                            0.1153587364154E-01 ,   0.6973923571738E+03 , ....,
--------------------------------------------------------------------------------

SHORT-CIRCUIT INPUT IMPEDANCES WHICH ARE OBTAINED FROM THE JUST-PRINTED IMPEDANCE MATRIX, BY REVERSE
COMPUTATION.   THIS IS SORT OF A CHECK ON THE COMPUTATION.
HIGH   TO MEDIUM        0.63532       14.16969
HIGH   TO LOW           2.78458       47.34108
MEDIUM TO LOW           0.69626        7.40642
REPEAT OF PRECEDING CALCULATION, ONLY THIS TIME THE STARTING POINT WILL BE THE IMPEDANCE MATRIX WITH ALL
ELEMENTS ROUNDED TO FIVE DECIMAL DIGITS.
HIGH   TO MEDIUM        0.63531       13.99977
HIGH   TO LOW           2.78459       47.33904
MEDIUM TO LOW           0.69626        7.41815
```

(b) XFORMER output.

Figure 3-2-1: Calculating the [R] and [L] matrices for single-phase three-winding transformer using XFORMER. This data is obtained from EMTP test case DC-15.

The reader must be warned that the XFORMER program is not reliable at extremely low frequencies. The reason for this erroneous behavior is related to the formation of the admittance matrix. XFORMER obtains the admittance without first separating [R] and [L] from the equation. As a result, the off-diagonal resistances in the branch impedance matrix becomes non-zero. At extremely low frequencies, when the magnitude of [R] becomes comparable with the magnitude of [ωL], the XFORMER will produce wrong results.

In general, the XFORMER can results in more stable model for multi-winding transformers. For two-winding transformers, the saturable transformer is believed to be equivalent to the [R] and [L] representation of the XFORMER. Similar to the saturable transformer, the XFORMER is limited to single-phase banks. The XFORMER program for single-phase transformer is somewhat obsolete, and has been superceded by BCTRAN.

3.3 Using TRELEG

To use the TRELEG program, a XFORMER special request card must be present at the beginning of a new data case. In addition, a value 33. must be entered in column 38 to 40 to request TRELEG input. A branch card may follow the special request card, however, this card is obsolete because the naming of winding terminals also appears in the winding data. The branch card will be removed from the future versions of the EMTP.

The data cards that follow specify the electrical parameters of the transformer. The first card contains the number of windings, the number of delta-connected windings, the power frequency (i.e. 60 Hz) and the rated three-phase power base (in MVA). The TRELEG program can support up to five windings. It assumes that the windings are concentrically located on the core, and winding data is inputted in the order from outer to inner winding. In addition, it also expects the data to be inputted in an order that the delta-connected windings appear last. This is occasionally a conflicting assumption. Since the windings can be non-concentric and the delta-connected windings may locate other than the center on the core. The TRELEG program resolves this conflict by restricting the delta-connected windings as the last windings and allowing the magnetizing impedance of each winding to be provided.

Standard manufacturer data may include test data from short-circuit tests performed with up to two windings connected in delta. In order to use these data, the TRELEG program requires three additional cards to specify the test data for two delta-connected windings. These data lines contain positive sequence short-circuit impedance between two delta-connected windings, the number of wye-connected winding for which zero sequence test with the two delta-connected windings closed is performed and the zero sequence short-circuit impedances between the wye-connected windings and the two delta-connected windings. In either cases, the positive and zero sequence short-circuit impedances are entered immediately follows. For N-winding transformer, there should be (N-1) N/2 + 1 test data lines. Since two data lines are already specified for two delta-connected windings, only (N-1) (N-2)/2 + 1 data lines are required.

The TRELEG program allows the output matrices to be either in per unit or in ohms. The output unit can be specified in the data line that appears right after the short-circuit data. Following this data line is the winding data. There will be one data line for each winding (rule book says N+1, why?). The winding data includes the winding number, the type of winding connection (wye or delta), the rated voltage, resistance and connections of the winding. The naming convention of the winding terminals are established from these winding connections.

Eventually, the magnetizing impedances must be entered. The TRELEG allows a magnetization branch in either the first winding or all the windings. If the implicit ordering assumption of the TRELEG program is in conflict with transformer physical windings order, magnetizing impedances for all windings must be included. In the absence of any test data, the positive sequence magnetizing impedance of windings in per unit can be assumed to increase with increasing diameter, while the zero sequence magnetizing impedance decreases. The variation from one winding to another will be approximately equal to the positive sequence short-circuit reactance between them. It is not believed that this approximation of magnetizing impedances has any significant effect on the resulting model. For single-phase transformer, the positive and zero sequence magnetization impedances are equal. An example of using TRELEG for a three-phase three-winding core-type transformer is shown in Figure 3-3-1.

```
C 3-PHASE, 3-LEG, CORE-TYPE TRANSFORMER
C
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER                              33.
C
C Electrical parameters (Class #1)
C N<-<-------Freq<-------SBVA
  3 1        60.        750.
C col: (2-3) N, (4-5) NDelta
C
C Measurement data (class #3)
C I<J<--------TPR<--------TPX<--------TZR<--------TZX
  1 2       .0017        .13       .0057        .115
  1 3       .0042        .35       .0096        .268
  2 3       .0044        .20       .0143        .136
C col: (2-3) I
BLANK card terminates measurement data
C
C Output units (Class #4)
C -
  1
C col: (2-3) KZOut

C Winding data (class #5)
C J < <--------VRj<---------RjNAi-->NBi-->NAi1->NBi1->NAi2->NBi2->
  1 0  288.6751346    0.473000HIGHA       HIGHB       HIGHC
  2 0  138.5640646    0.029875LOWA        LOWB        LOWC
  3 1   28.0000000    0.011280TERTA TERT1ATERTB TERT1BTERT1CTERTA
C col: (2-3) J, (5) INDD
BLANK card terminates winding data
C
C Magnetizing impedance input specifier (Class #6)
C -
  1
C col: (2-3) NT
C
C Magnetizing impedance data (Class #7)
C -------XPos<------XZero
       100.00      1.00
        99.87      1.13
        99.67      1.33
BLANK card terminates magnetizing impedance data
BLANK card terminates TRELEG data
BLANK card terminates EMTP solution-mode
```

(a) TRELEG input data.

```
**********   80-COLUMN CARD-IMAGE LISTING OF UNIT-7 PUNCHED CARDS   *********
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
         0         0         0         0         0         0         0         0
--------------------------------------------------------------------------------
51,HIGHA ,      ,,,              0.473000000000E+00,  0.223333333341E+05 ,,,,,
52,LOWA  ,      ,,,             -0.646793103332E-01,  0.107059927425E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
53,TERTA ,TERT1A,,,             -0.362556943699E-01,  0.215874652794E+04 $
                                -0.357184214476E-01,  0.103714560936E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
54,HIGHB ,      ,,,              0.000000000000E+00, -0.110000000004E+05 $
                                -0.733191019968E-01, -0.527320725720E+04 $
                                -0.494356580077E-01, -0.106342221589E+04 ,,,,,
                                 0.473000000000E+00,  0.223333333341E+05 ,,,,,
55,LOWB  ,      ,,,             -0.733191019968E-01, -0.527320725720E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                                -0.646793103332E-01,  0.107059927425E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
56,TERTB ,TERT1B,,,             -0.494356580077E-01, -0.106342221589E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                -0.362556943699E-01,  0.215874652794E+04 $
                                -0.357184214476E-01,  0.103714560936E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
57,HIGHC ,      ,,,              0.000000000000E+00, -0.110000000004E+05 $
                                -0.733191019968E-01, -0.527320725720E+04 $
                                -0.494356580077E-01, -0.106342221589E+04 ,,,,,
                                 0.000000000000E+00, -0.110000000004E+05 $
                                -0.733191019968E-01, -0.527320725720E+04 $
                                -0.494356580077E-01, -0.106342221589E+04 ,,,,,
                                 0.473000000000E+00,  0.223333333341E+05 ,,,,,
58,LOWC  ,      ,,,             -0.733191019968E-01, -0.527320725720E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                                -0.733191019968E-01, -0.527320725720E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 ,,,,,
                                -0.646793103332E-01,  0.107059927425E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
59,TERT1C,TERTA ,,,             -0.494356580077E-01, -0.106342221589E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                -0.494356580077E-01, -0.106342221589E+04 $
                                -0.325054568924E-01, -0.509650587464E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                -0.362556943699E-01,  0.215874652794E+04 $
                                -0.357184214476E-01,  0.103714560936E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
--------------------------------------------------------------------------------
```

(b) TRELEG output.

Figure 3-3-1: Using TRELEG to derive [R] and [L] matrices for a three-phase three-leg core-type transformer. This data is obtained from the EMTP test case DC-36.

Three-leg core transformers have different short-circuit impedances for positive and zero sequence impedances. It is also possible to use TRELEG to calculate the matrices for single-leg core, shell-type or five-leg core transformers. In this case, the values for short-circuit impedance and the magnetizing impedance are equal.

The TRELEG requires zero sequence test data to properly represents three-phase core-type transformers. It builds the impedance matrices of N-winding single-phase and three-phase transformers directly from the short-circuit and excitation data. It assumes that the excitation current is always be non-zero. Even with a very small excitation current, the impedance matrices can become singular. Modern transformers having less than one percent excitation currents are common. In order to avoid the ill-condition problem, the value for excitation current are usually increased for analysis. It is believed that the increase in excitation current does not have much influence in the result. Since these ill-conditioning problems do not exists in $[L]^{-1}$, the auxiliary program BCTRAN discussed in the next section should make these adjustments unnecessary.

3.4 Using BCTRAN

The auxiliary program BCTRAN is designed for three-phase core-type transformers and three-phase transformers consist of single-phase banks. The BCTRAN program can produce $[R]$ and $[L]^{-1}$ matrices as well as $[R]$ and $[L]$ matrices. Because the later formulation may encounter ill-conditioning problems, the use of $[L]^{-1}$ is preferred. The impedance matrices produced by BCTRAN and XFORMER differ mainly in the existence of non-zero off-diagonal resistance values which should make BCTRAN more accurate than XFORMER at very low frequencies.

Access to the BCTRAN program is similar to that for the TRELEG program. In the special request line, enter the keyword XFORMER and a value 44. in column 38 to 40. Then enter the transformer's excitation data in the line follows. The excitation data line expects both miscellaneous data as well as the positive and zero sequence excitation tests data. The miscellaneous data are the number of windings per core leg, the rated frequency for converting reactances into inductances, the core formation of three-phase transformer (single unit or three single-phase units), number of windings from which the excitation tests are made, number of winding across which the magnetization branch is to place and the output matrices ($[R]$ and $[L]$ or $[L]^{-1}$). For positive sequence test data, three-phase power ratings (in MVA) on which the positive sequence excitation test are based, the excitation current (in percent) based on the three-phase power rating and rated voltages and the excitation loss (in kilowatts) are needed. Similar data for zero sequence excitation test is required. Notice that the zero sequence excitation test really becomes short-circuit test for closed delta-connected windings. Therefore, open delta connections are expected in zero sequence excitation test. On transformers with closed deltas, any reasonable value can be used because the influence of this value will be overridden by short-circuit test data to closed-deltas.

For a N-winding transformer, there will be N winding data lines. Each data line consists of a winding number, voltage rating (in kilovolt), winding resistance of one phase and six terminal node names. The number of winding must not exceed 10. Line-to-line voltage can be used for delta-connected windings and line-to-ground for wye connections. The winding resistance is used only when the ILOSS field in the short-circuit data is zero.

There will be exactly N(N-1)/2 short-circuit data lines. A number pair is used to identify the two windings where the short-circuit test is made. In each data line, enter the load loss (in kilowatt) in positive sequence test. A flag ILOSS is used to determine whether the winding resistance in the winding data will be used. If ILOSS equals to zero, then the winding resistances specified in the winding data will be used. Otherwise, the winding resistance will be calculated from the load loss. On automatic calculation of winding resistance, the number of windings must be less than or equal to three and the load loss must be non-zero. For positive sequence tests, enter also the three-phase power rating and the input impedance (in percent) based on the three-phase power rating and the rated voltages of both windings involved. Same parameters are required for zero sequence tests. If any of the windings besides the two windings involved in the short-circuit test is short-circuited (e.g. closed deltas), a non-zero value indicating the number of additional short-circuited windings must be specified in the IDELTA field. Note however that the BCTRAN program cannot handle three delta connections. For three-phase transformer banks consist of single-phase units, the single-phase data should be entered as positive sequence data and leave the zero sequence parameters and IDELTA blank. For detail input format, refers to the templates in Appendix A.

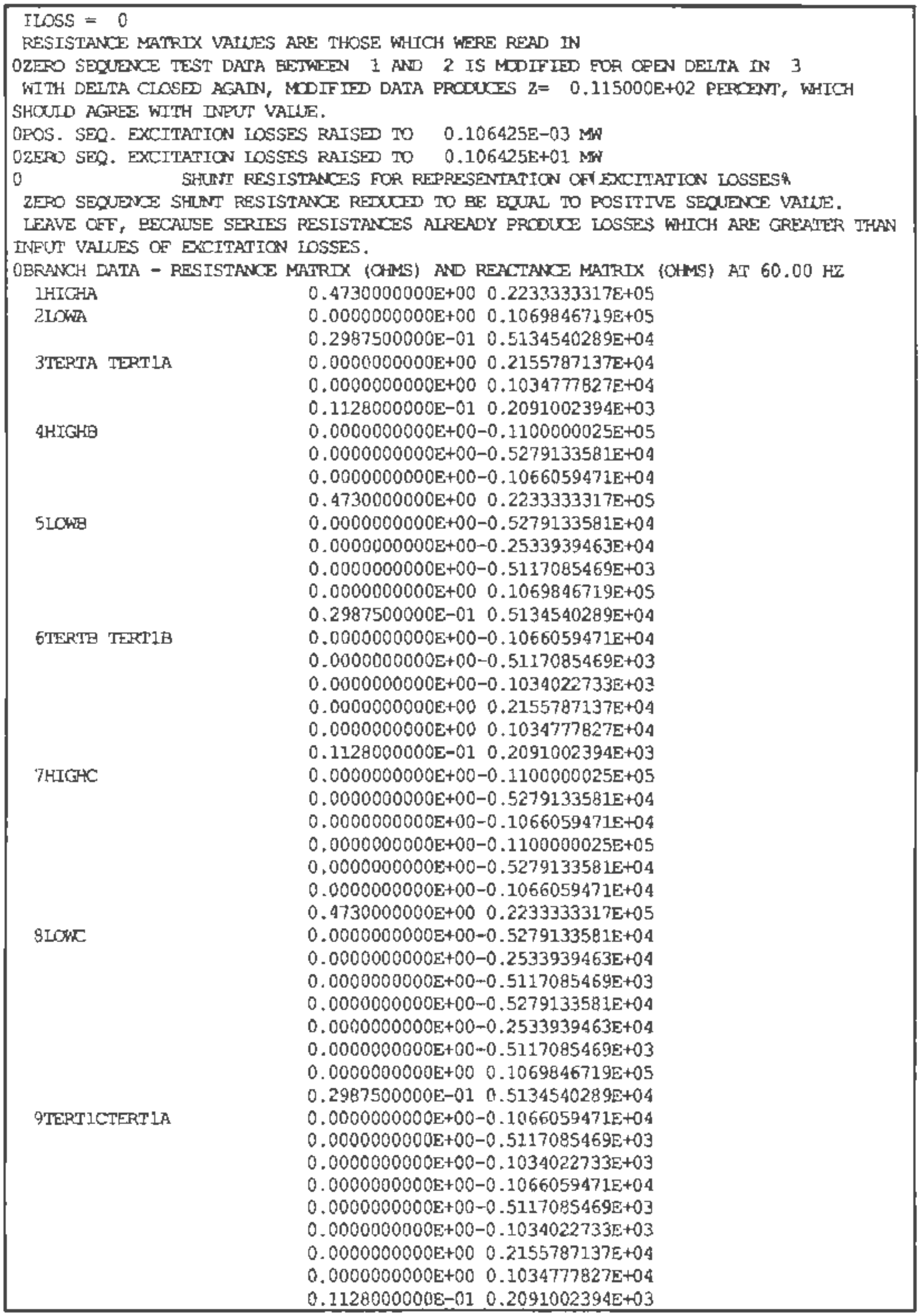
The following example compares the [R] and [L] matrices dervied by the TRELEG and the BCTRAN programs. The data case in Figure 3-3-1(a) is modified in such a way that the the positive sequence load loss is equal to zero (i.e. the short-circuit impendances are pure imaginery). The same data has been converted to BCTRAN format and the [R] and [L] matrices output are requested. Figure 3-4-1(a) illustrates the BCTRAN input. The result of the modified TRELEG and BCTRAN data cases are shown in Figure 3-4-1 (b) and (c) respectively. Notice that the [L] matrix produced by both TRELEG and BCTRAN are the same while the [R] matrix produced by TRELEG has some non-zero diagonal elements. This is the result of using complex number in the TRELEG program. A second example which produces a $[L]^{-1}$ matrix is shown in Figure 3-4-2.

```
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER                              44.
C Excitation data                                                        N     I
C                                                                        P I   P
C              pos       pos        pos      zero      zero       zero   h T I r
C    Freq    I         S        Loss       I         S        Loss      a e P i
C              excit     rating     excit    excit     rating     excit  s s u n
C <---------<---------<---------<---------<---------<---------<---------<e<t<t<t
 3       60.        1.      750.        0.      100.      750.        0. 0 1 3 1
C col: (1-2) N
C
C Winding data                       Winding k
C                         Phase 1     Phase 2     Phase 3
C k<-Vkrating<-------Rk Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
  1288.675135   .473000 HIGHA       HIGHB       HIGHC
  2138.564065   .029875 LOWA        LOWB        LOWC
  3 28.000000   .011280 TERTA TERT1ATERTB TERT1BTERT1CTERT1A
C col: (1-3) k
C
C Short circuit test data                              I
C                                                      D I
C                  pos     pos        zero    zero    e L
C  k    P         Z       S          Z       S        1 o
C       ik        ik      rating     ik      rating  t s
C <-<---------<---------<---------<---------<---------<a<s
 1 2        0.       13.      750.      11.5      750. 3 0
 1 3        0.       35.      750.      26.8      750.
 2 3        0.       20.      750.      13.6      750.
C col: (1-2) i
BLANK card terminates short circuit test data
BLANK card terminates BCTRAN data
BLANK card terminates EMTP solution-mode
```

(a) BCTRAN input data.

```
 **********   80-COLUMN CARD-IMAGE LISTING OF UNIT-7 PUNCHED CARDS    *********
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
         0         0         0         0         0         0         0         0
--------------------------------------------------------------------------------
51,HIGHA ,      ,,,              0.473000000000E+00,  0.223333333341E+05 ,,,,,
52,LOWA  ,      ,,,              0.149423253099E+00,  0.106905999938E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
53,TERTA ,TERT1A,,,              0.787417006561E-01,  0.215874627165E+04 $
                                 0.298263187673E-01,  0.103714540539E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
54,HIGHB ,      ,,,              0.000000000000E+00, -0.110000000004E+05 $
                                 0.478346143970E-02, -0.528860000605E+04 $
                                -0.234146778592E-02, -0.106342247072E+04 ,,,,,
                                 0.473000000000E+00,  0.223333333341E+05 ,,,,,
55,LOWB  ,      ,,,              0.478346143970E-02, -0.528860000605E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 ,,,,,
                                 0.149423253099E+00,  0.106905999938E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
56,TERTB ,TERT1B,,,             -0.234146778592E-02, -0.106342247072E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                 0.787417006561E-01,  0.215874627165E+04 $
                                 0.298263187673E-01,  0.103714540539E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
57,HIGHC ,      ,,,              0.000000000000E+00, -0.110000000004E+05 $
                                 0.478346143970E-02, -0.528860000605E+04 $
                                -0.234146778592E-02, -0.106342247072E+04 ,,,,,
                                 0.000000000000E+00, -0.110000000004E+05 $
                                 0.478346143970E-02, -0.528860000605E+04 $
                                -0.234146778592E-02, -0.106342247072E+04 ,,,,,
                                 0.473000000000E+00,  0.223333333341E+05 ,,,,,
58,LOWC  ,      ,,,              0.478346143970E-02, -0.528860000605E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 ,,,,,
                                 0.478346143970E-02, -0.528860000605E+04 $
                                 0.000000000000E+00, -0.252774399980E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 ,,,,,
                                 0.149423253099E+00,  0.106905999938E+05 $
                                 0.298750000000E-01,  0.514227199959E+04 ,,,,,
59,TERT1C,TERTA ,,,             -0.234146778592E-02, -0.106342247072E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                -0.234146778592E-02, -0.106342247072E+04 $
                                -0.110290218849E-02, -0.509650790505E+03 $
                                 0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                 0.787417006561E-01,  0.215874627165E+04 $
                                 0.298263187673E-01,  0.103714540539E+04 $
                                 0.112800000000E-01,  0.209767040000E+03 ,,,,,
--------------------------------------------------------------------------------
```

(b) TRELEG output.



```
 ILOSS =  0
 RESISTANCE MATRIX VALUES ARE THOSE WHICH WERE READ IN
0ZERO SEQUENCE TEST DATA BETWEEN  1 AND  2 IS MODIFIED FOR OPEN DELTA IN  3
 WITH DELTA CLOSED AGAIN, MODIFIED DATA PRODUCES Z=  0.115000E+02 PERCENT, WHICH
SHOULD AGREE WITH INPUT VALUE.
0POS. SEQ. EXCITATION LOSSES RAISED TO   0.106425E-03 MW
0ZERO SEQ. EXCITATION LOSSES RAISED TO   0.106425E+01 MW
0               SHUNT RESISTANCES FOR REPRESENTATION OF EXCITATION LOSSES%
 ZERO SEQUENCE SHUNT RESISTANCE REDUCED TO BE EQUAL TO POSITIVE SEQUENCE VALUE.
 LEAVE OFF, BECAUSE SERIES RESISTANCES ALREADY PRODUCE LOSSES WHICH ARE GREATER THAN
INPUT VALUES OF EXCITATION LOSSES.
0BRANCH DATA - RESISTANCE MATRIX (OHMS) AND REACTANCE MATRIX (OHMS) AT 60.00 HZ
  1HIGHA                     0.4730000000E+00 0.2233333317E+05
  2LOWA                      0.0000000000E+00 0.1069846719E+05
                             0.2987500000E-01 0.5134540289E+04
  3TERTA TERT1A              0.0000000000E+00 0.2155787137E+04
                             0.0000000000E+00 0.1034777827E+04
                             0.1128000000E-01 0.2091002394E+03
  4HIGHB                     0.0000000000E+00-0.1100000025E+05
                             0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.1066059471E+04
                             0.4730000000E+00 0.2233333317E+05
  5LOWB                      0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.2533939463E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00 0.1069846719E+05
                             0.2987500000E-01 0.5134540289E+04
  6TERTB TERT1B              0.0000000000E+00-0.1066059471E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00-0.1034022733E+03
                             0.0000000000E+00 0.2155787137E+04
                             0.0000000000E+00 0.1034777827E+04
                             0.1128000000E-01 0.2091002394E+03
  7HIGHC                     0.0000000000E+00-0.1100000025E+05
                             0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.1066059471E+04
                             0.0000000000E+00-0.1100000025E+05
                             0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.1066059471E+04
                             0.4730000000E+00 0.2233333317E+05
  8LOWC                      0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.2533939463E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00-0.5279133581E+04
                             0.0000000000E+00-0.2533939463E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00 0.1069846719E+05
                             0.2987500000E-01 0.5134540289E+04
  9TERT1CTERT1A              0.0000000000E+00-0.1066059471E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00-0.1034022733E+03
                             0.0000000000E+00-0.1066059471E+04
                             0.0000000000E+00-0.5117085469E+03
                             0.0000000000E+00-0.1034022733E+03
                             0.0000000000E+00 0.2155787137E+04
                             0.0000000000E+00 0.1034777827E+04
                             0.1128000000E-01 0.2091002394E+03
```

(c) BCTRAN output.

Figure 3-4-1: Comparing the [R] and [L] matrices produced by the TRELEG and BCTRAN programs.

```
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER                              44.
C Excitation data                                                        N     I
C                                                                        P I   P
C              pos       pos        pos       zero      zero       zero  h T I r
C     Freq    I         S        Loss        I         S        Loss     a e P i
C              excit     rating     excit     excit     rating     excit s s u n
C <---------<---------<---------<---------<---------<---------<---------<e<t<t<t
 3       60.      .428      300.    135.73      .428      300.    135.73 0 1 3 0
C col: (1-2) N
C
C Winding data                       Winding k
C                         Phase 1     Phase 2     Phase 3
C k<-Vkrating<-------Rk Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
  1132.790560  .2054666 H-1         H-2         H-3
  2 63.393059  .0742333 L-1         L-2         L-3
  3 50.000000  .0822000 T-1   T-2   T-2               T-1
C col: (1-3) k
C
C Short circuit test data                              I
C                                                      D I
C                  pos     pos        zero     zero    e L
C  k    P         Z       S          Z        S        l o
C        ik        ik      rating     ik       rating  t s
C <-<---------<---------<---------<---------<---------<a<s
 1 2        0.      8.74      300. 7.3431941      300. 3 1
 1 3        0.      8.68       76.26.2581830      300.
 2 3        0.      5.31       76.18.5528240      300.
C col: (1-2) i
BLANK card terminates short circuit test data
BLANK card terminates BCTRAN data
BLANK card terminates EMTP solution-mode
```

(a) BCTRAN input data.

```
 ILOSS =  0
 RESISTANCE MATRIX VALUES ARE THOSE WHICH WERE READ IN
0ZERO SEQUENCE TEST DATA BETWEEN  1 AND  2 IS MODIFIED FOR OPEN DELTA IN  3
 WITH DELTA CLOSED AGAIN, MODIFIED DATA PRODUCES Z=  0.734319E+01 PERCENT, WHICH
 SHOULD AGREE WITH INPUT VALUE.
0                SHUNT RESISTANCES FOR REPRESENTATION OF EXCITATION LOSSES%
 ZERO SEQUENCE SHUNT RESISTANCE REDUCED TO BE EQUAL TO POSITIVE SEQUENCE VALUE.
 PLACE SHUNT RESISTANCE MATRIX ACROSS WINDING  3 WITH R(SELF/OHM)=   0.550983E+05
 AND R(MUTUAL/OHM)=   0.000000E+00
0BRANCH DATA - RESISTANCE MATRIX (OHMS) AND INVERSE INDUCTANCE MATRIX (1/HENRIES)
  1H-1                      0.2054666000E+00 0.2651269237E+02
  2L-1                      0.0000000000E+00-0.5957848438E+02
                            0.7423330000E-01 0.1808547434E+03
  3T-1   T-2                0.0000000000E+00 0.5124542161E+01
                            0.0000000000E+00-0.7106950227E+02
                            0.8220000000E-01 0.7656071131E+02
  4H-2                      0.0000000000E+00 0.1317410104E+01
                            0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00-0.2174181664E+01
                            0.2054666000E+00 0.2651269237E+02
  5L-2                      0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00 0.1002467097E+00
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00-0.5957848438E+02
                            0.7423330000E-01 0.1808547434E+03
  6T-2                      0.0000000000E+00-0.2174181664E+01
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00 0.2417436248E+01
                            0.0000000000E+00 0.5124542161E+01
                            0.0000000000E+00-0.7106950227E+02
                            0.8220000000E-01 0.7656071131E+02
  7H-3                      0.0000000000E+00 0.1317410104E+01
                            0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00-0.2174181664E+01
                            0.0000000000E+00 0.1317410104E+01
                            0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00-0.2174181664E+01
                            0.2054666000E+00 0.2651269237E+02
  8L-3                      0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00 0.1002467097E+00
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00-0.1044760157E+01
                            0.0000000000E+00 0.1002467097E+00
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00-0.5957848438E+02
                            0.7423330000E-01 0.1808547434E+03
  9      T-1                0.0000000000E+00-0.2174181664E+01
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00 0.2417436248E+01
                            0.0000000000E+00-0.2174181664E+01
                            0.0000000000E+00 0.2647586814E+01
                            0.0000000000E+00 0.2417436248E+01
                            0.0000000000E+00 0.5124542161E+01
                            0.0000000000E+00-0.7106950227E+02
                            0.8220000000E-01 0.7656071131E+02
```

(b) BCTRAN output.

Figure 3-4-2: Using BCTRAN for three-phase transformer. This is an EMTP test case, DCNEW-8.

3.5 Using CONVERT

The EMTP has two magnetic saturation programs. The first saturation program CONVERT is described in this section. The CONVERT program is designed to convert RMS voltage-current saturation curves or current verses incremental inductance curves into peak flux-current curves with the hysteresis loop begin ignored. Typical transformer test data consists of RMS voltage and current readings. However, the saturation curves used in the saturable transformer and pseudo-nonlinear reactance branch requires a flux-current saturation curve to be specified.

The program CONVERT works under the following assumptions. It assumes that the voltage-current is inputted as a sequence of points with intermediate values obtained from linear interpolation. Sinusoidal excitation is approximated by finite differencing at one degree step size. And, hysteresis is ignored. The output is also a piecewise linear curve with the same number of points as the input.

The CONVERT program can be requested by a keyword SATURATION at the beginning of a new data case. Following the special request data line is a miscellaneous data line. For the conversion of RMS voltage current curves, enter into this line the frequency of sinusoidal excitation (e.g. 60 Hz), the base voltage (in kilovolt) and base power (in MVA) on which the input RMS voltage-current curve is based. The output data may cover either first quadrant, as requested by saturable transformer and type 98 branch, or both first and third quadrants. The data points on the RMS voltage-current curve are entered in per unit on the previously specified base. The data is specified in monotonically increasing order. Beginning with first data point nearest to the origin and the origin excluded. Terminate the last data line with a value 9999. in the current field. Figure 3-5-1 illustrates the input and output for CONVERT using RMS voltage-current data.

```
BEGIN NEW DATA CASE
SATURATION
C --Freq<--VBase<--PBase<-IPunch<-KThird
     60. 132.791  66.667       0        0
C ------Irms(pu)<-------Vrms(pu)
            .005           0.90
            .008           1.00
            .015           1.10
            .050           1.20
            .150           1.25
           9999.
BLANK card terminates CONVERT data
BLANK card terminates EMTP solution-mode
```

(a) CONVERT input data.

```
DERIVED SATURATION CURVE GIVING PEAK CURRENT VS. FLUX
     ROW                  CURRENT (AMP)                FLUX (VOLT-SEC)
       1                   0.0000000000                  0.0000000000
       2                   3.5499911727                448.3271397706
       3                   7.9501058958                498.1412664117
       4                  15.9271288023                547.9553930529
       5                  61.4854155098                597.7695196941
       6                 219.1499933591                622.6765830147
                                   9999

CHECK OF DERIVED CURVE BY INDEPENDENT REVERSE COMPUTATION.  ASSUMING SINUSOIDAL
VOLTAGE (FLUX) AT LEVEL OF EACH POINT, RMS CURRENT IS FOUND NUMERICALLY.  THIS
CURVE SHOULD BE EQUAL TO THE ORIGINAL I-V POINTS INPUTTED.
 ROW     CURRENT IN P.U.     VOLTAGE IN P.U.
   2          0.00500000          0.90000000
   3          0.00800000          1.00000000
   4          0.01500000          1.10000000
   5          0.05000000          1.20000000
   6          0.15000000          1.25000000
```

(b) CONVERT output.

Figure 3-5-1: Converting RMS voltage-current saturation curve to flux-current curve using CONVERT

The CONVERT program.can also convert current verses incremental inductance curve into flux-current saturation curve using Trapezoidal integration. To perform this conversion, enter the keyword SATURATION in the beginning of a new data case. Then, enter -1.0 in the frequency field of the miscellaneous data line that follows. In the same line enter the current scaling factor in the VBASE field and inductance scaling factor into the PBASE field. Enter also the request for the first or first and third quadrant output. In the following data lines, enter the current and incremental inductance pairs. The current must start with a value zero and increase monotonically. The incremental inductance must all be positive. The data points are terminated by a value 9999. in the current field. An example of converting current verses incremental inductance to flux-current curve is shown in Figure 3-5-2.

```
BEGIN NEW DATA CASE
SATURATION
C --Freq<--VBase<--PBase<-IPunch<-KThird
    -1.     10.    .001       0       0
C -----------ik<------------Lk
            0.             5.0
            2.             5.0
            3.             3.5
            4.             2.0
            5.             1.0
           10.             1.0
         9999.
BLANK card terminates CONVERT data
BLANK card terminates EMTP solution-mode
```

(a) CONVERT data case.

```
 DERIVED SATURATION CURVE GIVING PEAK CURRENT VS. FLUX
 ROW                  CURRENT (AMP)                FLUX (VOLT-SEC)
---------------------------------------------------------------------------
REMEMBER.   THE JUST-COMPLETED CONVERSION BEGAN WITH A CURRENT VS. INCREMENTAL
INDUCTANCE CHARACTERISTIC, DUE TO MISCELLANEOUS DATA PARAMETER
'FREQ'  OF COLUMNS 1-8 BEING PUNCHED WITH A VALUE OF -1.0   .
TRAPEZOIDAL RULE INTEGRATION OF THE INDUCTANCE CURVE WAS USED, TO PRODUCE FLUX.
---------------------------------------------------------------------------
 1                  0.0000000000               0.0000000000
 2                 20.0000000000               0.1000000000
 3                 30.0000000000               0.1425000000
 4                 40.0000000000               0.1700000000
 5                 50.0000000000               0.1850000000
 6                100.0000000000               0.2350000000
                        9999
```

(b) CONVERT output.

Figure 3-5-2: Using CONVERT to convert current verses incremental inductance curve to flux-current curve.

The CONVERT program supports up to a hundred data points. Templates for CONVERT program is available in Appendix A.

3.6 Using HYSDAT

The auxiliary program HYSDAT is designed to provide the data needed to represent hysteresis in transformer core. The flux-current curve generated by HYSDAT can be used in the pseudo-nonlinear hysteretic reactor in a transformer using the matrix models. The data required to represent the major hysteresis loop characteristics is often not available from the manufacturers. HYSDAT is an attempt to catalogue the hysteresis characteristics for some common transformer core materials. In Version 1.0 of the EMTP, only 1 ARMCO M4 oriented silicon steel is supported. Additions of other core materials is expected in future versions.

To request HYSDAT, the keyword SATURATION must be specified followed by a value 88. in the frequency field of the miscellaneous data line immediately follows. The desired number of data points in the output flux-current curve can be controlled. It is recommended that 15 to 25 data points be used in this curve. The data can also be written to a "punch" file with the correct format for the type 96 branch.

The HYSDAT program actually stores the shape of the hysteresis loop for the material specified. The shape of the hysteresis loop depends primarily on the material of the core. Scaling of the hysteresis loop depends on the geometry, the number of turns, and other factor of the actual construction of the reactor. Therefore, it is necessary to provide information for the reactor being specified to allow correct scaling to be performed.

The data used by HYSDAT in scaling is the positive saturation point of the actual reactor. This is a point in the first quadrant of the flux-current plane where the hysteresis loop changes from being multi-valued to single-valued.

Since the hysteresis loop curves are less readily available, the saturation point can be determined from the ordinary magnetization curve of the transformer. This magnetization curve may have been previously determined by a prior execution of the CONVERT program as described in section 3.5. Figure 3-6-1 illustrates a method for the determination of the saturation point to be used in HYSDAT.

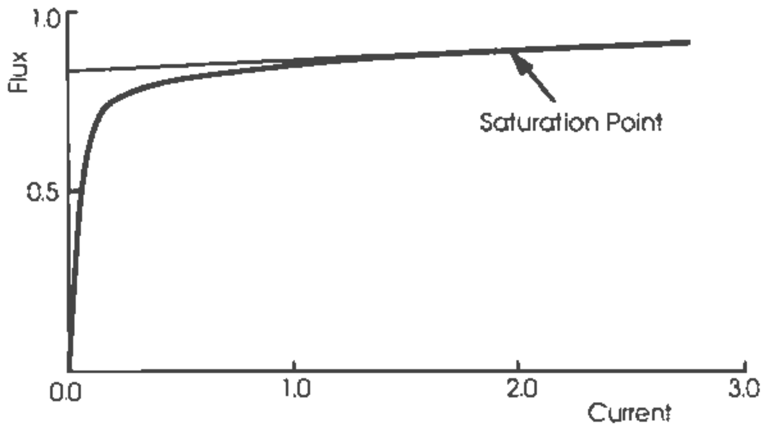


Figure 3-6-1: The determination of the saturation point from a magnetization curve.

Contrary to statements in the Rule Book, the required point appears to be the extreme point of the major hysteresis cycle. Therefore, a point well into the saturation curve seems to be required, a point at which the behavior of the magnetic material becomes once again linear. The reader should be cautioned when determining the saturation point, since any error in calculating the current coordinate of the saturation point will be translated to a corresponding error in the width of the hysteresis loop. This error can be very drastic near zero flux, but it is quite possible that the error near the saturation point is relatively small. Templates for HYSDAT input id available in Appendix A. An example of using HYSDAT is shown in Figure 3-6-2.

```
BEGIN NEW DATA CASE
SATURATION
C --Freq
    88.
C -Itype<--Level<-Ipunch
       1       3       0
C -Cusat<-FlxSat
    2.0     0.9
BLANK card terminates hysteresis curve requests
BLANK card terminates HYSDAT data
BLANK card terminate EMTP solution-mode
```

(a) HYSDAT input data.

```
                        DERIVED TYPE-96 CHARACTERISTIC FOLLOWS:
                                 CURRENT              FLUX
                         -0.7500000E+00  -0.8788235E+00
                         -0.3750000E+00  -0.8682353E+00
                         -0.1250000E+00  -0.8417647E+00
                         -0.2500000E-01  -0.8152941E+00
                          0.4375000E-01  -0.7517647E+00
                          0.8250000E-01  -0.6352941E+00
                          0.1500000E+00   0.4552941E+00
                          0.2375000E+00   0.6511765E+00
                          0.3375000E+00   0.7305882E+00
                          0.5000000E+00   0.7941176E+00
                          0.7375000E+00   0.8364706E+00
                          0.1150000E+01   0.8682353E+00
                          0.2000000E+01   0.9000000E+00
                          0.2750000E+01   0.9052941E+00
                          0.9999000E+04
```

(b) HYSDAT output.

Figure 3-6-2: Using HYSDAT to generate hysteresis curve for type 96 branch.

SECTION 4

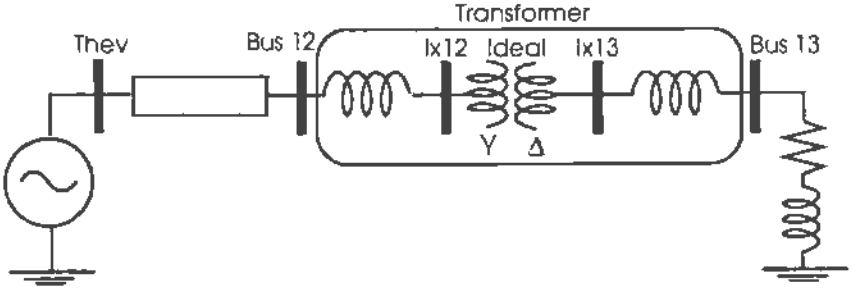
USING TRANSFORMER MODELS

In this chapter we illustrate a few examples of using the transformer models described in the previous chapter. We will illustrate the use of the ideal transformer model using a steady state example involving a Y-Delta connected transformer. We will then compare the TRELEG and the BCTRAN models. We will show how the nonlinear branch of a transformer can lead to ferroresonance. Finally, we will illustrate an inrush current calculation.

4.1 Ideal Single Phase Transformer Example

In this example we consider the transformer connecting buses 12 and 13. The transformer is represented as an ideal transformer with series leakage impedances. The transformer total leakage impedance is assumed divided equally between primary and secondary on a per unit basis. The leakage impedances are represented as part of the system impedances, as lumped inductances. The system is represented using Thevenin equivalents described in Workbook I. The load is represented as an RL impedance, also discussed in Workbook I. The objective is to look at the "internal" transformer voltages in both the primary and secondary of the "ideal" transformer. The internal nodes are designated as "IX12" and "IX13". We perform only steady state phasor analysis. We first consider the "normal" system and look at the primary and secondary voltages in the ideal transformer. We then apply a solid three phase short circuit at the secondary bus.

For mostly historical reasons, the ideal transformer model in the EMTP exists in combination with the model for an ideal voltage source between two branches. In fact, the specification of these sources is somewhat unusual. Notice that two data lines are used. The first data line specifies an ordinary source (you must have a dummy or actual source, even though no source may be intended - see below). This line also specifies one of the four terminals to which the ideal transformer is connected. The second data line specifies the ideal transformer, as well as the other three terminals of the connection. Since the primary side of the ideal transformer is grounded, one of the names in this card is blank, denoting ground. The other two nodes are named to indicate delta connection of the ideal transformer. In this example we have connected the leakage reactances as external impedances. The reactance for the Delta side has been located at the machine terminals rather than within the Delta. Is this correct? It is to the positive sequence (balanced operation), but is not correct to the zero sequence (unbalanced operation). Figure 4-1-1 illustrates our complete example of an ideal transformer test.



(a) Circuit diagram.

```
C Three phase short circuit at the delta connected secondary of an ideal
C transformer connecting buses 12 and 13.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
             -1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
                               3
C
C ............................ Circuit data  ...................................
C Bus-->Bus-->            <----R<----------L
51THEVA BUS12A            8.5288   135.95600                                   0
52THEVB BUS12B            2.6073    93.50861                                   0
53THEVC BUS12C                                                                 0
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS12AIX12A                    35.08                                         1
  BUS12BIX12B BUS12AIX12A                                                      1
  BUS12CIX12C BUS12AIX12A                                                      1
  IX13A BUS13ABUS12AIX12A                                                      1
  IX13B BUS13BBUS12AIX12A                                                      1
  IX13C BUS13CBUS12AIX12A                                                      1
  BUS13A                  22.61519.717                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
BLANK card terminates circuit data
C
C ............................ Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS13A          -1.E-3     9999.                                             0
  BUS13B          -1.E-3     9999.                                             0
  BUS13C          -1.E-3     9999.                                             0
BLANK card terminates switch data
C
C ............................ Source data  .....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14THEVA       187.79       60.        0.        0.                 -1.     9999.
14THEVB       187.79       60.     -120.        0.                 -1.     9999.
14THEVC       187.79       60.      120.        0.                 -1.     9999.
C
C Ungrounded voltage sources and ideal transformers
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
C Bus1->  <----RatioBusk->Busm->Busx->
14IX12A         .001       60.        0.        0.               9999.     9999.
18        3.33333333IX13A IX13B IXA
14IX12B         .001       60.     -120.        0.               9999.     9999.
18        3.33333333IX13B IX13C IXB
14IX12C         .001       60.      120.        0.               9999.     9999.
18        3.33333333IX13C IX13A IXC
BLANK card terminates source data
C
C ............................. Output requests  ...............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  IX12A IX12B IX12C IX13A IX13B IX13C IXA   IXB   IXC
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(b) Input data for ideal transformer. Notice that TSTART for the voltage sources in series with the ideal transformer was made 9999. and that the voltage magnitude was made 0.001 (although any other nonzero value would have given the same results).

```
BUS K                                 NODE VOLTAGE                  BRANCH CURRENT        POWER FLOW     POWER LOSS
          BUS M         RECTANGULAR          POLAR       RECTANGULAR          POLAR           P AND Q        P AND Q
BUS12A                0.1742557E+03  0.1742582E+03     0.2044993E-02  0.3837838E+00    -0.3461071E-13 -0.5746272E-17
                      0.9285353E+00         0.3053    -0.3837783E+00       -89.6947     0.3343874E+02  0.9739438E+00
          IX12A       0.1691803E+03  0.1691827E+03    -0.2044993E-02  0.3837838E+00     0.3460497E-13
                      0.9014906E+00         0.3053     0.3837783E+00        90.3053    -0.3246479E+02

BUS12B               -0.8632374E+02  0.1742582E+03    -0.3333843E+00  0.3837838E+00     0.1122644E-12  0.5828671E-15
                     -0.1513742E+03      -119.6947     0.1901181E+00       150.3053     0.3343874E+02  0.9739438E+00
          IX12B      -0.8380945E+02  0.1691827E+03     0.3333843E+00  0.3837838E+00    -0.1116815E-12
                     -0.1469652E+03      -119.6947    -0.1901181E+00       -29.6947    -0.3246479E+02

BUS12C               -0.8793201E+02  0.1742582E+03     0.3313393E+00  0.3837838E+00     0.2137700E-13  0.1162265E-15
                      0.1504456E+03       120.3053     0.1936602E+00        30.3053     0.3343874E+02  0.9739438E+00
          IX12C      -0.8537088E+02  0.1691827E+03    -0.3313393E+00  0.3837838E+00    -0.2126077E-13
                      0.1460637E+03       120.3053    -0.1936602E+00      -149.6947    -0.3246479E+02

IX13A                 0.2545512E+02  0.2930331E+02    -0.1097648E+01  0.2215777E+01    -0.5325601E-15 -0.5325601E-15
                     -0.1451622E+02       -29.6947    -0.1924795E+01      -119.6947     0.3246479E+02  0.3246479E+02
          BUS13A      0.0000000E+00  0.0000000E+00     0.1097648E+01  0.2215777E+01     0.0000000E+00
                      0.0000000E+00         0.0000     0.1924795E+01        60.3053     0.0000000E+00

IX13B                -0.2529898E+02  0.2930331E+02    -0.1118098E+01  0.2215777E+01    -0.1006140E-15 -0.1006140E-15
                     -0.1478667E+02      -149.6947     0.1912988E+01       120.3053     0.3246479E+02  0.3246479E+02
          BUS13B      0.0000000E+00  0.0000000E+00     0.1118098E+01  0.2215777E+01     0.0000000E+00
                      0.0000000E+00         0.0000    -0.1912988E+01       -59.6947     0.0000000E+00

IX13C                -0.1561428E+00  0.2930331E+02     0.2215745E+01  0.2215777E+01     0.3290554E-16  0.3290554E-16
                      0.2930289E+02        90.3053     0.1180677E-01         0.3053     0.3246479E+02  0.3246479E+02
          BUS13C      0.0000000E+00  0.0000000E+00    -0.2215745E+01  0.2215777E+01     0.0000000E+00
                      0.0000000E+00         0.0000    -0.1180677E-01      -179.6947     0.0000000E+00

BEGIN STEADY-STATE PRINTOUT OF EMTP OUTPUT VARIABLES.   NODE VOLTAGE OUTPUT FOLLOWS.
  BUS              PHASOR      ANGLE IN             REAL        IMAGINARY
  NAME          MAGNITUDE       DEGREES             PART             PART
  IX12A    0.16918274E+03      0.305302   0.16918034E+03   0.90149059E+00
  IX12B    0.16918274E+03   -119.694698  -0.83809455E+02  -0.14696522E+03
  IX12C    0.16918274E+03    120.305302  -0.85370882E+02   0.14606372E+03
  IX13A    0.29303310E+02    -29.694698   0.25455122E+02  -0.14516223E+02
  IX13B    0.29303310E+02   -149.694698  -0.25298979E+02  -0.14786671E+02
  IX13C    0.29303310E+02     90.305302  -0.15614275E+00   0.29302894E+02
  IXA      0.38378377E+00    -89.694698   0.20449926E-02  -0.38377832E+00
  IXB      0.38378377E+00    150.305302  -0.33338427E+00   0.19011814E+00
  IXC      0.38378377E+00     30.305302   0.33133928E+00   0.19366018E+00
```

(c) Portion of steady state phasor solution.

Figure 4-1-1: Steady state three phase short circuit voltages and currents at the transformer terminals using EMTP ideal transformer model.

The following are the primary and secondary voltages at the internal bus of the ideal transformer with and without the fault. Notice that the ideal transformer maintains an exact voltage ratio among the two regardless of conditions.

	Primary	Secondary	Ratio
Normal Voltage	0.18153698E+03	0.31443127E+02	$(10/3)\sqrt{3}$
Fault Voltage	0.16918274E+03	0.29303310E+02	$(10/3)\sqrt{3}$

Note: The ideal transformer model does not permit at present the use of a truly zero series voltage source. When a source is defined, the amplitude must be non-zero (contrary to what is stated in the Rule Book) and the frequency must also be positive. To obtain zero voltage across the voltage source, specify a starting time greater than the maximum simulation time.

4.2 Short Circuit Tests using BCTRAN and TRELEG

In this section we compare use the BCTRAN and TRELEG models. We use these models to calculate the fault currents caused by a single line to ground fault. Figure 4-2-1 shows the circuit of interest. In the following example, transformer windings matrices are calculated using BCTRAN and TRELEG. The data for the transformer is obtain from the cases in Section 3. The data have been adjusted to correspond to a transformer meeting the specifications of a 200 MVA 3 phase transformer bank, with a Y-connected primary winding of 230 kV connected to bus 12, a Y-connected secondary winding, not connected, and a 69 kV delta connected tertiary winding connected to bus 13. All test resistances and reactances were adjusted to maintain the same pu values. These adjustments were necessary to permit meaningful comparisons, since the data used in Section 3 was for quite different units. Three windings were retained, although one of the windings was not connected.

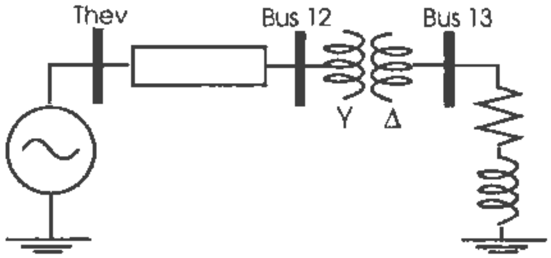


Figure 4-2-1: Circuit diagram for three-phase and SLG fault studies.

```
C BCTRAN - modified DCNEW-8 benchmark case to apply to transformer between buses
C 12 and 13.  Winding 2 is left unconnected.
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER                              44.
C Excitation data                                                        N     I
C                                                                        P I   P
C              pos       pos       pos       zero      zero       zero   h T I r
C     Freq    I         S        Loss       I         S        Loss      a e P i
C              excit     rating    excit     excit     rating     excit  s s u n
C <---------<---------<---------<---------<---------<---------<---------<e<t<t<t
 3       60.        1.      200.        0.      100.      200.        0. 0 1 3-1
C col: (1-2) N
C Winding data                       Winding k
C                         Phase 1     Phase 2     Phase 3
C k<-Vkrating<-------Rk Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
  1132.790562 .37453200 BUS12A      BUS12B      BUS12C
  2132.790562 .10288981 XA          XB          XC
  3 69.000000 .02492167 BUS13ABUS13BBUS13BBUS13CBUS13CBUS13A
C col: (1-3) k
C Short circuit test data                              I
C                                                      D I
C                  pos     pos        zero     zero    e L
C  k    P         Z       S          Z        S        l o
C       ik        ik      rating     ik       rating  t s
C <-<---------<---------<---------<---------<---------<a<s
 1 2        0.      13.      200.      11.5      200. 3 0
 1 3        0.      35.      200.      26.8      200.
 2 3        0.      20.      200.      13.6      200.
C col: (1-2) i
BLANK card terminates short circuit test data
BLANK card terminates BCTRAN data
BLANK card terminates EMTP solution-mode
```

(a) Input data for BCTRAN.

```
C TRELEG - modified DC-36 benchmark case to apply to transformer between
C buses 12 and 13.  Winding 2 is left unconnected.
BEGIN NEW DATA CASE
C XFORMER card-----------------------><-N
XFORMER                              33.
C
C Electrical parameters (class #1)
C N<-<-------Freq<--------SBVA
  3 1         60.        200.
C col: (2-3) N, (4-5) NDelta
C
C Measurement data (class #3)
C I<J<--------TPR<--------TPX<--------TZR<--------TZX
  1 2          0.         .13          0.        .115
  1 3          0.         .35          0.        .268
  2 3          0.         .20          0.        .136
C col: (2-3) I
BLANK card terminates measurement data
C
C Output units (class #4)
C -
  1
C col: (2-3) KZOut
C
C Winding data (class #5)
C J < <--------VRj<---------RjNAi-->NBi-->NAi1->NBi1->NAi2->NBi2->
  1 0 132.7905619    .37453200BUS12A      BUS12B      BUS12C
  2 0 132.7905619    .10288981XA          XB          XC
  3 1  69.0000000    .02492167BUS13ABUS13BBUS13BBUS13CBUS13CBUS13A
C col: (2-3) J, (5) INDD
BLANK card terminates winding data
C
C Magnetizing impedance specifier (class #6)
C -
  1
C col: (2-3) NT
C
C Magnetizing impedance data (class #7)
C -------XPos<------XZero
       100.00        1.00
        99.87        1.13
        99.67        1.33
BLANK card terminates magnetizing impedance data
BLANK card terminates TRELEG data
BLANK card terminates EMTP solution-mode
```

(b) Input data for TRELEG.

Figure 4-2-2: Calculating winding data for transformer connecting buses 12 and 13. The data used in both cases are the scaled down version of the cases in section 3. Notice that only winding #1 and #3 are used in our study.

```
C Single-line-to-ground fault at the wye connected primary of a transformer
C connecting bus 12 and bus 13.  Transformer parameters ([R] and inverse of [L]
C matrices) are obtained from BCTRAN run.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
             -1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
                               3
C
C ............................ Circuit data  ..................................
C Bus-->Bus-->            <----R<----------L
51THEVA BUS12A            8.5288   135.95600                                   1
52THEVB BUS12B            2.6073    93.50861                                   1
53THEVC BUS12C                                                                 1
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS13A                  22.61519.717                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Three phase transformer data from a BCTRAN run.  The field A takes the inverse
C [L] matrix and B takes the [R] matrix.
C Bus1->
  USE AB
$VINTAGE, 1
C Bus1->Bus2->            <--------------A<--------------B
 1BUS12A                   1.147006000E+01 3.745320000E-01
 2XA                      -1.208797000E+01 0.000000000E+00
                           2.098391000E+01 1.028898000E-01

 ...Some data omitted ...

 9BUS13CBUS13A             1.294836000E-01 0.000000000E+00
                          -2.292546000E+00 0.000000000E+00
                           6.549006000E+00 0.000000000E+00
                           1.294836000E-01 0.000000000E+00
                          -2.292546000E+00 0.000000000E+00
                           6.549006000E+00 0.000000000E+00
                           1.189165000E+00 0.000000000E+00
                          -1.712026000E+01 0.000000000E+00
                           3.309857000E+01 2.492167000E-02
$VINTAGE, 0
BLANK card terminates circuit data
C
C ............................ Switch data  ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
  BUS12A          -1.E-3     9999.                                             1
BLANK card terminates switch data
C
C ............................ Source data  ...................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14THEVA       187.79       60.        0.        0.                 -1.     9999.
14THEVB       187.79       60.     -120.        0.                 -1.     9999.
14THEVC       187.79       60.      120.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................. Output requests ...............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS12ABUS12BBUS12CBUS13ABUS13BBUS13C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(a) Using `[R]` and `[L]`$^{-1}$ matrices obtained from `BCTRAN` run. Notice that the use of `[R]` and `[L]`$^{-1}$ matrices is indicated by a "USE AB" data line.

```
C Single-line-to-ground fault at the wye connected primary of a transformer
C connecting bus 12 and bus 13.  Transformer parameters ([R] and [L] matrices)
C are obtained from BCTRAN run.  Notice the [L] matrix is in ohms.
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
             -1.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
                               3
C
C ...........................  Circuit data  ...................................
C Bus-->Bus-->            <----R<----------L
51THEVA BUS12A            8.5288    51.25420                                   1
52THEVB BUS12B            2.6073    35.25192                                   1
53THEVC BUS12C                                                                 1
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS13A                  22.6157.4331                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Three phase transformer data from a BCTRAN run.
C Bus1->
  USE RL
$VINTAGE, 1
C Bus1->Bus2->            <--------------R<--------------L
 1BUS12A                   3.745320000E-01 1.772150000E+04
 2XA                       0.000000000E+00 1.768590000E+04
                           1.028898000E-01 1.768341000E+04

 ... Some data omitted ...

 9BUS13CBUS13A             0.000000000E+00-4.531705000E+03
                           0.000000000E+00-4.531705000E+03
                           0.000000000E+00-2.354743000E+03
                           0.000000000E+00-4.531705000E+03
                           0.000000000E+00-4.531705000E+03
                           0.000000000E+00-2.354743000E+03
                           0.000000000E+00 9.164016000E+03
                           0.000000000E+00 9.164016000E+03
                           2.492167000E-02 4.761762000E+03
$VINTAGE, 0
BLANK card terminates circuit data
C
C ...........................  Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS12A          -1.E-3     9999.                                             1
BLANK card terminates switch data
C
C ...........................  Source data  ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14THEVA       187.79       60.        0.        0.                 -1.     9999.
14THEVB       187.79       60.     -120.        0.                 -1.     9999.
14THEVC       187.79       60.      120.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................  Output requests  ...............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS12ABUS12BBUS12CBUS13ABUS13BBUS13C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(b) Using [R] and [L] matrices obtained from BCTRAN run. Notice that the use of [R] and [L] matrices is indicated by a "USE RL" data line.

```
C Single-line-to-ground fault at the wye connected primary of a transformer
C connecting bus 12 and bus 13.  Transformer parameters ([R] and [L] matrices)
C are obtained from TRELEG run.  Notice the [L] matrix is in ohms.
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
             -1.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
                               3
C
C ...........................  Circuit data  ...................................
C Bus-->Bus-->            <----R<----------L
51THEVA BUS12A            8.5288    51.25420                                   1
52THEVB BUS12B            2.6073    35.25192                                   1
53THEVC BUS12C                                                                 1
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS13A                  22.6157.4331                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Three phase transformer data from a TRELEG run.
$VINTAGE, 1
C Bus1->Bus2->            <-------------R<-------------L<-------------C
51,BUS12A,      ,,,              0.374532000000E+00,  0.177214999964E+05 ,,,,,
52,XA    ,      ,,,              0.246596704012E+00,  0.176983341565E+05 $
                                 0.102889810000E+00,  0.177100383297E+05 ,,,,,

 ... Some data omitted ...

59,BUS13C,BUS13A,,,              0.921971311781E-02, -0.452049497167E+04 $
                                 0.313461520604E-03, -0.451348108632E+04 $
                                 0.000000000000E+00, -0.234098370000E+04 ,,,,,
                                 0.921971311781E-02, -0.452049497167E+04 $
                                 0.313461520604E-03, -0.451348108632E+04 $
                                 0.000000000000E+00, -0.234098370000E+04 ,,,,,
                                 0.130514227386E+00,  0.917659911749E+04 $
                                 0.510259064350E-01,  0.918498745391E+04 $
                                 0.249216700000E-01,  0.477694935000E+04 ,,,,,
$VINTAGE, 0
BLANK card terminates circuit data
C
C ...........................  Switch data  ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
  BUS12A          -1.E-3     9999.                                             1
BLANK card terminates switch data
C
C ...........................  Source data  ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <----Tstart<----Tstop
14THEVA       187.79       60.        0.        0.                 -1.     9999.
14THEVB       187.79       60.    -120.         0.                 -1.     9999.
14THEVC       187.79       60.     120.         0.                 -1.     9999.
BLANK card terminates source data
C
C ............................  Output requests  ...............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS12ABUS12BBUS12CBUS13ABUS13BBUS13C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(c) Using [R] and [L] matrices obtained from TRELEG run.

Figure 4-2-3: Comparing short circuit currents and voltages of a single-line-to-ground fault at the wye-connected primary of a transformer between buses 12 and 13 using BCTRAN and TRELEG models.

Note the USE AB parameter for [R] and [L]$^{-1}$ and USE RL parameter for [R] and [L]. In the case of USE AB the value of [L]$^{-1}$ come first. *This is not reported correctly in the users Rule Book.* The following tables illustrate quantitative comparisons of results. Notice that nearly identical results are obtained from either model.

Table 4-2-1 Steady-state Short Circuit Voltages and Currents for a Three-phase Fault at Delta-connected Secondary of the Transformer*

	BCTRAN		**TRELEG**
	[R] and [L]$^{-1}$	[R] and [L]	[R] and [L]
fault currents			
phase a	0.58693637E+01	0.58657700E+01	0.58685282E+01
phase b	0.81144765E+01	0.81132793E+01	0.81136773E+01
phase c	0.71875231E+01	0.71923559E+01	0.71859728E+01
primary voltages			
BUS12A	0.17085907E+03	0.17072208E+03	0.17087393E+03
BUS12B	0.23552475E+03	0.23563735E+03	0.23551410E+03
BUS12C	0.18778206E+03	0.18776895E+03	0.18776894E+03

Table 4-2-2 Steady-state Short Circuit Voltages and Currents for a Single-line-to-ground Fault at Wye-connected Primary side of the Transformer*

	BCTRAN		**TRELEG**
	[R] and [L]$^{-1}$	[R] and [L]	[R] and [L]
fault current			
phase a	0.60118126E+01	0.60161989E+01	0.60151460E+01
voltage at unfaulted phases			
BUS12B	0.32122477E+03	0.32135446E+03	0.32123789E+03
BUS12C	0.18778535E+03	0.18777782E+03	0.18777770E+03
secondary voltages			
BUS13A	0.28007018E+02	0.27969333E+02	0.28005859E+02
BUS13B	0.47904162E+02	0.47865451E+02	0.47910605E+02
BUS13C	0.58598322E+02	0.58551224E+02	0.58595135E+02

* All values presented in the tables are magnitudes.

4.3 Ferroresonance Studies

Ferroresonance may occur when a nonlinear inductor resonates with a capacitor. The phenomena differs from ordinary resonance conditions in a number of ways. The nonlinearity of the saturation characteristics of the transformer magnetizing impedance is essential. This nonlinearity precludes the definition of a single "inductance value" for the magnetizing inductance, thus, no single well defined resonant frequency can be determined. Ferroresonance, when it occurs, may be self-sustaining. That is, the same circuit that is able to operate without experiencing ferroresonance may, under identical conditions, experience ferroresonance. This can happen when prior conditions in the system (a fault or an energization transient) have pushed the system into a ferroresonant regime, that may maintain itself even after source voltages return to normal or the fault is removed.

Ferroresonance can result in sub-harmonic and aperiodic behavior of the system. Ferroresonance can also result in higher frequency oscillations and significant waveform distortion.

In power systems, condition for ferroresonance sometimes occurs under unexpected circumstances, away from normal operating conditions and often involve unenergized portions of the system. The following are situations that may lead to possible ferroresonance [1]:

- When a transformer is connected to a disconnected high voltage line that runs along (and is therefore capacitively coupled to) a second energized line, particularly when the lines are of different voltage ratings. This situation can lead to subharmonic ferroresonance, possibly at a frequency of around 1/5 of the fundamental frequency.

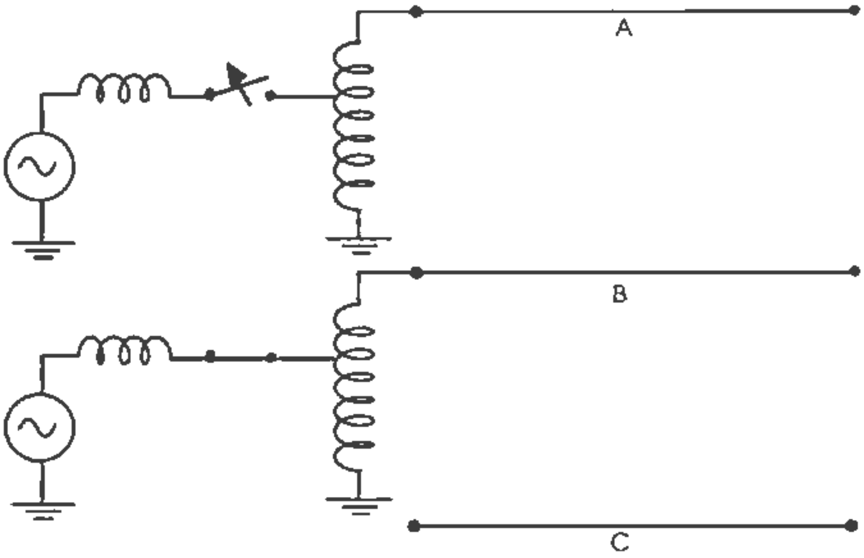
- When an energized ungrounded transformer is connected to a second unloaded transformer with a grounded neutral through a cable or line, a single line to ground fault on the source side of the ungrounded transformer can induce fundamental frequency ferroresonance between the parallel resonant circuit consisting of the unloaded transformer and the cable capacitance. The resonance is precipitated by the rise in voltage in the unfaulted phases of the ungrounded transformer and the series primary to secondary capacitance in the ungrounded transformer. The phenomena may persist even after the fault is removed.

- The capacitance across an open circuit breaker may be sufficient to produce ferroresonance with the winding of a transformer. This phenomena generally will result in subharmonic resonance.

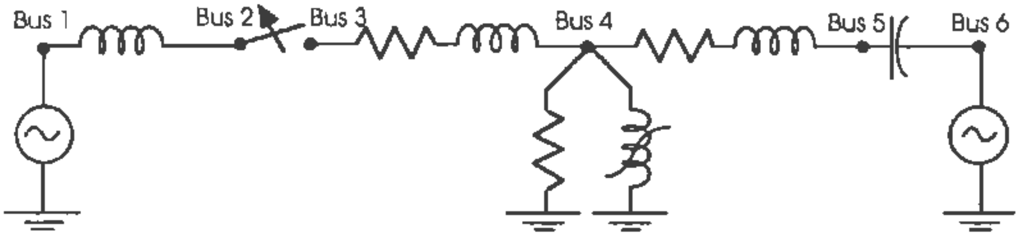
- An ungrounded generator connected to a grounded neutral transformer (generally unloaded) may by itself result in ferroresonance if the zero sequence capacitance of the transformer is sufficiently small to produce a ferroresonance circuit with the transformer leakage reactance. This can result in subharmonics and higher harmonic (wave distortion) resonant conditions. This is the "classic" ferroresonance case studied by many, in which a nonlinear reactor is connected in parallel with a capacitor and the voltage is increased until a ferroresonance condition is detected.

- If a transformer is accidentally energized in only one or two phases, ferroresonance can occur between the capacitance among phases and the transformer.

In the remainder of this subsection we illustrate a specific study that was performed with the EMTP [2] to determine a ferroresonant condition that involved the energization of a single phase of an 1100 kV test line connected to an autotransformer. The study was originally conducted by R. Hasibar of BPA, and the line in question is described in [3]. Figure 4-3-1 illustrates a diagram of the system conditions, including the setup and parameters that were used in the EMTP simulation of the phenomena. We also illustrate the nature of the developing ferroresonant oscillations that develop.



(a) Diagram of the test system.



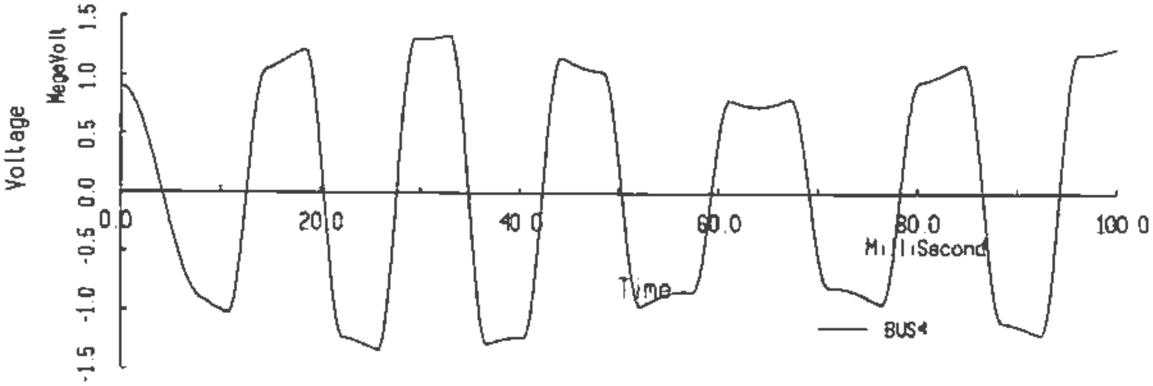
(b) Circuit setup for EMTP study.

```
C CONVERT - data case for ferroresonance study.
BEGIN NEW DATA CASE
SATURATION
C --Freq<--VBase<--PBase<-IPunch<-KThird
     60.   635.1     50.       0       0
C ------Irms(pu)<-------Vrms(pu)
           .0056             0.9
           .0150             1.0
           .0401             1.1
           9999.
BLANK card terminates CONVERT data
BLANK card terminates EMTP solution-mode
```

(c) Convert RMS voltage-current saturation curve to flux-current curve for type 98 non-linear inductor input.

```
C Ferroresonance study
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  50.E-6 100.E-3     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25       1                                               1
C
C ............................ Circuit data ....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   0
  BUS1  BUS2                     152.0                                         0
  BUS3  BUS4                11.3 742.0                                         0
  BUS4  BUS5                11.3 742.0                                         0
C Damping resistors
  BUS3  BUS4               1000.                                               0
  BUS4  BUS5               1000.                                               0
  BUS5  BUS6                          .02616                                   0
  BUS4                    4.49E6                                               0
C Pseudononlinear reactor (type 98 element)
C Bus1->Bus2->Bus3->Bus4-><--iss<Phiss                                         0
98BUS4                        0.    0.
C -------Current<-----------Flux
    0.6234920445 2144.2158464677
    2.7237617069 2382.4620516307
    7.2487228360 2620.7082567938
           9999.
BLANK card terminates circuit data
C
C ............................ Switch data .....................................
C Bus1->Bus2-><---Tclose<----Topen<-------Ie                                   0
  BUS2  BUS3         -1.        0.
BLANK card terminates switch data
C
C ............................ Source data .....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14BUS1     898.146E3       60.        0.                          -1.0     9999.
14BUS6     185.262E3       60.     -120.                          -1.0     9999.
BLANK card terminates source data
C
C ............................ Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS4
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(d) Input data.



(e) Output results.

Figure 4-3-1: A ferroresonant case study using the EMTP.

Notice that damping resistors are placed across the RL branches to remove numerical oscillations.

4.4 Inrush Current Calculations

Since hysteresis is often quite important in inrush current calculations, we will use the EMTP transformer models for the calculation of the inrush current upon energization of a transformer. Three cases will be considered: The energization of a saturable but non-hysteretic transformer, the energization of a hysteretic transformer without any remnant flux, and the energization of a hysteretic transformer with a remnant flux.

The first step in the use of a hysteretic transformer model is to generate the B-H curves for the transformer. The user must specify point by point the lower portion of the current vs. flux curve. If this data is not readily available, the user may resort to the use of the auxiliary program `HYSDAT` as discussed in section 3.6. The curves generated by `HYSDAT` are based entirely on the knowledge of the material used and the knowledge of the nominal saturation point. The output of `HYSDAT` gives the required input for the simulation of hysteresis. Figure 4-4-1 illustrates the flux-current curve expected by the pseudo-nonlinear hysteretic reactance (`type 96`) branch.

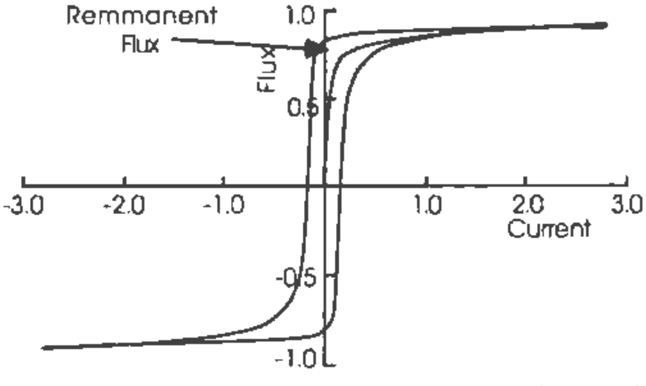
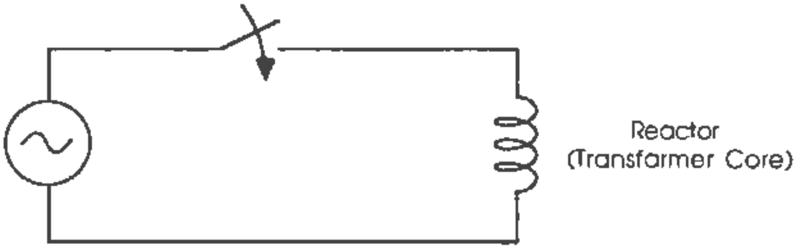


Figure 4-4-1: The computed hysteresis loop superimposed on the given magnetization curve.

Figure 4-4-2(a) shows the circuit diagram for transformer core representation. To simplify the problem, transformer windings are not represented in this example. The transformer core is represented using both the pseudo-nonlinear reactance (`type 98`) branch and pseudo-nonlinear hysteretic reactance (`type 96`) branch. Figure 4-4-2(b) and (c) illustrate the core representation using type 98 and type 96 branches. Figure 4-4-2(d) to (f) shows the currents for non-hysteretic reactance, hysteretic reactance in steady-state and transient condition.



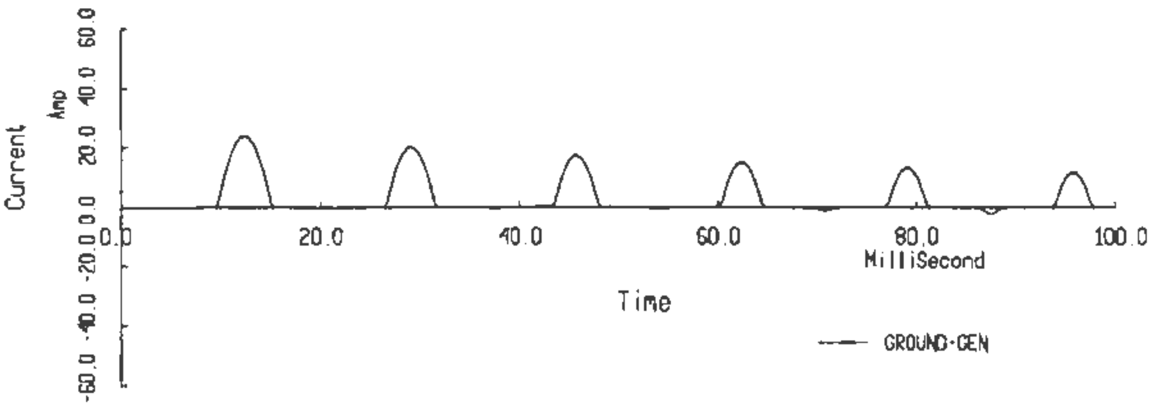
(a) Circuit diagram.

```
C Energization of non-hysteretic transformer represented as pusedononlinear
C reactance (type 98 element).
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  50.E-6 100.E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25       1                                               1
C
C ........................... Circuit data  .................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                    O
  SRC   GEN                    1.                                               0
  SRC                          1.                                               0
  GEN   GROUND             1.0E6                                                0
C Pseudo-nonlinear reactor
C Bus1->Bus2->Bus3->Bus4-><--iss<Phiss                                          O
98GROUNDGEN                    1.0.8682                                         1
C -------Current<----------Flux
             0.1             0.7
             0.3             0.8
             0.8            0.85
             1.5            0.88
            2.75         0.90529
           9999.
BLANK card terminates circuit data
C
C ............................ Switch data  ...................................
C Bus1->Bus2-><---Tclose<----Topen<Ie|NSteps<---Vflash<-Spec ReqBus5->Bus6->   O
  GROUND           1.E-3     9999.                                              1
BLANK card terminates switch data
C
C ........................... Source data  ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14SRC        377.000       60.        0.        0.                 -1.     9999.
BLANK card terminates source data
C
C ........................... Output requests  ................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

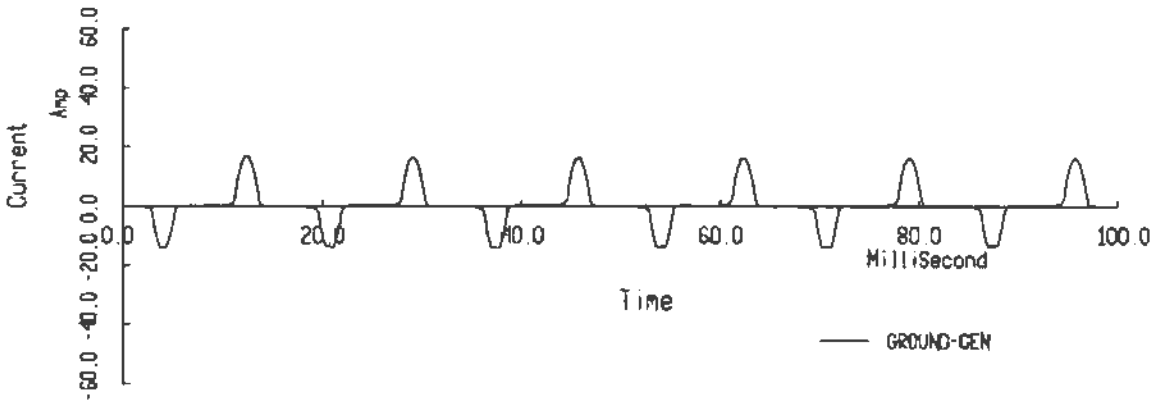
(b) Transformer core represented as non-linear inductance.

```
C Hysteretic transformer in steady state, no rememant flux.  Transformer is
C represented as a peusdononlinear hysteretic reactor (type 96 element).
C Hysteresis curve is obtained from HYSDAT study.
C
BEGIN NEW DATA CASE
C ............................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  50.E-6 100.E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25       1               1                               1
C
C ............................  Circuit data  .................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                    0
  SRC   GEN                   1.                                                0
  SRC                         1.                                                0
  GEN   GROUND             1.0E6                                                0
C
C Pseudo-nonlinear hysteretic reactor
C Bus1->Bus2->Bus3->Bus4-><--iss<Phiss<PhiRe                                    0
96GROUNDGEN                   1.0.8682   .75                                    1
C -------Current<-----------Flux
  -0.7500000E+00  -0.8788235E+00
  -0.3750000E+00  -0.8682353E+00
  -0.1250000E+00  -0.8417647E+00
  -0.2500000E-01  -0.8152941E+00
   0.4375000E-01  -0.7517647E+00
   0.8250000E-01  -0.6352941E+00
   0.1500000E+00   0.4552941E+00
   0.2375000E+00   0.6511765E+00
   0.3375000E+00   0.7305882E+00
   0.5000000E+00   0.7941176E+00
   0.7375000E+00   0.8364706E+00
   0.1150000E+01   0.8682353E+00
   0.2000000E+01   0.9000000E+00
   0.2750000E+01   0.9052941E+00
   0.9999000E+04
BLANK card terminates circuit data
C
C ............................  Switch data  ...................................
C Bus1->Bus2-><---Tclose<----Topen<Ie|NSteps<---Vflash<-Spec ReqBus5->Bus6->   0
  GROUND           1.E-3     9999.                                              1
BLANK card terminates switch data
C
C ............................  Source data  ...................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14SRC           377.       60.        0.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................  Output requests  ...............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

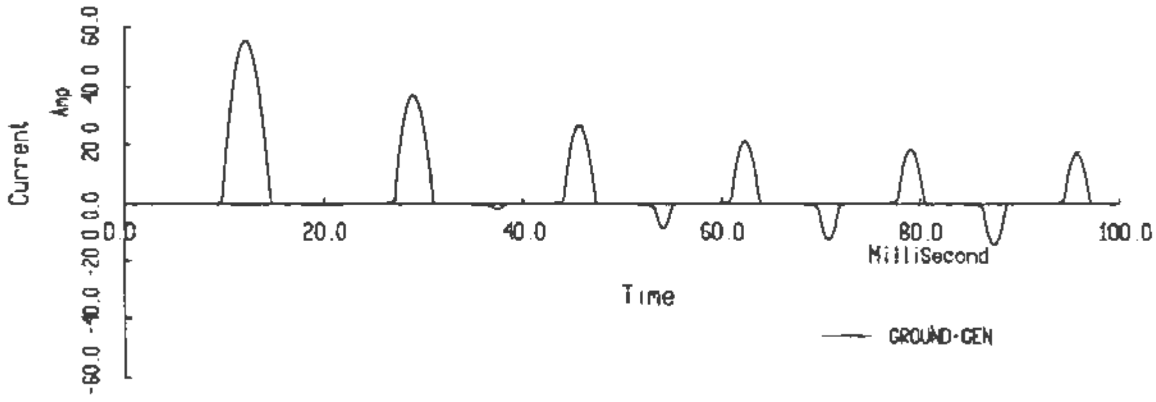
(c) Transformer core represented as hysteretic reactor with remnant flux. Data for type 96 branch is obtained from previous HYSDAT run in section 3.6.



(d) Non-linear inductor (type 98) branch current.



(e) Steady-state current of hysteretic reactor with no remnant flux, i.e. switch closed at t < 0 in case (c).



(f) Inrush current of hysteretic reactor with no remnant flux, i.e PhiRe equals to zero in (c).

Figure 4-4-2: Comparing inrush current during transformer core energization

Note: The remnant flux representation in the type-96 branch does not work in the current version of the EMTP. In fact, it is the opinion of some that the type 96 model should be the subject of further verification, it may lead to conservative estimates of the decay of inrush currents. Exercise your judgement when using these models.

4.5 References

[1] N. Germay, S. Master and J. Vroman, "Review of Ferro-Resonance Phenomena in High-Voltage Power System and Presentation of a Voltage Transformer Model for Predetermining Them," CIGRE paper 33-18, CIGRE Conference August 21-29, 1974, Paris.

[2] H. Dommel, A. Yan, R. J. Ortiz de Marcano, A. B. Miliani, "Case Studies for Electromagnetic Transient Studies," Department of Electrical Engineering, The University of British Columbia, Vancouver, B. C. Canada, V6T 1W5.

[3] S. A. Annestrand and G. A. Parks, ",Bonneville Power Administration's Prototype 1100.1200 kV Transmission Line Project," IEEE Transaction on Power Apparatus and Systems, Vol. 96, pp. 357-366. March/April 1977.

SECTION 5

SYNCHRONOUS MACHINES: ELECTRICAL REPRESENTATION

As in other cases of this workbook series, the main emphasis will be on enabling the user to prepare EMTP data cases using whatever reasonable information a user may have about a machine at any given time, and to enable the user to understand what information to get and how to use it to perform simulations. However, in order to make effective use of the EMTP machine models and to understand some of their limitations, an overview of some of the features of the built-in mathematical models is essential. This chapter gives a brief outline of the "classic" models used by the EMTP to represent a machine. These models make use of certain "internal parameters" such as winding self and mutual inductances. While it is possible to calculate these parameters if exact details of machine materials and construction are available, in practice this information is not generally available but must be obtained based on other more readily available information. The information upon which the internal models must be developed is usually "test" information. Typical tests include sudden short tests.

The EMTP has the ability of accepting either "internal parameter" information or "test data" type information. Either way, the EMTP will develop an internal model based on internal parameters. Thus, if test data is given to the EMTP we must understand what the EMTP does to this test data to construct the internal model in order to understand any possible limitations of this approach. As an alternative, internal data may be provided. The reasons for doing so may be that this data may indeed be available for a machine of interest, or it may be that we have elected to use an independent procedure for the calculation of the internal parameters. This chapter also explains why and how one may use such independent procedures.

5.1 The Equations for the Synchronous Machine

The electrical state variable equations of the synchronous machine as used by the EMTP are stated in Park (or Blondel) transformed variables using the flux linkages λ as state variables. The equations assume a machine with the following windings:

- Three stator windings `a`, `b` and `c`, one for each phase. The voltages and currents in these windings are applied to the system.
- One field winding `f` along the direct axis. The voltage v_f applied to this winding comes as the output of the excitation system. For simple studies this voltage is assumed constant and is either given or determined based on initial conditions for the system. For more complicated studies it may be regulated from TACS.
- One "winding" `D` designating the damper bars on the direct axis of the machine. This is not an actual winding with a well-defined number of turns, but it represents the effects of currents in the damper bars.
- One "winding" `Q` designating the damper bars on the quadrature axis of the machine. This is not an actual winding with a well-defined number of turns, but it represents the effects of currents in the damper bars.

- One "winding" g designating the eddy currents effects on the quadrature axis. This effect is sometimes neglected.

It is sometimes possible to add a third direct axis winding to represent the direct axis eddy current effects.

In simple studies the actual speed of the machine ω (and therefore the position of the rotor β at any time) is assumed known. In more complex studies, this angular speed may vary. *The EMTP machine model always allows for this speed (and hence the frequency) to vary. Therefore you must always be prepared to provide the inertia of the machine rotor, even though you may wish to make this a very large number.*

The equations will be written in terms of flux linkages. Flux linkages are related to currents by inductance matrices.

The initial equation neglect saturation effect. Saturation is considered separately. The equations that regulate the electrical behavior of the machine are easiest to write if the armature currents, voltages and flux linkages are first transformed into new variables. The following is the transformation matrix used:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = [T]^{-1} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = [T]^{-1} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$[T]^{-1} = \begin{bmatrix} \sqrt{\frac{2}{3}}\cos\beta & \sqrt{\frac{2}{3}}\cos(\beta-120^\circ) & \sqrt{\frac{2}{3}}\cos(\beta+120^\circ) \\ \sqrt{\frac{2}{3}}\sin\beta & \sqrt{\frac{2}{3}}\sin(\beta-120^\circ) & \sqrt{\frac{2}{3}}\sin(\beta+120^\circ) \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix}$$

This particular definition of the **Park** transformation matrix has the advantage of being orthogonal, that is:

$$[T] = ([T]^{-1})^t$$

This transformation of variables results in many advantages too numerous to describe here. In terms of these transformed quantities, the state variable equations that describe the behavior of a synchronous machine are given by:

$$\frac{d}{dt}\begin{bmatrix} \lambda_d \\ \lambda_q \\ \lambda_0 \\ \lambda_f \\ \lambda_g \\ \lambda_D \\ \lambda_Q \end{bmatrix} = -\begin{bmatrix} v_d \\ v_q \\ v_0 \\ v_f \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_f & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_g & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_Q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ i_0 \\ i_f \\ i_g \\ i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} -\omega\lambda_q \\ +\omega\lambda_d \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The dq0 flux linkages are related to the dq0 currents according to some time-invariant algebraic equations:

$$\begin{bmatrix} \lambda_d \\ \lambda_f \\ \lambda_D \end{bmatrix} = \begin{bmatrix} L_d & M_{df} & M_{dD} \\ M_{df} & L_{ff} & M_{fD} \\ M_{dD} & M_{fD} & L_{DD} \end{bmatrix} \begin{bmatrix} i_d \\ i_f \\ i_D \end{bmatrix}$$

$$\begin{bmatrix} \lambda_q \\ \lambda_g \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_q & M_{qg} & M_{qQ} \\ M_{qg} & L_{gg} & M_{gQ} \\ M_{qQ} & M_{gQ} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_q \\ i_g \\ i_Q \end{bmatrix}$$

$$\lambda_0 = L_0 \; i_0$$

This model of the synchronous machine requires the knowledge of 13 inductance parameters and 5 resistance parameters.

5.2 Relationship Between Internal Parameters and Test Parameters

The equations for the synchronous machine are often written in either per unit or actual internal machine parameter values, which require the knowledge of all the appropriate machine inductances and resistances. However, the information necessary to develop these models generally comes from machine tests. These tests are well standardized and understood. Since we expect that most users will have available machine test parameters, it is quite important to understand how to use these. The EMTP will perform the conversion internally, but the user must be aware that some small inconsistencies exist between test parameters and internal parameters.

The test parameters available for most machines according to IEEE [1] and IEC [2] standards and Mello-Ribeiro [3] are:

R_a: Armature Resistance
X_l: Armature Leakage Reactance
X_0: Zero Sequence Reactance
X_d', X_q' or L_d', L_q': Transient Reactances
X_d'', X_q'' or L_d'', L_q'': Subtransient Reactances
T_d', T_q': Transient Short Circuit Time Constants
T_d'', T_q'': Subtransient Short Circuit Time Constants

Saturation is considered separately. For this reason, these constants are often obtained from short circuit tests. The unsaturated short circuit time constants are uniquely related to the corresponding open circuit time constants, which are preferred in some computations. It is sometimes useful to obtain the open circuit time constants from the expressions:

$$T_{d0}' + T_{d0}'' = \frac{L_d}{L_d'} T_d' + T_d'' \left(1 - \frac{L_d}{L_d'} + \frac{L_d}{L_d''}\right)$$

$$T_{d0}' \; T_{d0}'' = T_d' \; T_d'' \frac{L_d}{L_d''}$$

$$T_{q0}' + T_{q0}'' = \frac{L_q}{L_q'} T_q' + T_q'' \left(1 - \frac{L_q}{L_q'} + \frac{L_q}{L_q''}\right)$$

$$T_{q0}' \; T_{q0}'' = T_q' \; T_q'' \frac{L_q}{L_q''}$$

From the test parameters, one must calculate the internal parameters that describe the behavior of the machine. For a machine with three armature windings and two windings in each rotor axis, these parameters include:

$$R_a,\ R_f,\ R_g,\ R_D,\ R_Q$$
$$L_d,\ M_{df},\ M_{dD},\ L_{ff},\ M_{fD},\ L_{DD}$$
$$L_q,\ M_{qg},\ M_{qQ},\ L_{gg},\ M_{gQ},\ L_{QQ}$$
$$L_0$$

This leaves us with a total of thirteen distinct inductances and five resistances to determine from the eleven measurements. We are five measurements short. Thus, it is not possible to uniquely determine the machine inductances without additional assumptions and information:

- The magnitude of the field i_f current that will induce nominal voltage on the "air gap line" must be known. This requires the assumption that the machine is unsaturated. This additional item adds an equation:

  $$M_{df} = \frac{v_q^0}{\omega\ i_f^{ag}}$$

  where the voltage v_q^0 is the open circuit nominal voltage and i_f^{ag} is the field current required to induce this voltage.

- The "number of turns" that the damper winding "coils" D and Q have can be assumed arbitrary. Similarly, the number of turns in an eddy current "winding" can also be assumed arbitrary. Neither of these windings is an actual winding and we are seldom interested in the actual quantitative values for these currents. These assumptions lead to three additional equations:

$$M_{dD} = M_{df}\ \ (= M_d) \qquad M_{qQ} = M_{qg}\ \ (= M_q) \qquad M_{qQ} = M_{gQ}\ \ (= M_q)$$

- A final equation can be obtained that relates the mutual inductance between the field winding f and the damper winding D, and the mutual inductance between the winding d and the field winding f:

  $$M_{df} = k\sqrt{\frac{3}{2}}\,M_{fD}$$

  The value of k can be calculated by means of an additional test quantity, which has not yet been prescribed in the IEEE or IEC standards. However, in practice it is advantageous to choose $k=1$. This has the effect of making all the mutual inductances equal, allowing the representation of the machine as a star circuit. Unfortunately, doing this is equivalent to stating that we do not need quantitative values for the field current, which is not always true.

This last assumption will insure that *the amplitude of the rotor field current oscillation will be quantitatively incorrect*. However, the qualitative behavior of this quantity is correct, as well as the effect that this has on the stator currents and voltages. This also allows us to find a relationship between the mutual inductance M_d and the leakage inductance L_l:

$$M_d = L_d - L_l$$

Based on the scaling factor k defined above one can rescale λ_f and i_f:

$$\lambda_{fm} = k\sqrt{\frac{3}{2}}\,\lambda_f \quad \text{and} \quad i_{fm} = \frac{1}{k}\sqrt{\frac{2}{3}}\,i_f$$

This scaling does not affect stator quantities. With all these conventions, the equations for the flux linkage definition become (the subscript m has been dropped for clarity):

$$\begin{bmatrix}\lambda_d\\ \lambda_f\\ \lambda_D\end{bmatrix} = \begin{bmatrix} L_d & M_d & M_d\\ M_d & L_{ff} & M_d\\ M_d & M_d & L_{DD}\end{bmatrix}\begin{bmatrix}i_d\\ i_f\\ i_D\end{bmatrix}$$

$$\begin{bmatrix}\lambda_q\\ \lambda_g\\ \lambda_Q\end{bmatrix} = \begin{bmatrix} L_q & M_q & M_q\\ M_q & L_{gq} & M_q\\ M_q & M_q & L_{QQ}\end{bmatrix}\begin{bmatrix}i_q\\ i_g\\ i_Q\end{bmatrix}$$

$$\lambda_0 = L_0\ i_0$$

We not that now we have the following variables to determine:

$$R_a,\ R_f,\ R_g,\ R_D,\ R_Q$$
$$L_d,\ M,\ L_{ff},\ L_{DD}$$
$$L_q,\ M_q,\ L_{gg},\ L_{QQ}$$
$$L_0$$

R_a, L_d, L_q and L_0 are known directly from standard measurements. The remaining unknown variables are related to the measurements according to the following equations (Canay's procedure [4] for k=1):

$$M_d = L_d - L_l$$

$$T_{1d} + T_{2d} = (T_{d0}' + T_{d0}'')\ \frac{M_d - L_d}{M_d} + (T_d' + T_d'')\ \frac{L_d}{M_d}$$

$$T_{1d}\ T_{2d} = T_{d0}'\ T_{d0}''\ \frac{L_{//MfD}}{M_d}$$

$$L_{//MfD} = M_d - L_d + L_d''$$

$$L_{//Mf} = \frac{M_d\ (T_{1d} - T_{2d})}{T_{d0}' + T_{d0}'' - \left(1 + \frac{M_d}{L_{//MfD}}\right) T_{2d}}$$

$$\frac{1}{L_{//Mf}} = \frac{1}{M_d} + \frac{1}{L_f}$$

$$\frac{1}{L_{//MfD}} = \frac{1}{L_{//Mf}} + \frac{1}{L_D}$$

$$R_f = \frac{L_f}{T_{1d}} \qquad R_D = \frac{L_D}{T_{2d}}$$

$$L_{ff} = L_f + M_d \qquad L_{DD} = L_D + M_d$$

And for the quadrature axis quantities:

$$M_q = L_q - L_l$$

$$T_{1q} + T_{2q} = (T_{q0}' + T_{q0}'')\,\frac{M_q - L_q}{M_q} + (T_q' + T_q'')\,\frac{L_q}{M_q}$$

$$T_{1q}\,T_{2q} = T_{q0}'\,T_{q0}''\,\frac{L_{//MqQ}}{M_q}$$

$$L_{//MqQ} = M_q - L_q + L_q''$$

$$L_{//Mq} = \frac{M_q\,(T_{1q} - T_{2q})}{T_{q0}' + T_{q0}'' - \left(1 + \frac{M_q}{L_{//MqQ}}\right) T_{2q}}$$

$$\frac{1}{L_{//Mq}} = \frac{1}{M_q} + \frac{1}{L_q}$$

$$\frac{1}{L_{//MqQ}} = \frac{1}{L_{//Mq}} + \frac{1}{L_Q}$$

$$R_q = \frac{L_q}{T_{1q}} \qquad R_Q = \frac{L_Q}{T_{2q}}$$

$$L_{qq} = L_q + M_q \qquad L_{QQ} = L_Q + M_q$$

These are the equations used by the EMTP to obtain the desired reactances for the machine model based on the standard measurements. This set of equations is sequential. They must be solved in the prescribed order to be able to get a solution, but there is a cleaner and easier way to calculate these parameters. The new technique is based on the original definition of the eigenvalues of the fluxes (state variables). It uses back solving techniques to allow the user to go back and forth from one set of parameters to the other, and to include the effect of the armature resistance R_a in the process. A detailed explanation of this new procedure can be found in reference [5].

5.3 Units and Typical Values

Table 5-3-1 shows some typical values for different types of generators. These tables were copied from the EMTP Application Guide [6]. All the inductances are in p.u., and all time constants and inertia constant H are in seconds.

Table 5-3-1: Typical Generator Impedances

	Turbine Generators			
	2-Pole		4-Pole	
	Conventional Cooled	Conductor Cooled	Conventional Cooled	Conductor Cooled
X_d	1.7-1.82	1.72-2.17	1.21-1.55	1.6-2.13
X_d'	.18-.23	.264-.387	.25-.27	.35-.467
X_d''	.11-.14	.23-.323	.184-.197	.269-.32
X_q	1.63-1.69	1.71-2.14	1.17-1.52	1.56-2.07
X_q'	.245-1.12	.245-1.12	.47-1.27	.47-1.27
X_q''	.116-.332	.116-.332	.12-.308	.12-.308
T_{do}'	7.1-9.6	4.8-5.36	5.4-8.43	4.81-7.713
T_{do}''	.032-.059	.032-.059	.031-.055	.031-.055
T_{qo}'	.3-1.5	.3-1.5	.38-1.5	.38-1.5
T_{qo}''	.042-.218	.042-.218	.055-.152	.055-.152
X_l	.118-.21	.27-.42	.16-.27	.29-.41
R_a	.00081-.00119	.00145-.00229	.00146-.00147	.00167-.00235
H	2.5-3.5	2.5-3.5	3-4	3-4

Table 5-3-1 cont'd

	Salient-Pole		Combustion Turbines	Synchronous Condensors
	Dampers	No Dampers		
X_d	.6-1.5	.6-1.5	1.64-1.85	1.08-2.48
X_d'	.25-.5	.25-.5	.159--.225	.244-.385
X_d''	.13-.32	.2-.5	.102-.155	.141.257
X_q	.4-.8	.4-.8	1.58-1.74	.72-1.18
X_q'	$= X_q$	$= X_q$	.306	.57-1.18
X_q''	.135-.402	.135-.402	.1	.17-.261
T_{do}'	4-10	8-10	4.61-7.5	6-16
T_{do}''	.029-.051	.029-.051	.054	.039-.058
T_{qo}'	---------	---------	1.5	.15
T_{qo}''	.033-.08	.033-.08	.107	.188-.235
X_l	.17-.4	.17-.4	.113	.0987-.146
R_a	.003-.015	.003-.015	.034	.0017-.006
H	3-7	3-7	9-12	1-2

For all Generators:

$$X_0 = 0.1 \text{ to } 0.7 \text{ of } X_d''$$

$$H = \frac{0.231\ WR^2\ RPM^2 \times 10^{-6}}{KVA_{base}} \qquad \text{where: } [WR^2] = \text{lbm-ft}^2$$

Salient-pole generators do not have an iron path along the *q* axis, therefore there is no transient reactance X_q', which means that the *g* winding has to be removed from the simulation. To do this in the EMTP data cards, the transient time T_{qo}' is set equal to zero and the transient reactance X_q' is set equal to X_q.

5.4 References

[1] IEEE, "Test Procedures for Synchronous Machines," Standard 115, 1983.

[2] IEC, "Recommendations for Rotating Electric Machinery," Publication 34-4 A, 1972.

[3] F. P. de Mello, J. R. Ribeiro, "Derivation of Synchronous Machine Parameters from Tests," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, No. 4, July/August 1977, pp. 1211-1218.

[4] I. M. Canay, "Determination of Model Parameters of Synchronous Machines," Proceedings IEE, Vol. 130, part B, March 1983, pp. 86-94.

[5] F. L. Alvarado, C. A. Cañizares, "Synchronous Machine Parameters from Sudden-Short Test by Back-Solving," Paper 88 SM 605-8, IEEE/PES 1988 Summer Meeting, Portland, Oregon, July 24-29, 1988.

[6] Westinghouse Electric Corporation, *EMTP Application Guide*, EPRI Research Project 2149-1, August, 1986.

SECTION 6

SYNCHRONOUS MACHINES: MECHANICAL REPRESENTATION

6.1 Single-mass Representations of the Machine

For many transient studies of the machine the speed variation of the mechanical part is very small and can be ignored during the analysis. In all of these cases the angular position of the rotor β is simply represented by the equation:

$$\beta(t) = \beta(0) + \omega t$$

with ω constant. All quantities are referred to the electrical side.

When the speed variation of the machine has to be taken into account, the simplest mechanical model is the one used for transient stability studies:

$$J\frac{d\omega}{dt} + D\,\omega = T_{turbine} - T_{generator}$$

$$\frac{d\beta}{dt} = \omega$$

where J is the moment of inertia and D is the damping coefficient. These equations are valid either for the mechanical or the electrical side, and they can be converted from one side to the other by using the following equations:

$$\beta_{elec} = \frac{p}{2}\,\beta_{mech} \qquad T_{Elec} = \frac{2}{p}\,T_{mech}$$

$$J_{elec} = \left(\frac{2}{p}\right)^2 J_{mech} \qquad D_{elec} = \left(\frac{2}{p}\right)^2 D_{mech}$$

6.2 Multi-mass Representations of the Machine

Usually there is more than one mechanical mass connected to the shaft of the generator. For hydro units a one mass simulation of the machine is good enough, because the turbine and the generator itself are very close and connected by a stiff shaft, but this is not longer valid for thermal units. The lumped masses (6 to 20) of these latter units are very important, specially during subsynchronous resonance studies, where the torsional vibration of the mechanical parts of the machine have a severe effect on the system because of the low frequency mechanical transients that produce resonance effects on series capacitors in the network.

In order to take into account the effect of the different masses, the mechanical equation of the machine has to be changed. If we assume a linear mechanical system, the *n* spring-connected rotating masses can be represented by Newton's second law:

$$[J]\frac{d}{dt}[\omega] + [D][\omega] + [K][\theta] = [T_{turbine}] - [T_{gen/exc}]$$

$$\frac{d}{dt}[\theta] = [\omega]$$

Figure 6-2-1: The mechanical system.

where $[\omega]$ and $[\theta]$ are the vectors of speeds and angles, respectively, of each one of the n masses of the mechanical system. $[J]$ is a diagonal matrix of the moments of the inertia, $[D]$ is tridiagonal matrix of the damping coefficients, and $[K]$ is a tridiagonal matrix of the stiffness coefficients. The last two matrices are tridiagonal because they include the effect of the twisting of the shaft between adjacent masses.

6.3 Units

The usual units for these quantities are:

$$|J| = \mathrm{kgm}^2 \quad |D| = \frac{\mathrm{N{\cdot}m}}{\mathrm{rad/s}} \quad |T| = \mathrm{N{\cdot}m} \quad |\omega| = \frac{\mathrm{rad}}{\mathrm{s}}$$

Usually the inertia constant H (in seconds) is given instead of the moment of inertia J. This constant is a per unit representation of the kinetic energy E. The equation that relates this constant H with the moment of inertia J is:

$$H = \frac{E}{S_{rating}} = \frac{J\ \omega^2}{2\ S_{rating}}$$

with S_{rating} in KVA. Typical values for H are given in the previous section for different kinds of generators.

SECTION 7

USING SYNCHRONOUS MACHINE MODELS

7.1 Preparing Generator Data for Use in the EMTP

The data given to the EMTP depends on the type of generator and on the desired type of study. For example, if only electrical phenomena is of interest, the generator inertia can be set to a very large value (*). Typical data for different types of generators is given in the previous chapter.

When an Automatic Voltage Regulator (AVR) is included, its modelling has to be done using TACS. An AVR would not be of importance for fast electrical transients, where the main events take place in less than 5 to 10 cycles, unless the AVR was extremely fast.

The same criteria applies if a Governor is included in the study, i.e. it has to be simulated with TACS. Governor dynamics are only of interest when the time of analysis is greater that 1 second, which is a very long time for fast electric transients. As a general rule the governor is simulated when one is interested in the slow mechanical transients that are taking place in the system, e.g. in a multi-machine system.

For the simulation several things have to be taken into account:

- If there is not enough data available for the simulation, use typical data for generators of similar characteristics to the one that is being analyzed. See tables in chapter 6.

- Usually the transient reactance and time constant for the *q* axis are not available. In this case one can estimate their values by using typical data for the generator, or simply ignore these quantities. For the latter the value of the transient reactance x_q' has to be made equal to x_q, and the time constant T_{qo}' has to be set to zero, this will take the *g* winding out of the simulation.

- If one has the complete set of reactances of the machine but the one of the *g* winding, the mutual inductances for this winding have to be set equal to zero on the data cards, and an arbitrary value for x_q must be given to the program.

- The terminals of the machine must be always connected to some impedance, otherwise the program does not run. A typical case is when the breakers of the machine are open. In this instance resistances with a very large value (10^6) ought to be connected to the machine terminals to avoid any problem within the EMTP.

(*) The present version (V.1) of the EMTP has a bug that produces wrong results when the inertia is given a large value to simulate a constant speed machine. One has to be careful when defining the machine inertia to avoid getting unreasonable results.

A template with all the data needed for the representation of the generator is included in Appendix.

7.2 Short Circuit Studies

A most important study in synchronous machines is the study of the effect of short circuits in generators when the simple models of constant voltage behind transient or subtransient reactance are not sufficient. In this section we study the generator at bus 3 of our sample system, with small modifications to the value of its impedances to match the complete set of generator data provided in [1], pp. 102-103. The transient and subtransient parameters of the machine were calculated based on the complete set of impedances given in this reference. The calculation of internal paramter values was done using the eigenvalue/eigenvector technique [2] described previously.

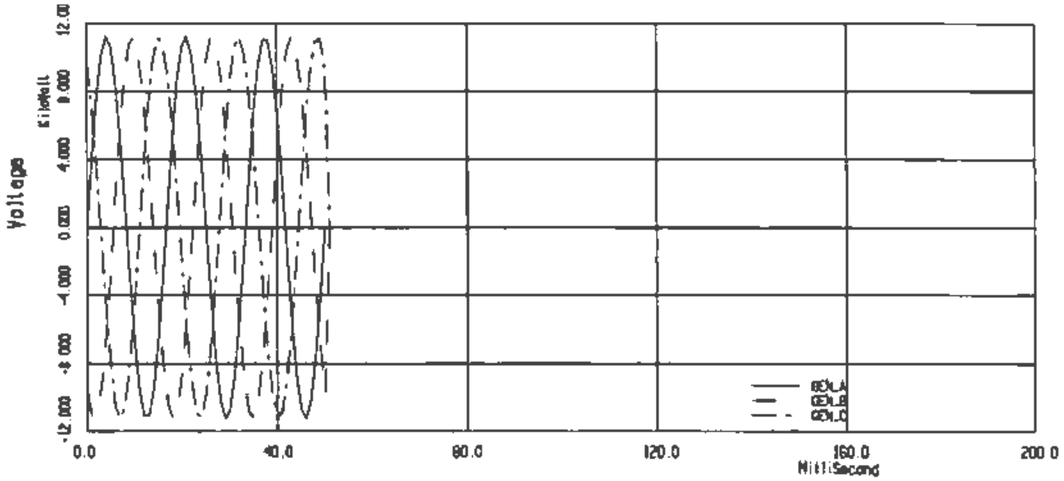
As mentioned in chapter 6, the machine model of the EMTP can accept as data either transient and subtransient reactances and time constants, or the internal impedances of the different windings. The results are the same either way. We use both to prove this point. If the complete set of impedances is given, the program does not go through the conversion routine, which sometimes is advantageous specially when one is not sure of the consistency of the test measurement values.

We illustrate two examples of use the EMTP for very detailed fault calculations using detailed machine modes. The first study considers a three phase solid short circuit directly at the terminals of the machine. The second case considers a Single Line to Ground fault at the terminals of the machine. In both cases the generator is open circuit before the fault is applied at 50 ms. For both cases we give the complete annotated input data, terminal voltages, and field and armature current plots.

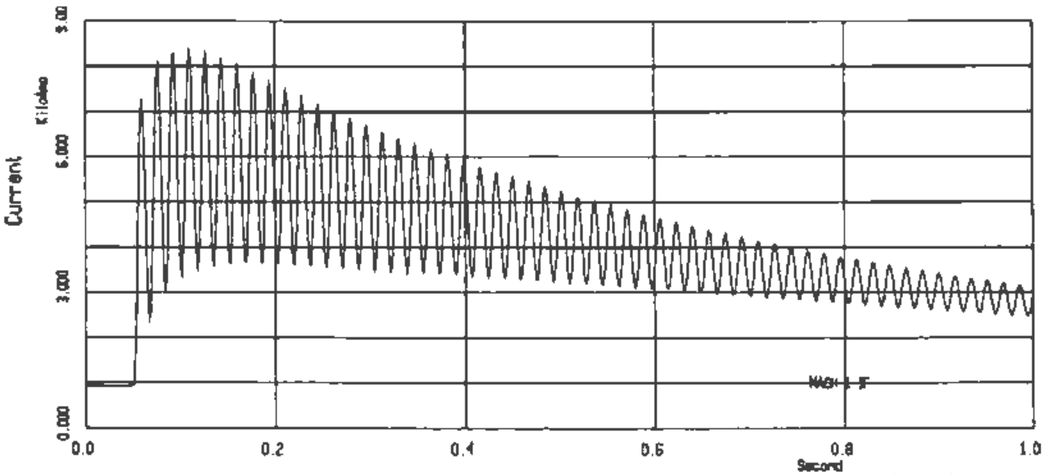
```
C Three phase fault at the terminal of the 200MVA generator at BUS3.
C Synchronous generator model with no saturation used.
C
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6      1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      51       1                                               1
C
C ............................ Circuit data  ...................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   0
  LOAD_A                  10000.
  LOAD_B                  10000.
  LOAD_C                  10000.
C A disconnected machine is not allowed by the program.
  BUS3A                   .00001
  BUS3B                   .00001
  BUS3C                   .00001
BLANK card terminates circuit data
C
C ............................ Switch data  ....................................
C Bus-->Bus--><---Tclose<---Topen<-------Ie                                     0
  GEN_A LOAD_A       -1.     9999.                                             1
  GEN_B LOAD_B       -1.     9999.                                             1
  GEN_C LOAD_C       -1.     9999.                                             1
  LOAD_ABUS3A      .5E-1     9999.                                             0
  LOAD_BBUS3B      .5E-1     9999.                                             0
  LOAD_CBUS3C      .5E-1     9999.                                             0
BLANK card terminates switch data
C
C ............................ Source data  ....................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN_A     11267.65       60.      -90.
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C ----------------------><-----FM
PARAMETER FITTING            1.
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<--------S1<-------S2
 1 1     2        1.        1.      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<-------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15      1.70      1.64   .238324      1.64   .184690   .185151
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40
C
C Mechanical parameters for the shaft system (Mass card)
```

```
C <----><----ExTrs<-----HIC0<------DSR<------DSM<-------HSP<-------DSD
 1                  1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C
C Output request.
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10        1     2     3     4    11
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><----><KI
  FINISH
BLANK card terminates source data
C
C ..............................  Output requests  ...........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

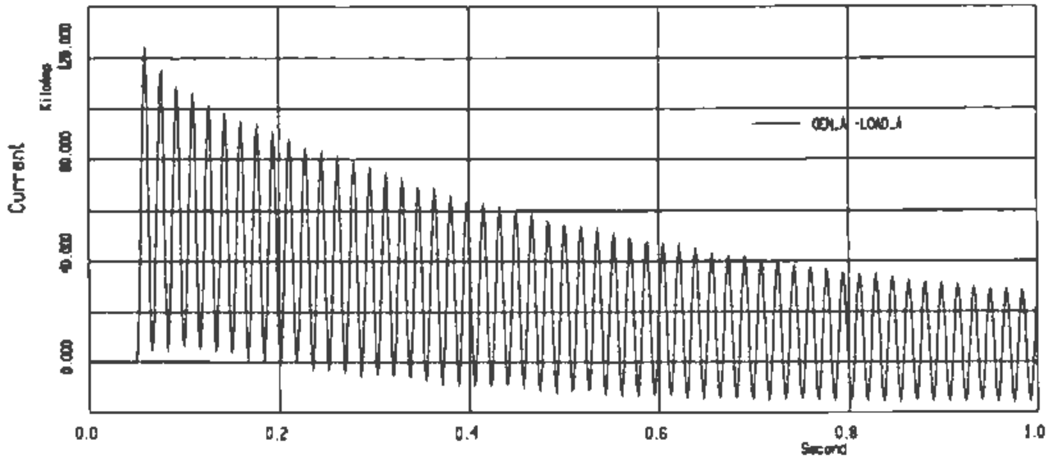
(a) Input data. Notice that "parameter fitting" has been requested, that test parameters are provided, and that the generator is represented as a single mechanical mass with an inertia constant equal to 0.181128.



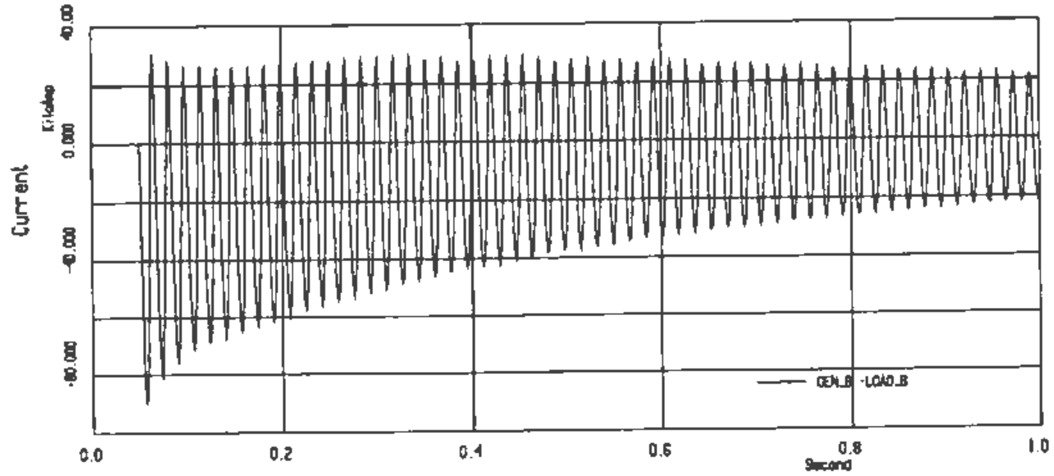
(b) Terminal voltage. All three voltages collapse at 50 ms.



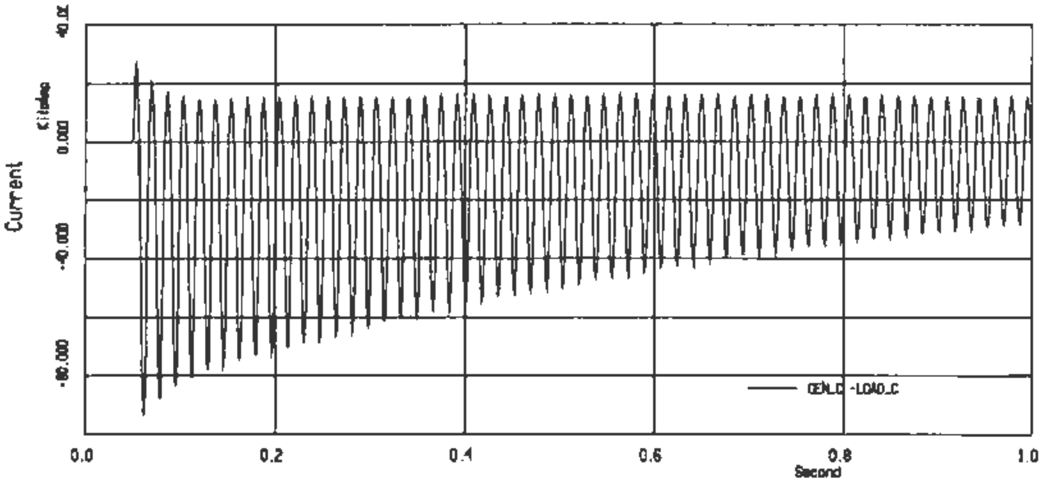
(c) Field current. Notice both the almost sudden development of a dc component, the gradual decay of the oscillatory behavior, and the settling of the current at a new steady state value.



(d) Armature current (phase a). Notice the easily recognizable unidirectional current, as well as the sightly easy to observe subtransient and transient current decay.



(e) Armature current (phase b).



(f) Armature current (phase c).

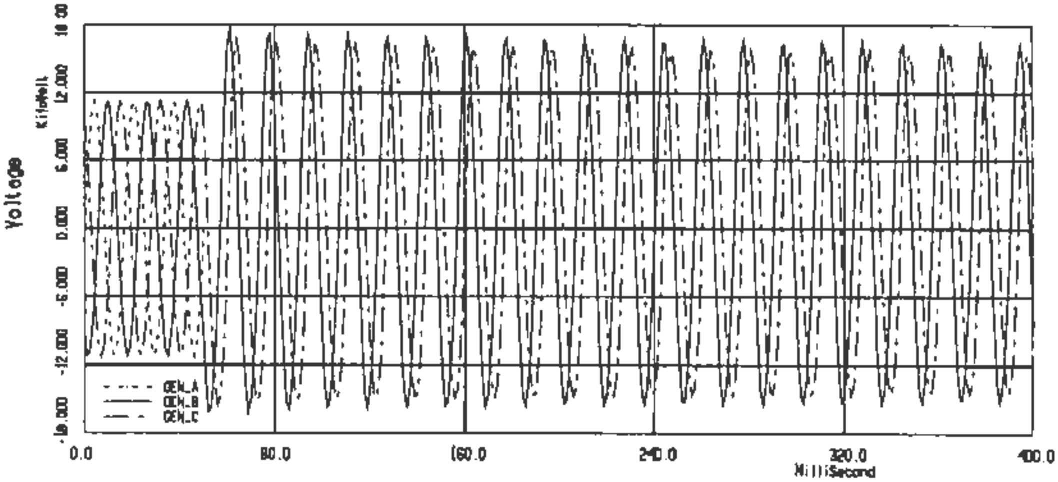
Figure 7-2-1: Three phase fault solid at terminals of generator at bus 3.

The results are what we expected for a sudden three phase short circuit at the machine terminals from no load initial conditions. The field current shows a 60 Hz oscillation that is damped by the resistances. It also has a unidirectional decreasing term containing the subtransient term, the transient term, and the new D.C. steady state of the two winding model used to simulate the synchronous machine. The steady state takes a long time to reach because of the small value of the resistances. Phases *a*, *b*, and *c* show the large change in current due to the fault, going from zero (open circuit) to several KAmps (short circuit). In all these currents there is just a slight deviation from the 60 Hz frequency, even though the inertia has a real value, which is one of the characteristics of the three phase sudden short circuit .

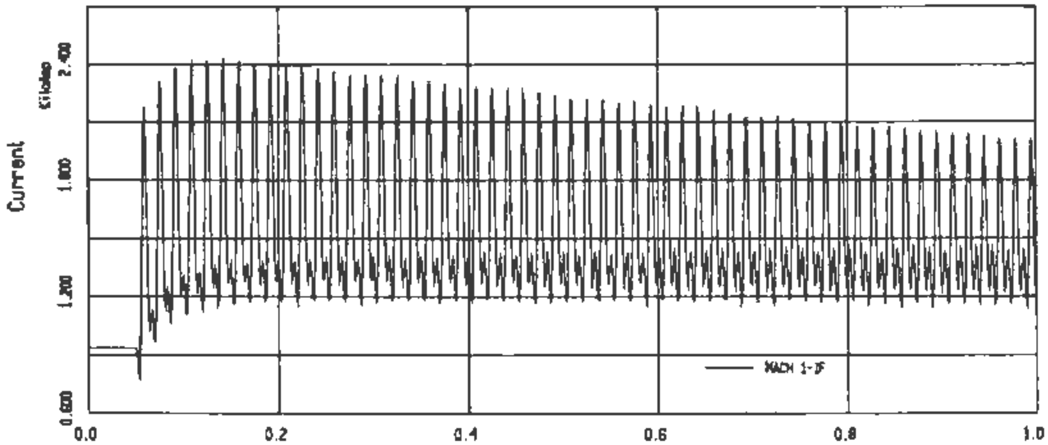
```
C SLG fault at the terminal of the 200MVA generator at BUS3.
C Synchronous generator model with no saturation used.
C
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6      1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      51       1                                               1
C
C ...........................  Circuit data  ..................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   0
  LOAD_A                  10000.
  LOAD_B                  10000.
  LOAD_C                  10000.
C A disconnected machine is not allowed by the program.
  BUS3A                   .00001
  BUS3B                   .00001
  BUS3C                   .00001
BLANK card terminates circuit data
C
C ...........................  Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  GEN_A LOAD_A       -1.     9999.                                             1
  GEN_B LOAD_B       -1.     9999.                                             1
  GEN_C LOAD_C       -1.     9999.                                             1
  LOAD_ABUS3A      .5E-1     9999.                                             0
  LOAD_BBUS3B      9999.     9999.                                             0
  LOAD_CBUS3C      9999.     9999.                                             0
BLANK card terminates switch data
C
C ...........................  Source data  ....................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN_A     11267.65       60.      -90.
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C ---------------------><-----FM
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Machine parameters (no PARAMETER FITTING)  *Diagonal elements cannot be zero
C -----Xf*<------Xaf<-----Xfkd<------Xd*<-----Xakd<-----Xkd*<------ Xl
      1.65      1.55      1.55      1.70      1.55     1.605       .15
C -----Xg*<------Xag<-----Xgkq<------Xq*<-----Xakq<-----Xkq*
   .000001                          1.64      1.49     1.526
C ------Xo<-------Ra<-------Rf<------Rkd<-------Rg<------Rkq<-------Rn<-------Xn
       1.4  0.001096  0.000742    0.0131              0.0540
C
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HICO<------DSR<------DSM<------HSP<------DSD
```

```
 1                1.    .181128
C col: (1-2) ML
BLANK card terminates mass data
C
C Output requests
C GA<-->< ---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10          1     2     3     4    11
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus-->< ---->< KI
  FINISH
BLANK card terminates source data
C
C ................................ Output requests .............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

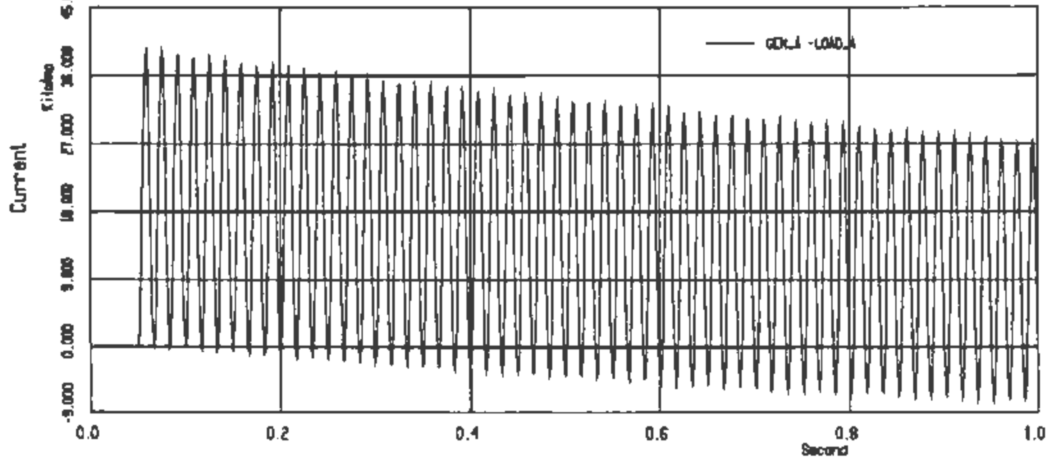
(a) Input data. The only difference with the previous case is the switches.



(b) Terminal voltages. Observe overvoltage develops in the unfaulted phases.



(c) Field current. Notice sustained nature of oscillatory behavior and presence of harmonics.



(d) Armature current (phase a).

Figure 7-2-2: SLG fault at terminal of generator at bus 3.

For the single-line-to-ground fault the currents present different characteristics than those for a three phase short circuit. The field current has a double frequency term (120 Hz) that induces a third harmonic in the current of phase *a*, which is difficult to see on the plots above. The currents in the other two phases are zero, because they are assumed to be open circuited, producing slightly different overvoltages at each phase, which is a typical characteristic of an unbalanced fault.

7.3 Unbalanced Operation Study

An interesting study that can be easily reproduced with the aid of the EMTP, is the effect of saliency on overvoltages during unbalanced faults (see chapter 2 of reference [3]).

It is known that unbalanced faults can generate overvoltages on the unfaulted phases, and that these overvoltages can be increased due to saliencies on the rotor and to the presence of line capacitances or capacitor banks near the terminals of the generator. The saliencies tend to distort the voltages on the unfaulted phases by introducing harmonics. On the other hand, the capacitances may produce resonance with the machine reactance, amplifying the distortion on the terminal voltages or even taking the whole system out of synchronism, as we shall see on the examples below.

The phenomenon described above can be clearly observed on the results obtained for the two cases shown on figures 7-3-2, 7-3-3, and 7-3-4. These examples were prepared using the generator at bus 3 of our 13 bus system, the transformer between buses 1 and 3, and a capacitor bank to represent the capacitance of the two lines connected to bus 1. A line-to-line fault was applied at 50 ms between phases *b* an *c* of bus 1, as it is shown on Figure 7-3-1. To produce the resonant effect on the voltage of the unfaulted phase, the value of the capacitors was calculated based on the following formula:

$$X_c = k\ X_2$$

$$X_2 = \frac{X_d" + X_q"}{2}$$

where k can be picked so the system becomes resonant.

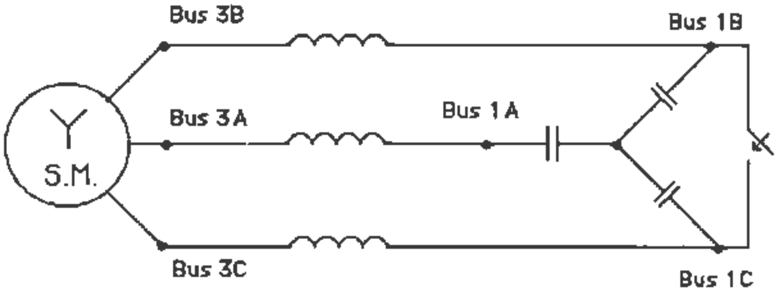


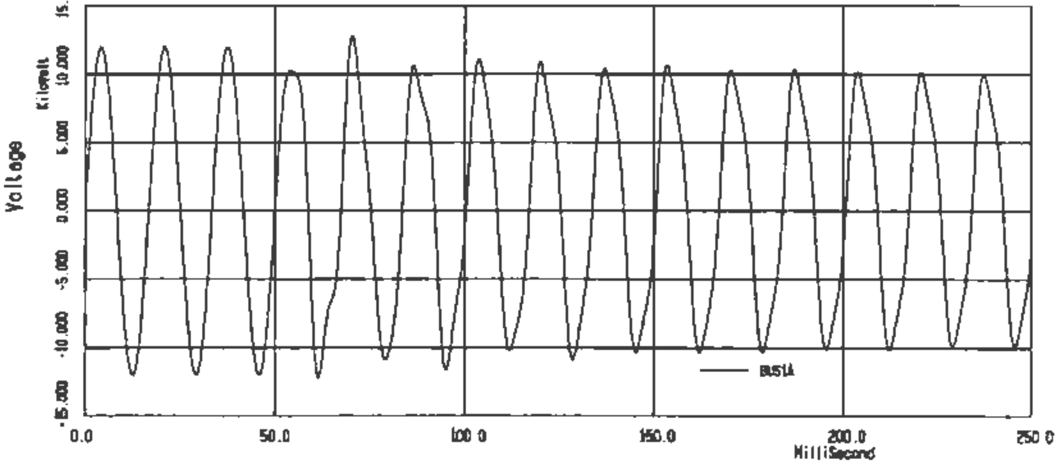
Figure 7-3-1: System used for study of unbalanced operation of salient pole machine.

Three cases were analyzed. The first one (Figure 7-3-2) uses the same parameters for the machine as in the previous section. The value of k was chosen so there is no resonant effect on the system. The results show little distortion of the terminal voltage and a relatively small overvoltage. For the second case (Figure 7-3-3) the subtransient reactance of the *q* axis ($x_q"$) was increased to reduce the damping effect of the amortisseur windings in that axis, and the value of k was chosen to produce resonance between the capacitances and impedances of the system. The results clearly show larger distortion and overvoltages on the unfaulted phase; it also shows the instability brought about by the resonance. The third case (Figure 7-3-4) is based on the same machine as in the previous figure, i.e. the machine has large saliency, but the value of k was chosen so that resonance does not occur. From the resulting plots one can see that the overvoltages are greatly reduced and the system becomes stable.

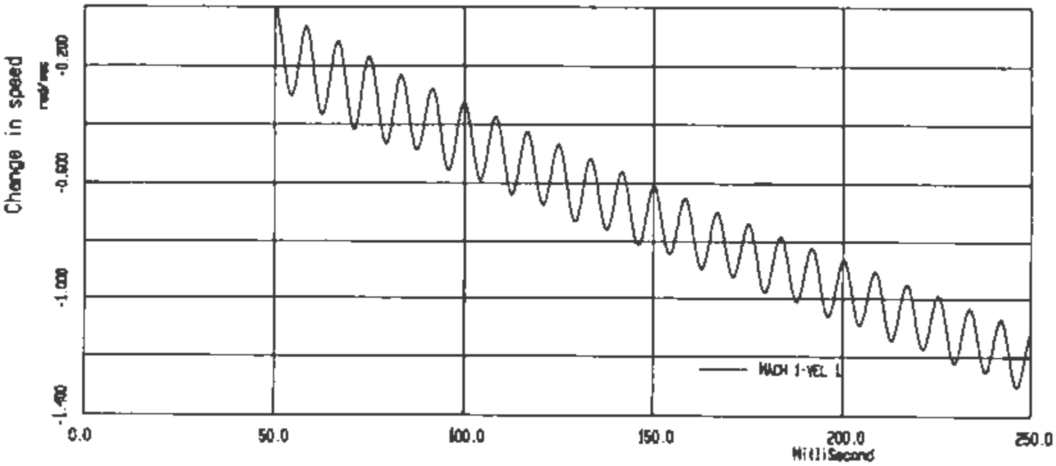
```
C Effect of saliency on overvoltages in Synchronous Machines during
C unbalanced faults (Line-to-Line).  Stable case.
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data ..............................
C DeltaT<----TMax<----XOpt<----COpt<-Epsiln<-TolMat<-TStart
 150.E-6     .25
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1                       1                       1
C
C ...........................  Circuit data  ..................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                    0
  GEN_A BUS1A                   .25257                                         1
  GEN_B BUS1B GEN_A BUS1A                                                      1
  GEN_C BUS1C GEN_A BUS1A                                                      1
  BUS1A                               1.67E3
  BUS1B       BUS1A
  BUS1C       BUS1A
BLANK card temrinates circuit data
C
C ...........................  Switch data  ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                    0
  BUS1B BUS1C      .5E-1     9999.                                             0
BLANK card terminates switch data
C
C ...........................  Source data  ...................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN_A     11267.65     60.        -90.
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C ---------------------><-----FM
PARAMETER FITTING             1.
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.       1..      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15      1.70      1.64   .238324      1.64   .184690   .185151
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40     9999.
C
C Mechanical parameters for the shaft system (Mass card)
C <-------><----ExTrs<-----HICO<-------DSR<------DSM<-------HSP<------DSD
 1                1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
```

```
  10         1     2     3     4    11
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus-->< ----><KI
  FINISH
BLANK terminates source data
C
C ..............................  Output requests  ...........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(a) Input data.



(b) Voltage at unfaulted phase (bus 1A). Notice slight distortion, slight overvoltage.



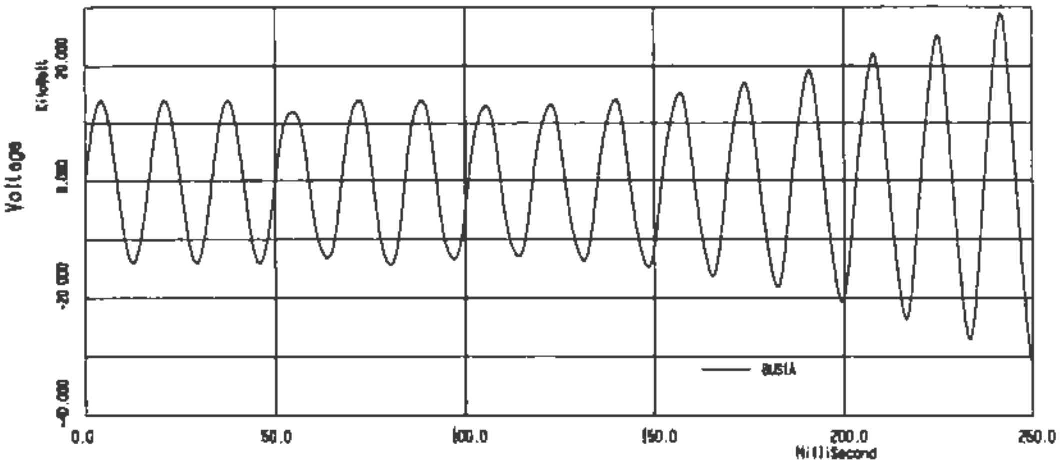
(c) Change in generator speed ($\Delta\omega$).

Figure 7-3-2: Generator with proper amortisseur windings. No resonance.

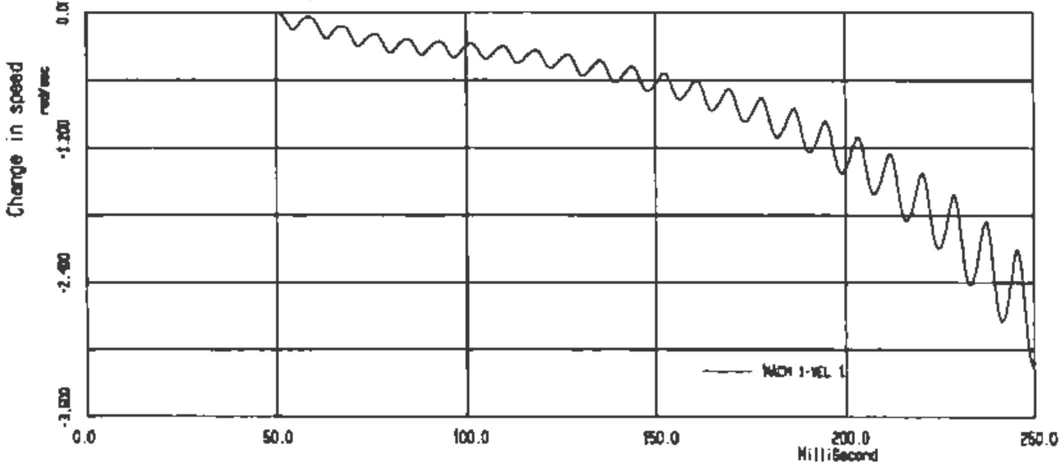
```
C Effect of saliency on overvoltages in Synchronous Machines during
C unbalanced faults (Line-to-Line).  Unstable case with Saliency.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data .............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 150.E-6     .25
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1                       1                       1
C
C ............................ Circuit data ..................................
C Bus1->Bus2->Bus3->Bus4-><----R<-----L<----C                                  O
  GEN_A BUS1A                   .25257                                         1
  GEN_B BUS1B GEN_A BUS1A                                                      1
  GEN_C BUS1C GEN_A BUS1A                                                      1
  BUS1A                               5.46E3
  BUS1B       BUS1A
  BUS1C       BUS1A
BLANK card terminates circuit data
C
C ............................ Switch data ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
  BUS1B BUS1C     .5E-1      9999.                                             0
BLANK card terminates switch data
C
C ............................ Source data ...................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN_A     11267.65       60.      -90.
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C ---------------------><-----FM
PARAMETER FITTING             1.
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<-----S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C -------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15     1.70       1.64   .238324      1.64   .184690   .295504
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40    9999.
C
C Mechanical parameters for the shaft system (Mass card)
C <-------><----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                1.   .181128
C ccl: (1-2) ML
BLANK card terminates mass data
C
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
```

```
  10        1     2     3     4    11
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus-->< ---><KI
  FINISH
BLANK card terminates source data
C
C ............................... Output requests ...........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(a) Input data. Machine reactances changed.



(b) Voltage at unfaulted phase (bus 1A). Notice distortion and unstable operation caused by resonance.



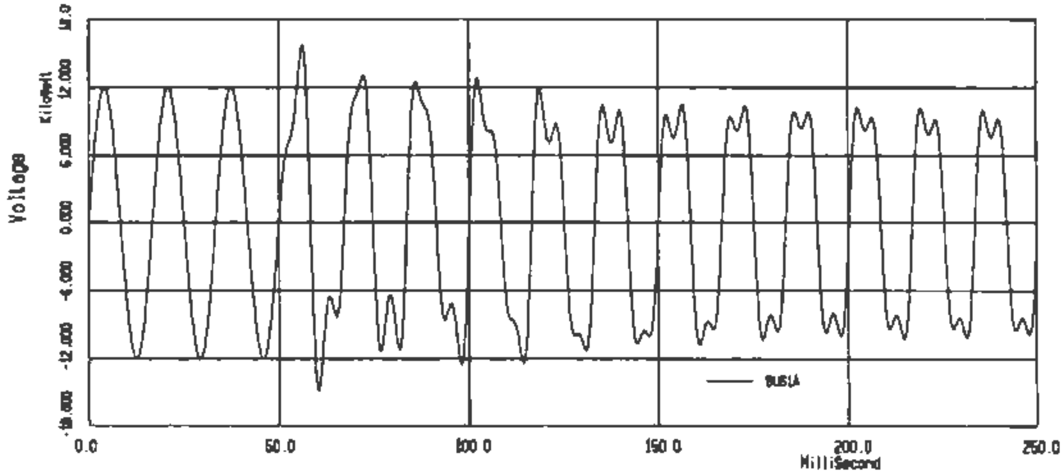
(c) Change in generator speed ($\Delta\omega$).

Figure 7-3-3: Generator with large subtransient reactance in the *q* axis. Resonant effect makes the system unstable.

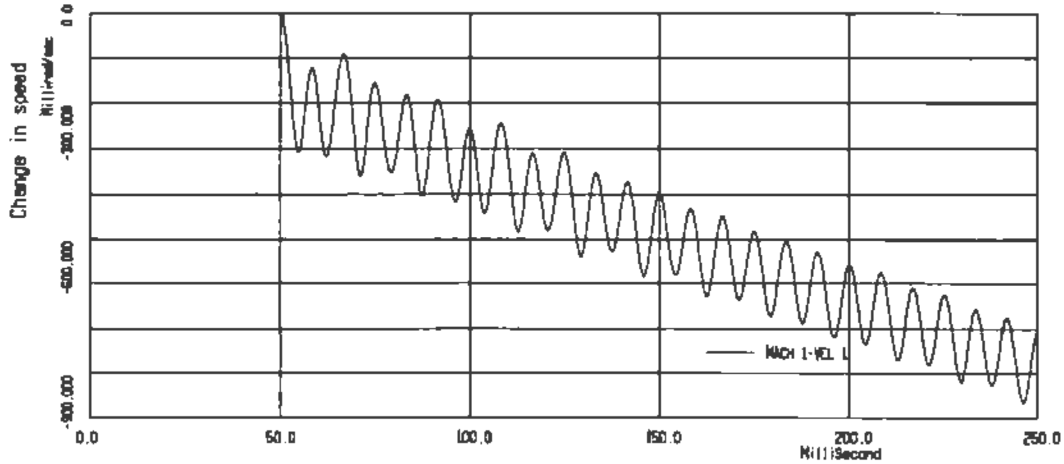
```
C Effect of saliency on overvoltages in Synchronous Machines during
C unbalanced faults (Line-to-Line).  Stable case with Saliency.
BEGIN NEW DATA CASE
C ........................... Miscellaneous data .............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 150.E-6     .25
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1                       1                       1
C
C ........................... Circuit data ..................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   0
  GEN_A BUS1A                   .25257                                         1
  GEN_B BUS1B GEN_A BUS1A                                                      1
  GEN_C BUS1C GEN_A BUS1A                                                      1
  BUS1A                               1.82E3
  BUS1B       BUS1A
  BUS1C       BUS1A
BLANK card terminates circuit data
C
C ........................... Switch data ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS1B BUS1C      .5E-1     9999.                                             0
BLANK card terminates switch data
C
C ........................... Source data ...................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<-----Angle
59GEN_A     11267.65       60.      -90.
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C --------------------><------FM
PARAMETER FITTING             1.
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C        In principle any value can be used here
C
C ------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15      1.70      1.64   .238324      1.64   .184690   .295504
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40     9999.
C
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
```

```
  10         1     2     3     4    11
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus-->(<---->(KI
  FINISH
BLANK card terminates source data
C
C .............................. Output requests ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(a) Input data. Capacitance value changed.



(b) Voltage at unfaulted phase (bus 1A). Large amount of distortions occurs.



(c) Change in generator speed ($\Delta\omega$).

Figure 7-3-4: Generator with large subtransient reactance in the q axis. No resonance.

7.4 A Transient Stability Study

Another interesting type of study that can be made with the generator model available in the EMTP, is a Transient Stability Analysis. There are many programs tailored to execute this kind of study. All of them use a simple one-phase model of the synchronous machine, which makes them useful for analyzing the effect of balanced faults (three phase faults) in the system. The complete model of the generator available in the EMTP allows us to study the impact of different unbalanced faults in the system, so a better level of understanding and design can be achieved.

Figure 7-4-1 depicts an equivalent of the 13 bus system that is going to be used to make basic Transient Stability Analyses, where voltage and speed regulation have not been taken into account. These two controls will be included in a later section.

Two examples are presented. In both cases a three-phase fault is applied at 30 ms on bus 12, and it is cleared by opening the line between buses 1 and 12. Figure 7-4-2 shows the input data and the results for a stable case, obtained when the breaker opens at 100 ms. Figure 7-4-3 depicts an unstable case obtained when the breaker opens at 300 ms.

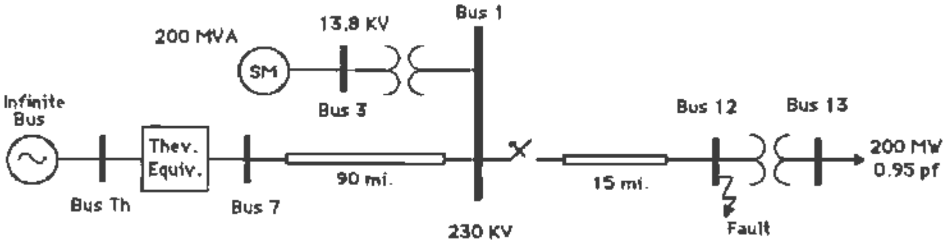


Figure 7-4-1: Reduced equivalent of the 13 bus Power System for Transient Stability Studies. The Thevenin equivalent was obtained with line 1-2 open.

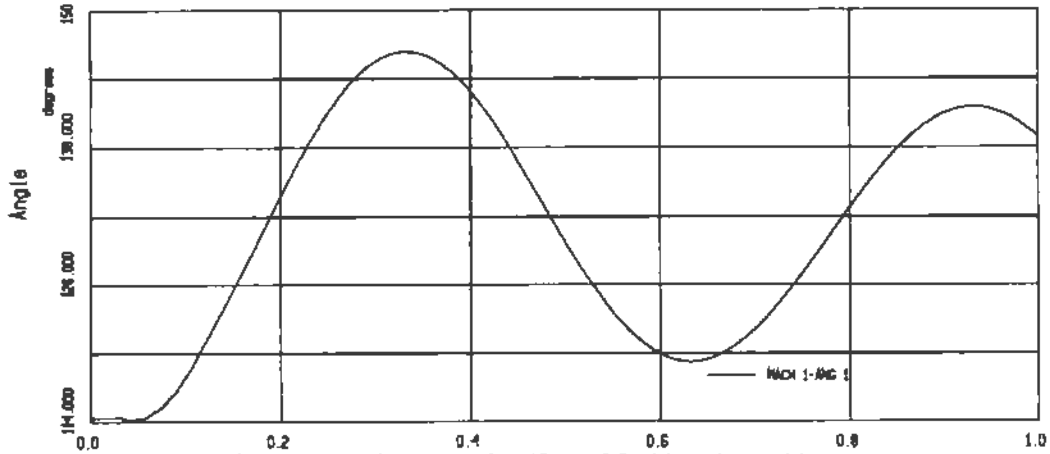
These studies also illustrate a new type of feature within the EMTP: the use of TACS blocks. The use of TACS blocks in this workbook is quite limited, restricted to a few simple tasks. In this case we wish to illustrate the use of a simple "RMS meter" to display RMS terminal voltage as may be obtained by a voltmeter in the system rather than the usual instantaneous values.

In order to show the kind of studies that can be done with the EMTP, which are beyond the limited scope of the traditional Transient Stability Analysis, another example (Figure 7-4-4) was run. This case deals with the effects upon the system of a single-line-to-ground fault at bus 12 at 30 ms, and that was removed by opening line 1-12 at 300 ms. Notice that the system is still stable, whereas for the three-phase fault that was not the case.

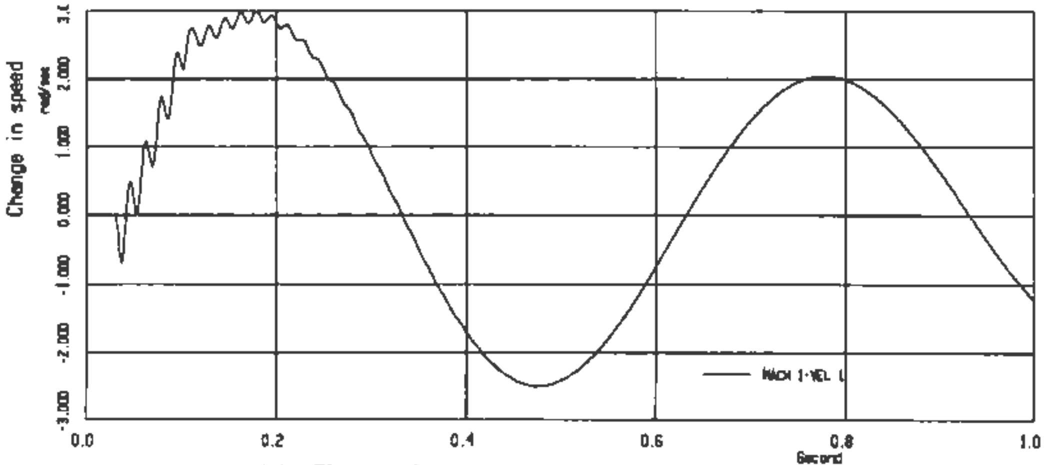
```
C Transient stability analysis for test system.  Stable case.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6      1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1               1                               1
TACS HYBRID
C Node_V
90GEN3A                    60.
90BUS1A                    60.
C RMS_Value
88Vt_A  66+GEN3A                                     60.
88Vrms1A66+BUS1A                                     60.
C TACS_output
33Vt_A  Vrms1A
BLANK card terminates TACS data
C
C ...............................Circuit data...................................
C Bus-->Bus--><----------><----R<----------L<----R<----------L<----R<----------L
51THEVA BUS7A                .13       23.71                                   0
52THEVB BUS7B                .06       39.99                                   0
53THEVC BUS7C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<--- C<----R<----L<--- C<----R<----L<--- C
 1BKR1A BUS12A            2.914240.834.26247
 2BKR1B BUS12B            2.370719.587-.06032.993440.714.27339
 3BKR1C BUS12C            2.317816.307-.01532.370719.587-.06032.914240.834.26247
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<-----Blank----------->O
-1BUS7A BUS1A             0.3167 3.222.00787 144.4 0 0 0                       0
-2BUS7B BUS1B             0.0243 .9238 .0126 144.4 0 0 0                       0
-3BUS7C BUS1C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   O
  BUS12ABUS13A                   70.16                                         0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                  221.41 38.26                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Saturable transformer components.
C -----------><-Bus3<----><----I<--Phi<BusSt<-Rmag<---------------------------->O
  TRANSFORMER                         DELTAB                                   0
C -------current<-----------flux
            9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<---Nk<--------------------------------->O
 1GEN3A GEN3B                    .1263  13.8                                   0
 2BUS1A                          35.08132.79
C Note.- These leakage values were calculated assuming a 10% p.u. reactance at
C        200 MVA for the transformer, divided in half between the two windings.
C <----------><-Bus3<----------------><BusSt
  TRANSFORMER DELTAB                  DELTBC
C <-Bus1<-Bus2
 1GEN3B GEN3C
 2BUS1B
  TRANSFORMER DELTAB                  DELTCA
 1GEN3C GEN3A
 2BUS1C
BLANK card terminates circuit data
C
C .............................Switch data......................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
  BUS1A BKR1A     -1.E-3   100.E-3         0                                   1
  BUS1B BKR1B     -1.E-3   100.E-3         0                                   1
  BUS1C BKR1C     -1.E-3   100.E-3         0                                   1
  BUS12A          30.E-3     9999.         0                                   1
```

```
  BUS12B          30.E-3     9999.         0                                   1
  BUS12C          30.E-3     9999.         0                                   1
BLANK card terminates  switch data
C
C .................................Source data..................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA     187.79E3      60.        0.        0.                   -1.      9999.
14THEVB     187.79E3      60.     -120.        0.                   -1.      9999.
14THEVC     187.79E3      60.      120.        0.                   -1.      9999.
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN3A     11267.65      60.    -28.00
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<-------><----Angle
  GEN3B
  GEN3C
C Machine parameter cards (Optional)
C ---------------------><-----FM
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2         1.         1.      200.      13.8  935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Machine parameters (no PARAMETER FITTING)  ***Diagonal elements cannot be zero
C -----Xf*<------Xaf<-----Xfkd<------Xd*<-----Xakd<-----Xkd*<------ Xl
      1.65      1.55      1.55      1.70      1.55     1.605       .15
C -----Xg*<------Xag<-----Xgkq<------Xq*<-----Xakq<-----Xkq*
   .000001                         1.64      1.49     1.526
C ------Xo<-------Ra<-------Rf<------Rkd<-------Rg<------Rkq<-------Rn<-------Xn
       1.4  0.001096  0.000742    0.0131               0.0540
C Mechanical parameters for the shaft system (Mass card).
C <------><----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10         1     2     3     4    11
  21
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C TACS input cards
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><----><KI
  FINISH
BLANK card terminates source data
C
C ..............................Output Request Data..............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN3A BUS1A BUS12A
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

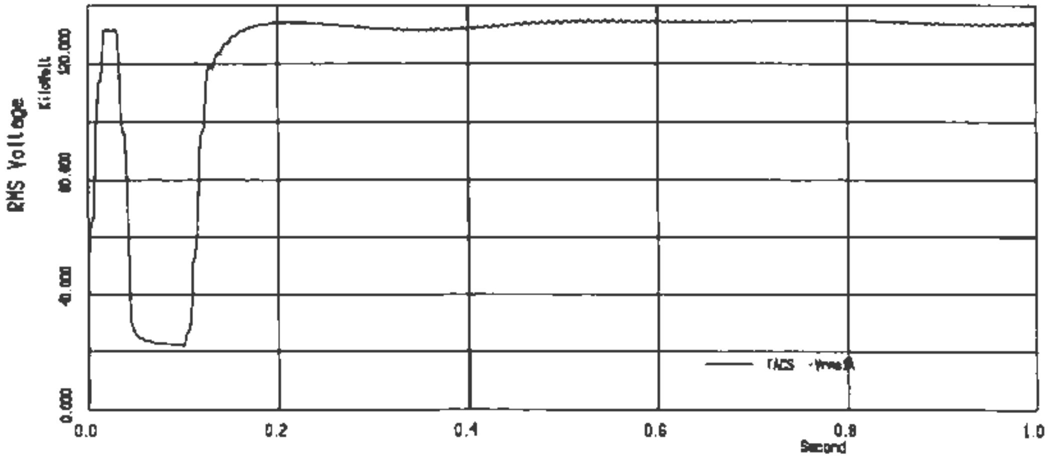
(a) Input data. Notice implementation of a "RMS meter" using TACS.



(b) Generator phase angle (δ). Machine is stable.



(c) Change in generator speed (Δω).



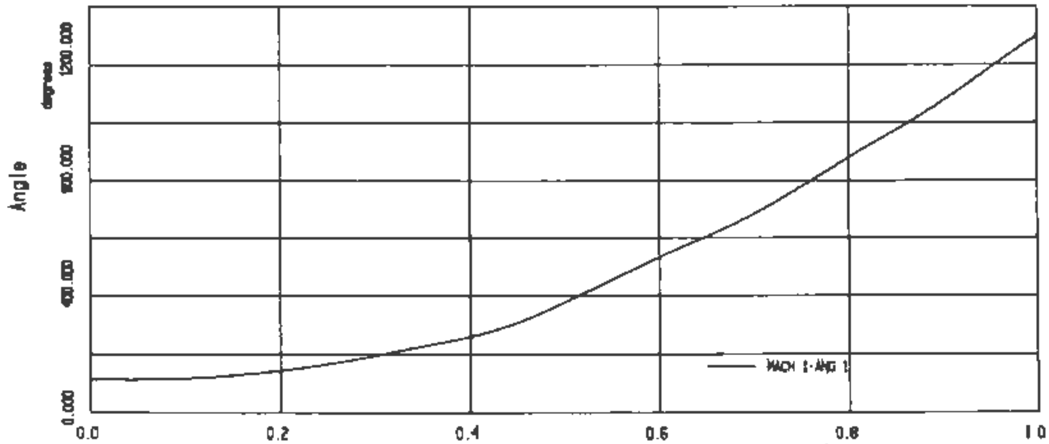
(d) RMS voltage at bus 1. This was obtained using the TACS-implemented RMS-meter. Notice initial settling time of the meter, then collapse of the voltage during the fault, and recovery after fault clearing.

Figure 7-4-2: Stable case, three phase fault cleared at 100ms. Results obtained with the EMTP.

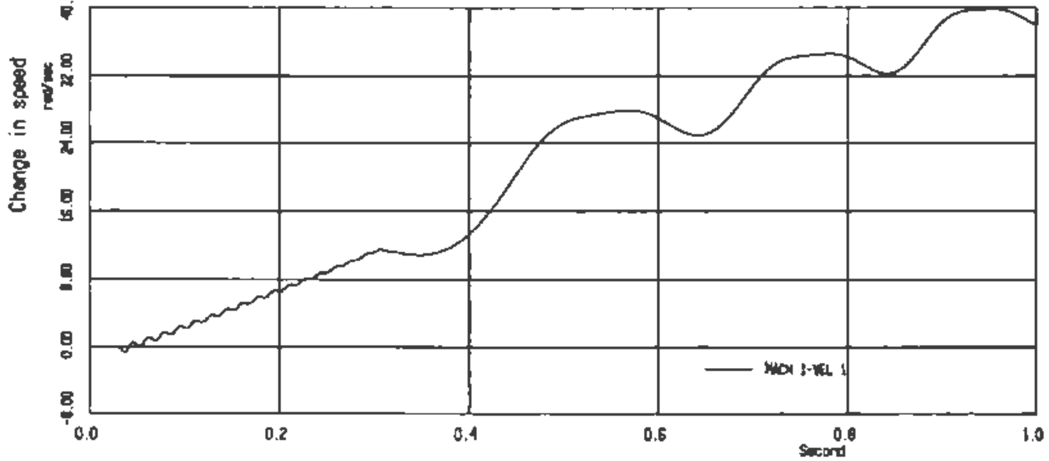
```
C Transient stability analysis for test system.  Unstable case.
BEGIN NEW DATA CASE
C ............................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6      1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1               1                               1
TACS HYBRID
C Node_V
90GEN3A                    60.
90BUS1A                    60.
C RMS_Value
88Vt_A  66+GEN3A                                     60.
88Vrms1A66+BUS1A                                     60.
C TACS_output
33Vt_A  Vrms1A
BLANK card terminates TACS data
C
C ................................Circuit data...................................
C Bus-->Bus--><----------><----R<----------L<----R<----------L<----R<----------L
51THEVA BUS7A                .13       23.71                                   0
52THEVB BUS7B                .06       39.99                                   0
53THEVC BUS7C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<---- C<----R<----L<---- C<----R<----L<--- C
 1BKR1A BUS12A            2.914240.834.26247
 2BKR1B BUS12B            2.370719.587-.06032.993440.714.27339
 3BKR1C BUS12C            2.317816.307-.01532.370719.587-.06032.914240.834.26247
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<------Blank----------->0
-1BUS7A BUS1A             0.3167 3.222.00787 144.4 0 0 0                       0
-2BUS7B BUS1B             0.0243 .9238 .0126 144.4 0 0 0                       0
-3BUS7C BUS1C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<-----L<----C                                  0
  BUS12ABUS13A                   70.16                                         0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                  221.41 38.26                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Saturable transformer components.
C ----------><-Bus3<----><----I<--Phi<BusSt<-Rmag<---------------------------->0
  TRANSFORMER                         DELTAB                                   0
C -------current<------------flux
            9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<---Nk<---------------------------------->0
 1GEN3A GEN3B                    .1263  13.8                                   0
 2BUS1A                          35.08132.79
C Note.- These leakage values were calculated assuming a 10% p.u. reactance at
C        200 MVA for the transformer, divided in half between the two windings.
C <----------><-Bus3<---------------><BusSt
  TRANSFORMER DELTAB                  DELTBC
C <-Bus1<-Bus2
 1GEN3B GEN3C
 2BUS1B
  TRANSFORMER DELTAB                  DELTCA
 1GEN3C GEN3A
 2BUS1C
BLANK card terminates circuit data
C
C ..............................Switch data.....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS1A BKR1A     -1.E-3   300.E-3         0                                   0
  BUS1B BKR1B     -1.E-3   300.E-3         0                                   0
  BUS1C BKR1C     -1.E-3   300.E-3         0                                   0
  BUS12A          30.E-3     9999.         0                                   1
```

```
  BUS12B          30.E-3    9999.          0                                   1
  BUS12C          30.E-3    9999.          0                                   1
BLANK card terminates switch data
C
C ................................Source data...................................
C Bus-->I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <---Tstart<----Tstop
14THEVA     187.79E3      60.         0.         0.                  -1.     9999.
14THEVB     187.79E3      60.      -120.         0.                  -1.     9999.
14THEVC     187.79E3      60.       120.         0.                  -1.     9999.
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN3A     11267.65      60.    -28.00
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<-------><----Angle
  GEN3B
  GEN3C
C Machine parameter cards (Optional)
C ---------------------><-----FM
PARAMETER FITTING             1.
C Electrical parameters of machine.
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2         1.        1.       200.      13.8  935.016      1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C ------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15      1.70      1.64  .238324      1.64  .184690   .185151
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40
C Mechanical parameters for the shaft system (Mass card)
C <------><-----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10         1     2     3     4    11
  21
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machoine output requests
C TACS input cards
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><-----><KI
  FINISH
BLANK card terminates source data
C
C .................................Output requests.........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN3A BUS1A BUS12A
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

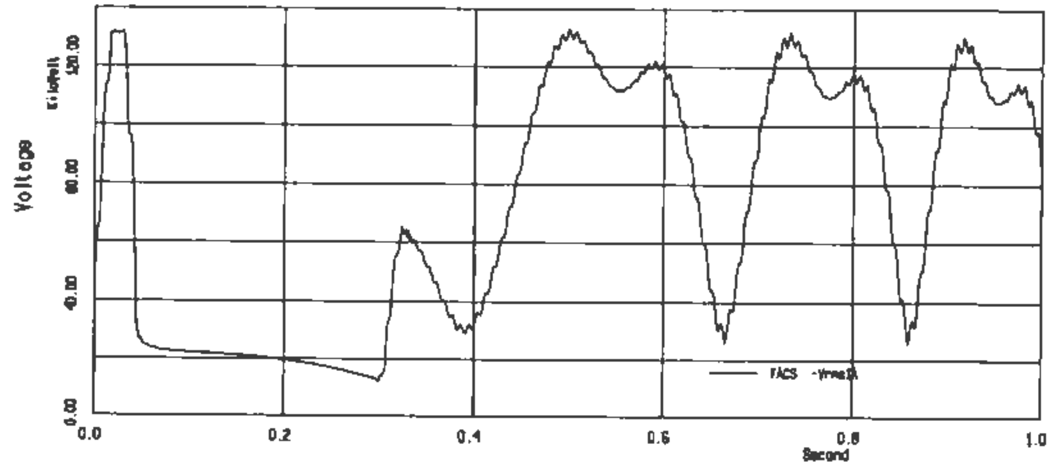
(a) Input data. Longer clearing time.



(b) Generator phase angle (δ). Machine is unstable.



(c) Change in generator speed (Δω).



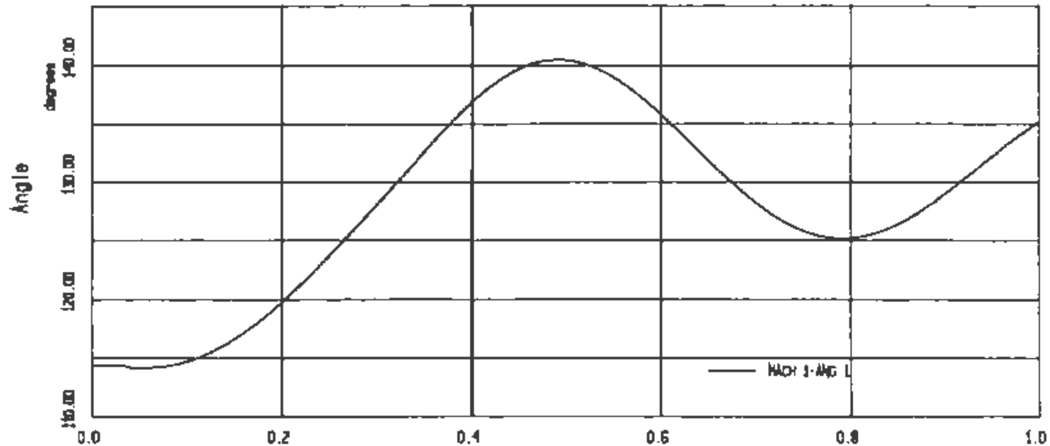
(d) RMS voltage at bus 1.

Figure 7-4-3: Unstable case. Results obtained with the EMTP.

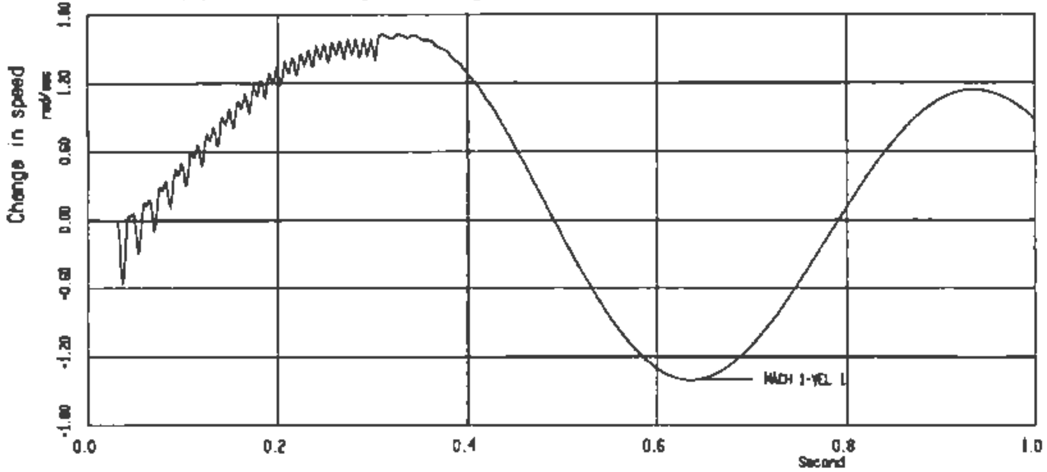
```
C Transient stability analysis for test system.  Unbalanced fault (Single-line-to-
C ground).
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6      1.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     101       1               1                               1
TACS HYBRID
C Node_V
90GEN3A                    60.
90BUS1A                    60.
C RMS_Value
88Vt_A  66+GEN3A                                     60.
88Vrms1A66+BUS1A                                     60.
C TACS_output
33Vt_A  Vrms1A
BLANK card terminates TACS data
C
C ..............................Circuit data...................................
C Bus-->Bus--><----------><---R<----------L<----R<----------L<----R<----------L
51THEVA BUS7A                .13       23.71                                   0
52THEVB BUS7B                .06       39.99                                   0
53THEVC BUS7C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<--- C<----R<----L<--- C<----R<----L<--- C
 1BKR1A BUS12A            2.914240.834.26247
 2BKR1B BUS12B            2.370719.587-.06032.993440.714.27339
 3BKR1C BUS12C            2.317816.307-.01532.370719.587-.06032.914240.834.26247
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<------Blank---------->0
-1BUS7A BUS1A             0.3167 3.222.00787 144.4 0 0 0                       0
-2BUS7B BUS1B             0.0243 .9238 .0126 144.4 0 0 0                       0
-3BUS7C BUS1C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   0
  BUS12ABUS13A                  70.16                                          0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                  221.41 38.26                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Saturable transformer components.
C ----------><-Bus3<----><----I<--Phi<BusSt<-Rmag<---------------------------->0
  TRANSFORMER                         DELTAB                                   0
C -------current<----------flux
            9999
C <-Bus1<-Bus2<----------><---Rk<---Lk<---Nk<--------------------------------->0
 1GEN3A GEN3B                   .1263  13.8                                    0
 2BUS1A                         35.08132.79
C Note.- These leakage values were calculated assuming a 10% p.u. reactance at
C        200 MVA for the transformer, divided in half between the two windings.
C <----------><-Bus3<---------------><BusSt
  TRANSFORMER DELTAB                  DELTBC
C <-Bus1<-Bus2
 1GEN3B GEN3C
 2BUS1B
  TRANSFORMER DELTAB                  DELTCA
 1GEN3C GEN3A
 2BUS1C
BLANK card terminates circuit data
C
C .............................Switch data.......................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                    0
  BUS1A BKR1A     -1.E-3   300.E-3         0                                   0
  BUS1B BKR1B     -1.E-3   300.E-3         0                                   0
  BUS1C BKR1C     -1.E-3   300.E-3         0                                   0
```

```
  BUS12A        30.E-3     9999.        0                                   1
  BUS12B         9999.     9999.        0                                   1
  BUS12C         9999.     9999.        0                                   1
BLANK card terminates switch data
C
C ................................Source data................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA     187.79E3        60.        0.        0.                -1.     9999.
14THEVB     187.79E3        60.`    -120.        0.                -1.     9999.
14THEVC     187.79E3        60.      120.        0.                -1.     9999.
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN3A     11267.65        60.    -28.00
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<-------><----Angle
  GEN3B
  GEN3C
C Machine parameter cards (Optional)
C -------------------><-----FM
PARAMETER FITTING             1.
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1    2         1.         1.       200.       13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C ------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Manufacturer supplied p.u. data (if PARAMETER FITTING is used)
C When transient data not available for Q axis, make: X'q=Xq, T'q0=0
C This will eliminate the G winding from the S.M. model
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
  0.001096      0.15      1.70      1.64   .238324      1.64   .184690   .185151
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
  6.194876        0.  0.028716  0.074960      1.40
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HICO<------DSR<------DSM<-------HSP<------DSD
 1                1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10         1     2     3     4    11
  21
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C TACS input cards
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><----><KI
  FINISH
BLANK card terminates source data
C
C ..............................  Output requests  ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN3A GEN3B GEN3C BUS1A BUS1B BUS1C BUS12ABUS12BBUS12C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

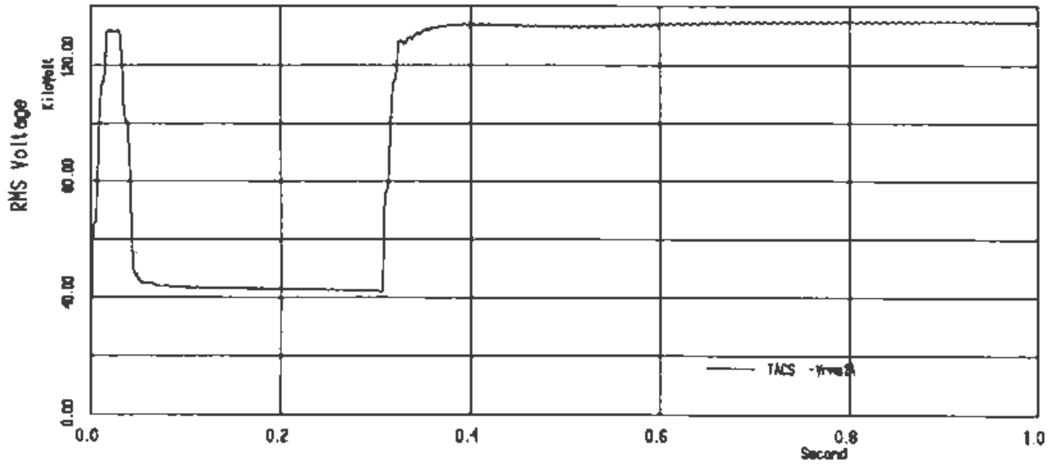
(a) Input data. The fault is a single line to ground fault.



(b) Generator phase angle (δ). This case is stable.



(c) Change in generator speed (Δω).



(d) RMS voltage at bus 1.

Figure 7-4-4: Transient stability study for an single-line-to-ground fault.

7.5 References

[1] P. M. Anderson, A. A. Fouad, *Power System Control and Stability*, The Iowa State University Press, 1977.

[2] F. L. Alvarado, C. A. Cañizares, "Synchronous Machine Parameters from Sudden-Short Test by Back-Solving," Paper 88 SM 605-8, IEEE/PES 1988 Summer Meeting, Portland, Oregon, July 24-29, 1988.

[3] H. A. Peterson, *Transients in Power Systems*, Dover Publications, New York, 1966.

SECTION 8

SYNCHRONOUS MACHINES: REPRESENTING THE CONTROL SYSTEM

8.1 Exciter Control Models Using TACS

Generators have always an automatic way of controlling the voltage at their terminals. Changes in the electric system conditions, such as variations on load or faults that are cleared by tripping lines and/or load, produce a severe change in the machine voltage that can be controlled by changing the field voltage of the generator exciter. This changed is made automatically by a control circuit that measures the terminal voltage and compares it against a preset value, if there is a difference the field voltage is changed to keep the terminal voltage constant.

Typical voltage regulators are the ones defined by the IEEE. The IEEE Automatic Voltage Regulators (AVRs) depicted in figures 8-2-1, 8-2-2, and 8-2-3 were taken from [1].

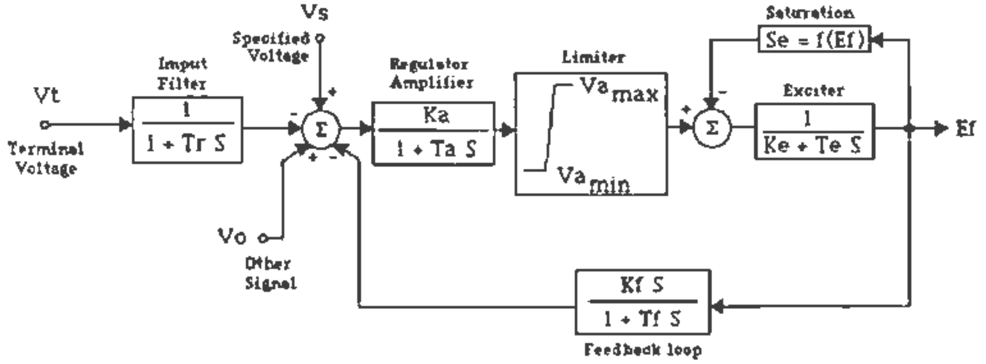


Figure 8-1-1: IEEE AVR type 1.

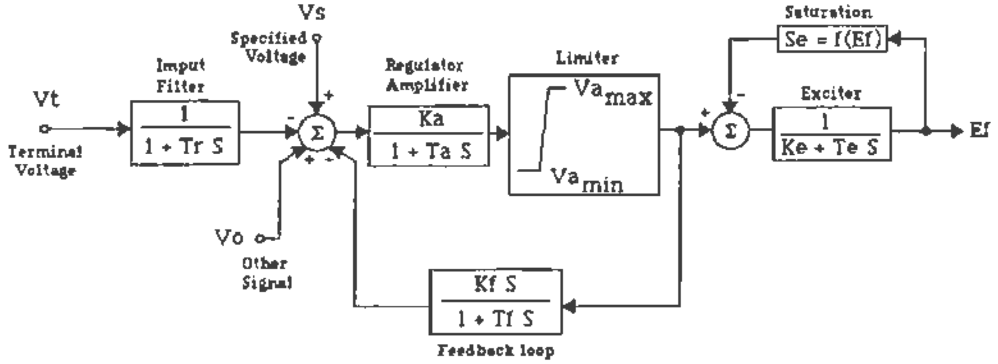


Figure 8-1-2: IEEE AVR type 2.

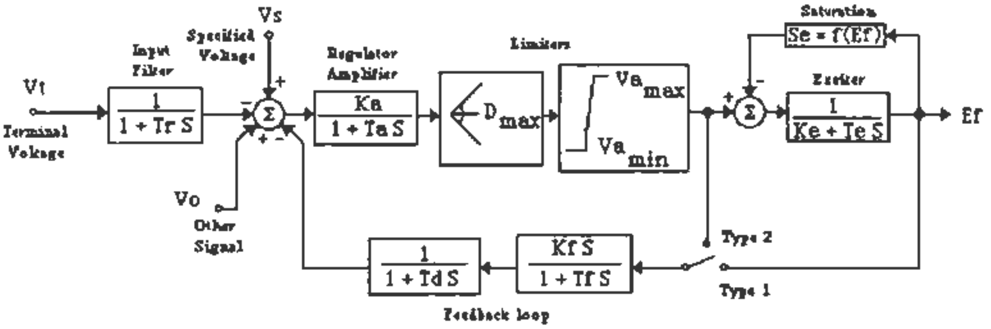


Figure 8-1-3: Composite IEEE AVR with additional limiter and feedback.

Typical values for the gains and time constants for the IEEE type 1 exciter, according to Anderson and Fouad [2], are shown in Table 8-1-1.

Table 8-1-1: Typical Parameters for the IEEE Type 1 Exciter

K_a	25 - 400
T_a	0.02 - 0.05
K_e	-0.17 - 1.0
T_e	0.015 - 0.95
K_f	0.03 - 0.04
T_f	0.5 - 1.0
T_r	0 - 0.06
Va_{min}	-3.5 - -7.3
Va_{max}	3.5 - 7.3

As a general rule the bigger the amplifier gain (K_a) and the smaller the time constants, the faster the AVR. One has to be careful on picking the values of these constants, because if the AVR is too slow or too fast the system can become unstable. There are several control techniques that allow us to chose these parameters so the system is stable, but they are out of the scope of this book.

8.2 Governor Control Models

Another control device of the generator is the governor. This element regulates the input power to the generator by controlling the valves of the turbine, trying to maintain a constant speed in the shaft. Because it is a mechanical control, and because of the large inertia of the machine, its response is very slow compared to the AVR. As we already mention in the previous section, this device would start to affect the behavior of the generator after one or two seconds, depending on the type of generator.

The IEEE Thermal and Hydro governors with valve are illustrated in Figures 8-2-1 and 8-2-2 [1].

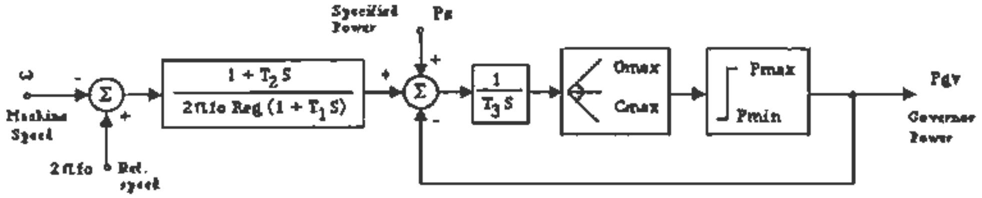


Figure 8-2-1: IEEE thermal governor and valve.

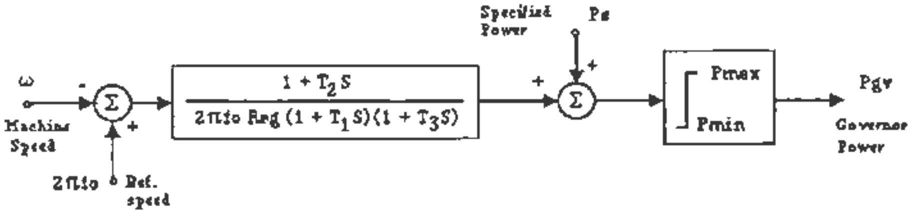


Figure 8-2-2: IEEE hydro governor and valve

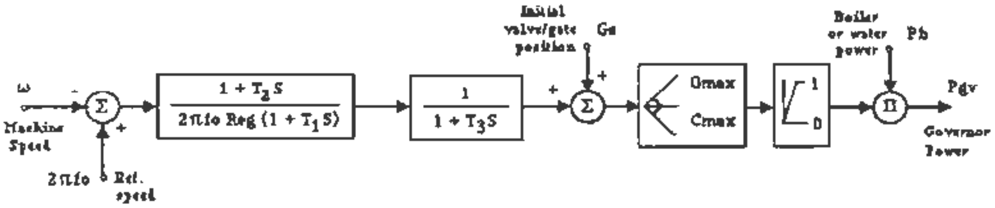


Figure 8-2-3: Generalized model of a speed governor and valve.

For hydro units the time constants of the governor are rather large (several seconds), while for thermal units these time constants are small (0.1 to 0.5 seconds).

The turbines, hydro and thermal, can be represented, according to Arrillaga [1], by the simple models shown on figures 8-2-4 and 8-2-5. These representations are valid for studies with time spans of 1 or 2 seconds, typical in transient stability studies. During these analyses just the High Pressure (HP) turbine has any important effect on the response of the system due to its relative small time constants. The Intermediate Pressure (IP) and Low Pressure (LP) turbines have large time constants that make them of little interest for these kind of studies.

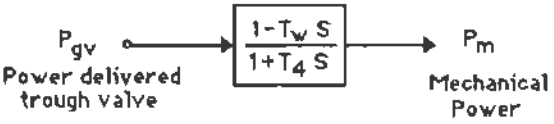


Figure 8-2-4: Model for a HP hydro turbine.

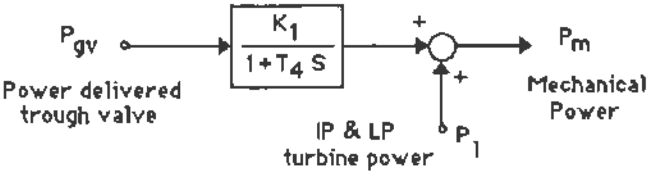


Figure 8-2-5: Model for a HP thermal turbine.

Typical values for the governor-turbine models are shown in the tables below. The values where extracted from Anderson and Fouad [2].

Table 8-2-1: Typical Parameters for Governer Control in Hydro Turbines

Reg (pu)	0.03 - 0.056 (0.05)
P_{max} (MW)	MVA-3 - MVA+46
P_{min} (MW)	0
T_1 (s)	0 - 124.47 (34.69)
T_2 (s)	0 - 8.590 (3.872)
T_3 (s)	0 - 0.92 (0.495)
T_4 (s)	0.3 - 1.545 (0.645)
T_w (s)	$2T_4$

Table 8-2-2: Typical Parameters for Grovernor Control in Thermal (Fossil Steam) Turbines

Reg (pu)	0.05 - 0.078 (0.05)
P_{max} (MW)	MVA-91 - MVA+17.7
P_{min} (MW)	0
T_1 (s)	0.08 - 0.22 (0.134)
T_2 (s)	0 - 0.03 (0)
T_3 (s)	0.04 - 0.4 (0.231)
T_4 (s)	0 - 0.3 (0.135)
K_1 (pu)	1

On these tables the maximum power that the turbine can deliver (MW) is determined based on the rated MVA of the generator.

8.3 Studies with Voltage and Speed Regulation

The case that we are going to analyze corresponds to the same generator as in the previous chapter. In this example we are interested in study the effect of a large change in resistive load on the terminal voltage. The load will change from open circuit to 1 p.u. We use a IEEE type 1 AVR of fast response in order to be able to see, in a relative short period of time, its effect on the terminal voltage. The constants chosen for the AVR are:

$K_a = 400$ $T_a = 0.02$
$K_e = 1.0$ $T_e = 0.015$
$K_f = 0.03$ $T_f = 0.5$ $T_r = 0.03$

The terminal voltage is usually measured by transforming the AC signal into DC using the rectifier bridge shown in Figure 8-3-1. The ideal bridge can he easily simulated by the following equation:

$$V_{dc_{pu}} = (|V_a| + |V_b| + |V_c|)\,\frac{\pi/6}{\sqrt{2/3}\;V_{ll_{RMS}}}$$

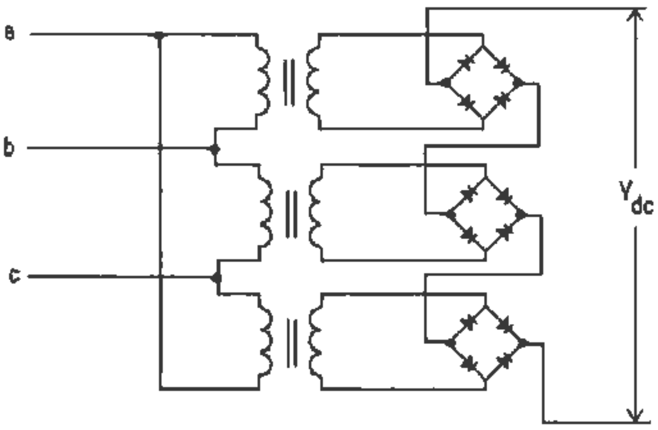


Figure 8-3-1: Measurement of the terminal voltage by a three phase AC-DC rectifier bridge.

These equations allow us to represent the AC-DC conversion with TACS. The complete, non ideal, rectifier bridge can be modelled with diodes in the EMTP, but this kind of analysis is not worth it from the point of view of the power system.

Each one of the blocks of the control circuit were represent by a TACS S_Block, and initial conditions where given to avoid difficulties with the initiation of the system, which is a problem to be considered due to the fast response of the exciter. Neither limits nor saturation were included in the simulation.

To avoid instabilities due to the change in speed, which is always controlled by the governor, the inertia of the generator was assumed infinite (in the EMTP this is simulated by a assigning a large number to the machine inertia, but this could produce wrong results if the value is too large).

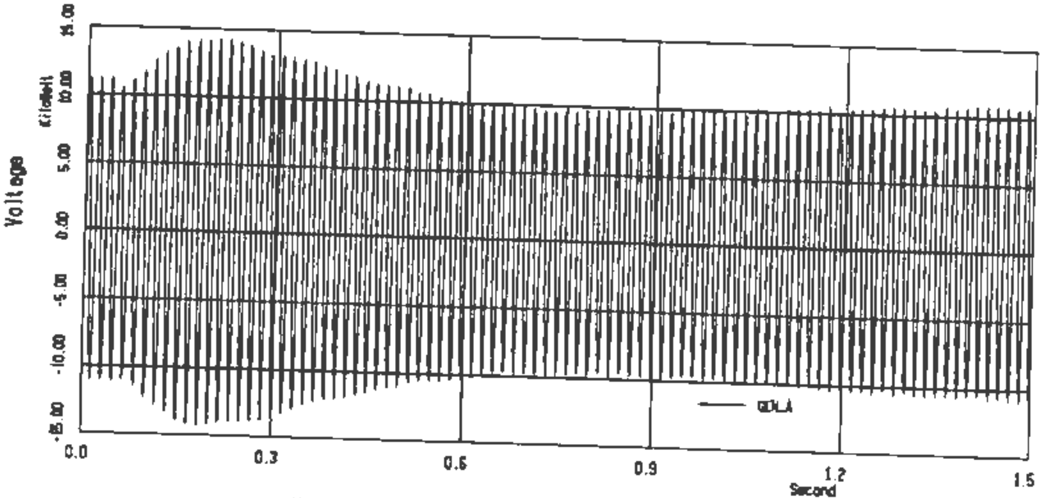
Another classical example of the use of voltage (AVR) and speed (governor) controllers in synchronous machines is the typical Transient Stability Analysis. In this case detailed models of an AVR and a hydro governor-turbine have been added to the unstable power system analyzed in the previous section. It is clear from the resulting plots that the system has become stable due to the presence of the voltage and speed regulators.

For this specific problem the EMTP does not present much advantage over a typical Transient Stability program, but one has to be clear that this is just a small example of the kind of analysis that the EMTP allows us to do. For instance, this example could be easily changed to make stability analysis with unbalaced faults, an impossible task for a traditional stability program.

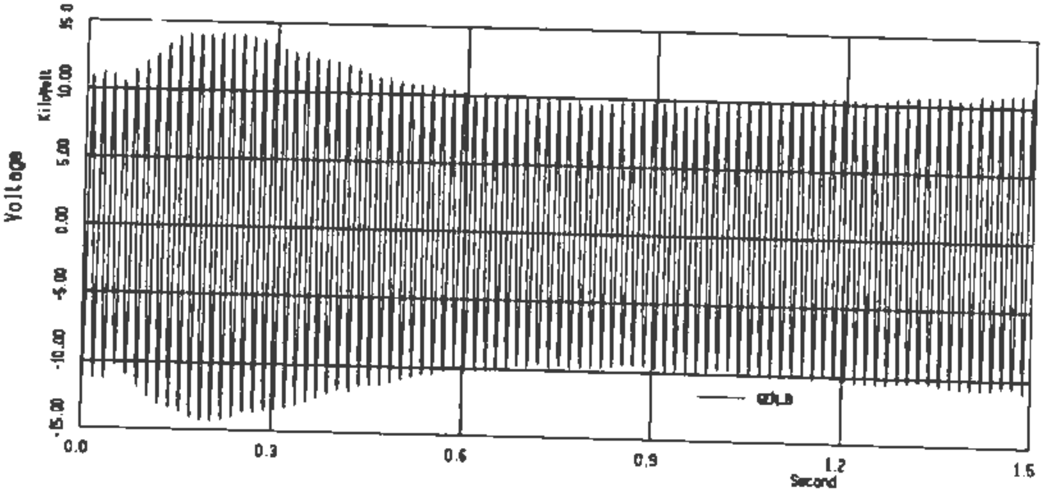
```
C Simulation of the complete loading of a Synchronous Machine with the complete
C representation of an IEEE AVR type 1.
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 300.E-6      2.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      51       1                                               1
TACS HYBRID
C Z_block
  Vr      +V2                                          1.
  Vf      +dVf    +UNITY                               1.
C S_block
 1V2      -V1     +UNITY  -V3                        400.
        1.
        1.       .02
 1V1      +Vdc                                         1.
 .52359878
        1.       .03
 1dVf     +Vr                                          1.
        1.
        1.      .015
 1V3      +dVf                                         1.
        0.       .03
        1.        .5
C Node_V
90LOAD_A                   60.
90LOAD_B                   60.
90LOAD_C                   60.
C RMS_Value
88Vt_A  66+LOAD_A                                     60.
C Simulation of an ideal three-phase Transformer-Rectifier arrange
88Vdc     =(ABS(LOAD_A)+ABS(LOAD_B)+ABS(LOAD_C))*SQRT(3/2)/13800
C TACS_output
33Vt_A  V1    V2    V3    Vr    Vf    Vdc
C TACS_IC
77Vdc       1.732051
77LOAD_A          0.
77LOAD_B   -9758.074
77LOAD_C    9758.074
77Vf              1.
77dVf             0.
77V2              0.
77Vr              0.
77V1              1
77V3              0
BLANK card terminates TACS data
C
C ...........................  Circuit data  ..................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                   0
  LOAD_A                  10000.
  LOAD_B                  10000.
  LOAD_C                  10000.
  BUS3A                    .9522
  BUS3B                    .9522
  BUS3C                    .9522
BLANK card terminates circuit data
C
C ...........................  Switch data  ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  GEN_A LOAD_A       -1.     9999.                                             1
  GEN_B LOAD_B       -1.     9999.                                             1
  GEN_C LOAD_C       -1.     9999.                                             1
  LOAD_ABUS3A      .5E-1     9999.                                             0
```

```
  LOAD_BBUS3B      .5E-1     9999.                                              0
  LOAD_CBUS3C      .5E-1     9999.                                              0
BLANK card terminates switch data
C
C ...........................  Source data  ...................................
C Dynamic synchronous machine
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN_A     11267.65        60.      -90
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN_B
  GEN_C
C Machine parameter cards (Optional)
C --------------------><-----FM
C PARAMETER FITTING           1.
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      200.      13.8  935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc.
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Machine parameters (no PARAMETER FITTING)  ***Diagonal elements cannot be zero
C -----Xf*<------Xaf<-----Xfkd<------Xd*<-----Xakd<-----Xkd*<------ Xl
      1.65      1.55      1.55      1.70      1.55     1.605       .15
C -----Xg*<------Xag<-----Xgkq<------Xq*<-----Xakq<-----Xkq*
   .000001                          1.64      1.49     1.526
C ------Xo<-------Ra<-------Rf<------Rkd<-------Rg<------Rkq<-------Rn<-------Xn
       1.4  0.001096  0.000742    0.0131               0.0540
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HICO<------DSR<------DSM<------HSP<------DSD
 1                1.     9999.
C col: (1-2) ML
BLANK card terminates mass data
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10          1     2     3     4    11
  21
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C TACS input cards
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><----><KI
71Vf
  FINISH
BLANK card terminates source data
C
C ..............................  Output requests  ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  GEN_A GEN_B GEN_C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

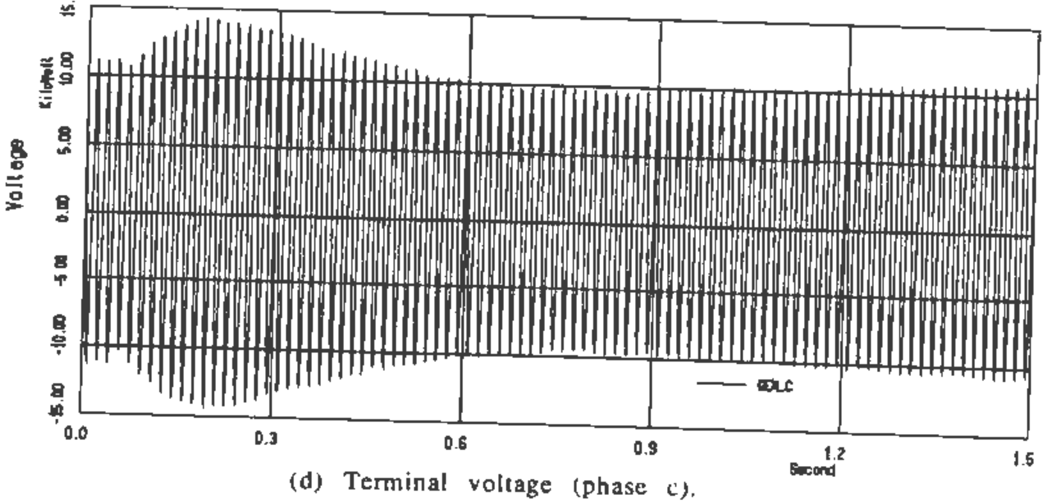
(a) Input data.



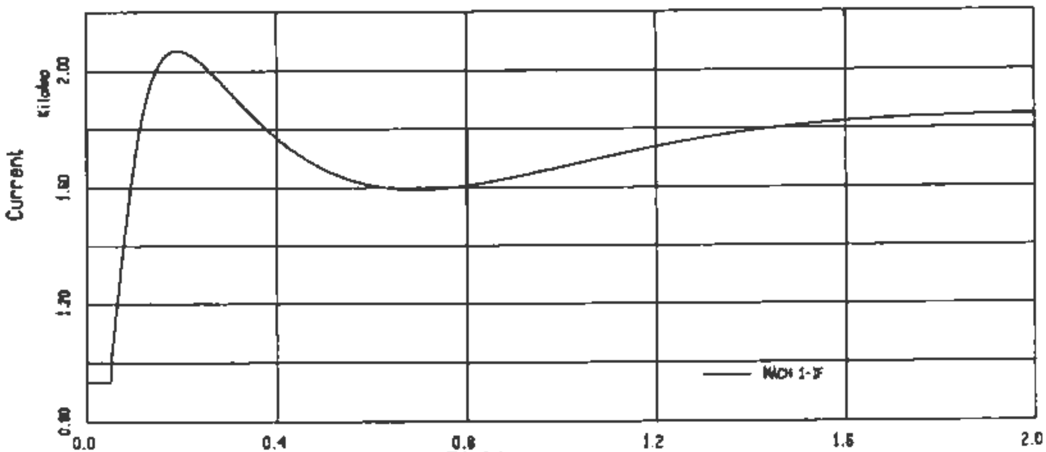
(b) Terminal voltage (phase a).



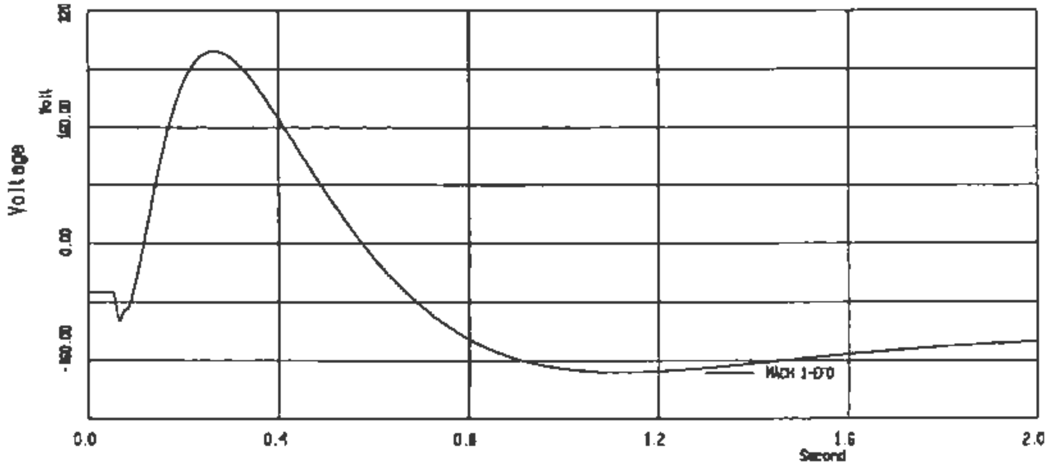
(c) Terminal voltage (phase b).



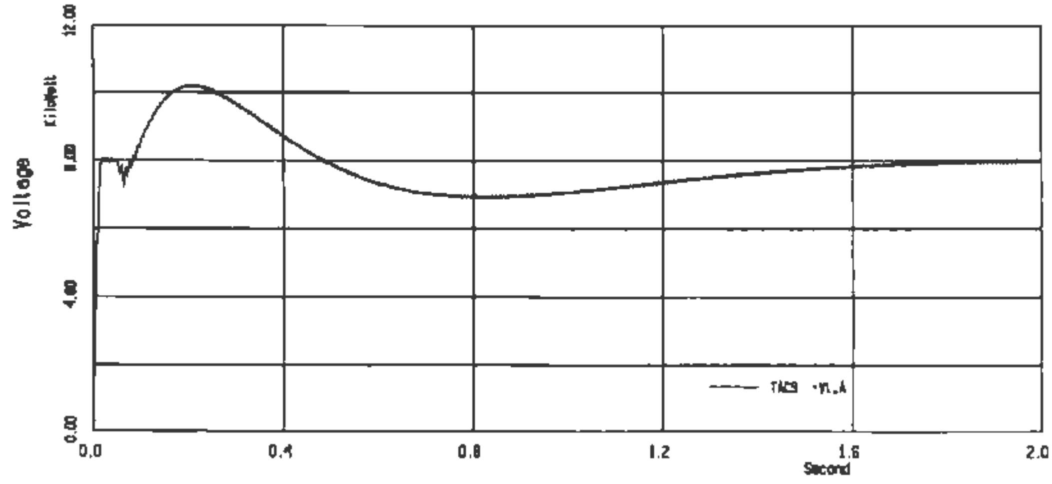
(d) Terminal voltage (phase c).



(e) Field current.



(f) Field voltage.



(g) RMS terminal voltage (phase a).

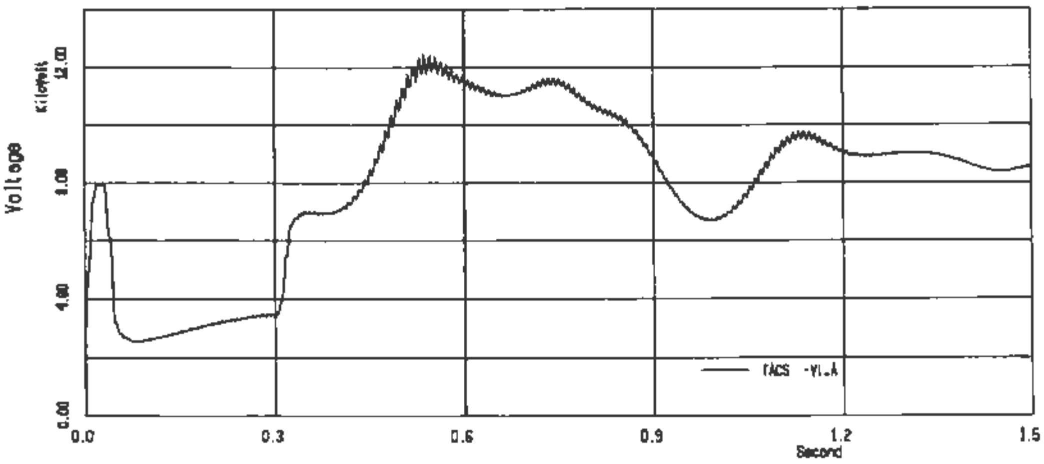
Figure 8-3-2: Fast voltage regulation of generator at bus 3. Sudden change in load from open circuit to 1 p.u.

```
C Transient Stability analysis of the unstable reduced Power System, including
C an IEEE AVR type 1 and a hydro governor-turbine mechanical speed control.
C The system is rendered stable due to the voltage and speed controllers.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
 200.E-6     1.5
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     121       1               1                                1
TACS HYBRID
C Z_block
  Vr      +V2                                          1.
  Vf      +dVf    +UNITY                               1.
  Pgv     +UNITY  +dPs                                 1.    0.1.0324
C S_block
 1V2      -V1     +UNITY  -V3                        400.
        1.
        1.        .02
 1V1      +Vdc                                         1.
 .52359878
        1.        .03
 1dVf     +Vr                                          1.
        1.
        1.       .015
 1V3      +dVf                                         1.
        0.        .03
        1.         .5
 1P1      -w      +wref                            .05305
        1.      3.872
        1.      34.69
 1dPs     +P1                                          1.
        1.
        1.      0.495
 1Pm      +Pgv                                         1.
        1.      -1.29
        1.      0.645
C Node_V
90GEN3A                    60.
90GEN3B                    60.
90GEN3C                    60.
C EMTP machine variables
92w
C RMS_Value
88Vt_A  66+GEN3A                                       60.
C S_Function
88Vdc       =(ABS(GEN3A)+ABS(GEN3B)+ABS(GEN3C))*SQRT(3/2)/13800
88wref      =2*PI*60
C TACS_output
33Vt_A  V1    Vf    w     P1    dPs   Pgv   Pm
C TACS_IC
77Vdc        1.732051
77GEN3A      9948.747
77GEN3B     -9555.512
77GEN3C      -393.235
77Vf               1.
77dVf              0.
77V2               0.
77Vr               0.
77V1               1.
77V3               0.
77Pm               1.
77Pgv              1.
77dPs              0.
77w         376.99112
```

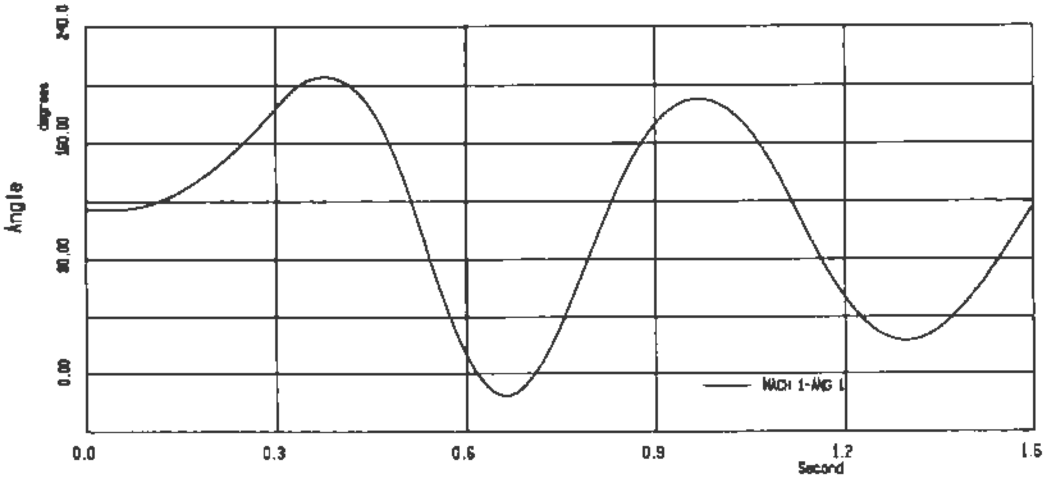
```
77wref     376.99112
77P1              0.
BLANK card terminates TACS data
C
C ...............................Circuit data...................................
C Bus-->Bus--><----------><----R<----------l<----R<----------L<----R<----------L
51THEVA BUS7A                .13       23.71                                   0
52THEVB BUS7B                .06       39.99                                   0
53THEVC BUS7C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----l<--- C<----R<----L<--- C<----R<----L<--- C
 1BKR1A BUS12A            2.914240.834.26247
 2BKR1B BUS12B            2.370719.587-.06032.993440.714.27339
 3BKR1C BUS12C            2.317816.307-.01532.370719.587-.06032.914240.834.26247
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<-----Blank----------->0
-1BUS7A BUS1A             0.3167 3.222.00787 144.4 0 0 0                       0
-2BUS7B BUS1B             0.0243 .9238 .0126 144.4 0 0 0                       0
-3BUS7C BUS1C                                                                  0
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   0
  BUS12ABUS13A                   70.16                                         0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                  221.41 38.26                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
C Saturable transformer components.
C ----------><-Bus3<----><-----I<--Phi<BusSt<-Rmag<--------------------------->0
  TRANSFORMER                         DELTAB                                   0
C -------current<-----------flux
           9999
C <-Bus1<-Bus2<----------><----Rk<---Lk<---Nk<-------------------------------->0
 1GEN3A GEN3B                    .1263  13.8                                   0
 2BUS1A                          35.08132.79
C Note.- These leakage values were calculated assuming a 10% p.u. reactance at
C        200 MVA for the transformer, divided in half between the two windings.
C
C <----------><-Bus3<-----------------><BusSt
  TRANSFORMER DELTAB                  DELTBC
C <-Bus1<-Bus2
 1GEN3B GEN3C
 2BUS1B
  TRANSFORMER DELTAB                  DELTCA
 1GEN3C GEN3A
 2BUS1C
BLANK card terminates circuit data
C
C .............................Switch data......................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS1A BKR1A    -1.E-3   300.E-3         0                                    1
  BUS1B BKR1B    -1.E-3   300.E-3         0                                    1
  BUS1C BKR1C    -1.E-3   300.E-3         0                                    1
  BUS12A         30.E-3     9999.         0                                    1
  BUS12B         30.E-3     9999.         0                                    1
  BUS12C         30.E-3     9999.         0                                    1
BLANK card terminates switch data
C
C ..................................Source data.................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA     187.79E3       60.        0.        0.                 -1.     9999.
14THEVB     187.79E3       60.     -120.        0.                 -1.     9999.
14THEVC     187.79E3       60.      120.        0.                 -1.     9999.
C Dynamic synchronous machine.
C Terminal connection for phase "a"
C Bus-->  <-----Volt<-----Freq<----Angle
59GEN3A     11267.65       60.       -28
```

```
C Connection for phase "b" and "c".  Column 1-2 should be left blank
C Bus-->  <-----Volt<--------><----Angle
  GEN3B
  GEN3C
C Machine parameter cards (Optional)
C --------------------><-----FM
C
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      200.      13.8   935.016     1000.     1440.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C Note: AGLine is used to get the real magnitude in AMP of the Field Current
C       In principle any value can be used here
C
C ------><-------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C
C Machine parameters (no PARAMETER FITTING)  ***Diagonal elements cannot be zero
C -----Xf*<------Xaf<-----Xfkd<------Xd*<-----Xakd<-----Xkd*<------ Xl
      1.65      1.55      1.55      1.70      1.55     1.605       .15
C -----Xg*<------Xag<-----Xgkq<------Xq*<-----Xakq<-----Xkq*
   .000001                              1.64      1.49     1.526
C ------Xo<-------Ra<-------Rf<------Rkd<-------Rg<------Rkq<-------Rn<-------Xn
       1.4  0.001096  0.000742    0.0131              0.0540
C
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                 1.   .181128
C col: (1-2) ML
BLANK card terminates mass data
C
C Output requests
C GA<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  10         1     2     3     4    11
  21
  31
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C
C TACS input cards
C
C Exciter (EMTP assumes that the exciter is regulating to 1p.u. => Vf-TACS = 1)
C Bus--><----><KI
71Vf
72Pm            1
74w             2
  FINISH
BLANK card terminates source data
C
C ............................... Output requests ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS1A BUS12A
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

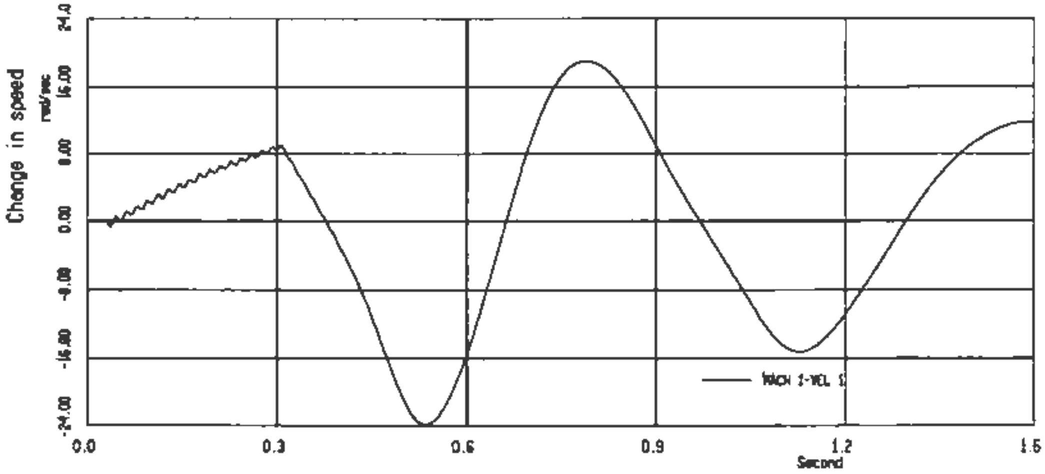
(a) Input data.



(b) RMS terminal voltage (phase *a*).



(c) S.M. phase angle (δ).



(d) S.M. speed change (Δω).

Figure 8-3-3: Transient stability study for the power system of Figure 7-4-1. An AVR and a hydro turbine-governor have been added to the system.

8.4 References

[1] J. Arrillaga, C. P. Arnold, B. J. Harker, *Computer Modelling of Electrical Power Systems*, John Wiley & Sons, 1983.

[2] P. M. Anderson, A. A. Fouad, *Power System Control and Stability*, The Iowa State University Press, 1977.

SECTION 9

SUBSYNCHRONOUS RESONANCE

9.1 Describing the Phenomena

Any Power System having compensated transmission lines with series capacitors, has natural frequencies of oscillation below the synchronous frequency of the system (50 or 60 Hz). Generators connected to the network are made up of several mechanical masses, i.e. the generator itself, the exciter, and the different parts of the prime mover, having also modes of oscillation at subsynchronous resonant frequencies, due to the elasticity of the shafts connecting them. When these frequencies of the electric and mechanical system are close to each other, a disturbance, such as a fault in the network, can create unstable conditions of operation that will increase the torques on the shafts and, if no corrective action is taken, these oscillations can destroy the generator. This phenomenon is known in the technical literature as SubSynchronous Resonance (SSR).

In order to analyze the SSR effects in the system, a detailed model of the mechanical system has to be introduced into the system equations. This model has to consider all the masses that conform the mechanical part of the generator, and also the elasticity of the shafts. A brief description of the equations for the mechanical system can be found in section 6.2. The equations for a general system of *n* spring-connected rotating masses has the following matrix form:

$$[J]\ \frac{d}{dt}[\omega]\ +\ [D]\ [\omega]\ +\ [K]\ [\theta]\ =\ [T_{turbine}]\ -\ [T_{gen/exc}]$$

$$\frac{d}{dt}[\theta]\ =\ [\omega]$$

Where the vectors $[\theta]$ and $[\omega]$ are the angles and speeds of each one of the masses that conform the mechanical system. The vector $[T_{turbine}]$ stands for the torques applied to the turbines. Torques are directly related to powers ($P_{turbine} = \omega\ T_{turbine}$) delivered to each one of the turbines of the prime mover. The vector of electromagnetic torques $[T_{gen/exc}]$, and the rotor position of the generator link the mechanical and electric systems:

$$\theta_{gen}\ \frac{p}{2} = \beta_{elec}$$

$$T_{gen} = \frac{p}{2}\ (\lambda_d\ i_q\ -\ \lambda_q\ i_d)$$

$$T_{exc} = \frac{-v_f\ i_f\ +\ i_f^2\ R_{exc}}{\omega_{mech}}$$

The matrices appearing in the differential equation of the mechanical system, can be easily explained based on the system shown in Figure 9-1-1.

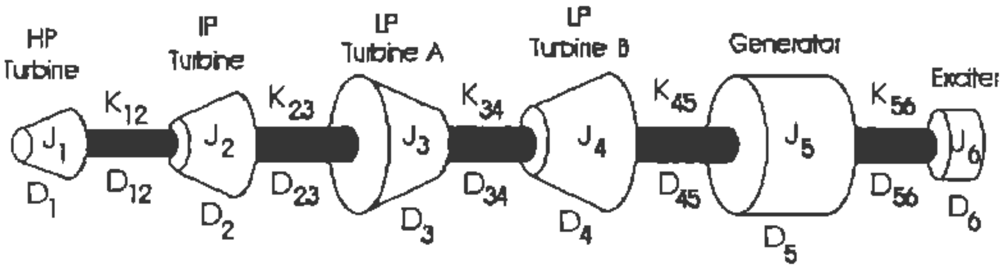


Figure 9-1-1: Prime mover (High Pressure, Low Pressure, and Intermediate Pressure turbines), exciter and generator for a typical turbine-generator unit.

The inertia for each one of the masses of the system form the diagonal of the inertia matrix $[J]$:

$$[J] = \begin{bmatrix} J_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & J_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & J_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & J_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & J_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & J_6 \end{bmatrix}$$

The damping matrix $[D]$ has a tridiagonal form, because each one of the masses has a self damping (D_i), and each shaft connecting these masses has also a damping term (D_{ij}). The matrix is:

$$[D] = \begin{bmatrix} D_1+D_{12} & -D_{12} & 0 & 0 & 0 & 0 \\ -D_{12} & D_{12}+D_2+D_{23} & -D_{23} & 0 & 0 & 0 \\ 0 & -D_{23} & D_{23}+D_3+D_{34} & -D_{34} & 0 & 0 \\ 0 & 0 & -D_{34} & D_{34}+D_4+D_{45} & -D_{45} & 0 \\ 0 & 0 & 0 & -D_{45} & D_{45}+D_5+D_{56} & -D_{56} \\ 0 & 0 & 0 & 0 & -D_{56} & D_{56}+D_6 \end{bmatrix}$$

The elasticity matrix $[K]$ has a tridiagonal form too. The terms off the diagonal represent the elasticity constant of each shaft connecting masses *i* and *j* (K_{ij}), and the diagonal terms are just the two elasticity constants of the shafts connected at the corresponding masses. The matrix is:

$$[K] = \begin{bmatrix} K_{12} & -K_{12} & 0 & 0 & 0 & 0 \\ -K_{12} & K_{12}+K_{23} & -K_{23} & 0 & 0 & 0 \\ 0 & -K_{23} & K_{23}+K_{34} & -K_{34} & 0 & 0 \\ 0 & 0 & -K_{34} & K_{34}+K_{45} & -K_{45} & 0 \\ 0 & 0 & 0 & -K_{45} & K_{45}+K_{56} & -K_{56} \\ 0 & 0 & 0 & 0 & -K_{56} & K_{56} \end{bmatrix}$$

The eigenvalues of the matrix differential equation determine the subsynchronous resonant frequencies of the mechanical system alone. These eigenvalues are always stable (in the left hand plane). However, they are quite close to the imaginary axis because damping is usually quite low. When the machine is connected to the network, the eigenvalues for the connected system are not exactly the same as those of the stand-alone shaft system. Its eigenvalues for incremental operation can become unstable. This instability can be physically explained by considering the induction motor operation of the generator whenever its frequency deviates from the synchronous frequency: at the machine accelerates, under certain conditions of the ac system, the effect on the generator can be a net accelerating force. And as it decelerates, a net additional decelerating force may develop. The mathematical models used within the

EMTP are, without any modification, capable of capturing this effect in time domain simulations.

9.2 Systems with Possible SSR

The most SSR-prone systems are those where large generators are relatively close to series compensated transmission lines, a usual case in the Western United States. Series capacitors in the network introduce subsynchronous resonant frequencies. These frequencies can interact with those of the turbine-generator unit to produce unusually large torsional torques on the machine shaft that can destroy them. This happened in 1970 and 1971 at the Mohave units.

When the possibility of SSR is suspected because of the configuration of the system, an eigenvalue analysis of the mechanical system is helpful in detecting the mechanical subsynchronous resonant frequencies. A complete set of values for the elasticity constants of the shafts, shaft dimensions and inertia constants of the turbine-generator unit are needed in order to do any kind of analysis. Also desirable but not essential for preliminary studies are measuments or calculations of expected mechanical system modal damping time constants. The presence of mechanical subsynchronous frequencies in itself does not necessarily signal the presence of SSR. To consider the effect of SSR frequencies on the mechanical system one must also include the electric network in the analysis. The EMTP is a very useful tool to perform these studies, as we shall see on the next section.

9.3 A Classic SSR Example

The set of EMTP input cards shown below correspond to a SSR Test Case as set up by Vladimir Brandwajn in August 1982. This is a 6-mass mechanical system analyzed with and without generator saturation. The data comes from a case reported in [1] and shown here in Figure 9-3-1. The SSR event is triggered by a fault simulated by a breaker closing, and the subsequent clearing of the fault by opening the same breaker. This leads to an interaction between the resonant frequencies of the shaft and the subsynchronous resonant frequencies of the electric network, which exist due to the presence of series capacitors.

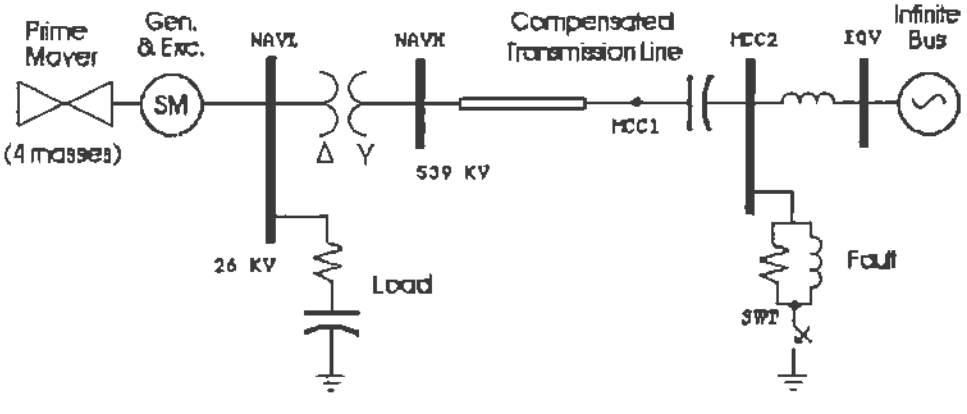
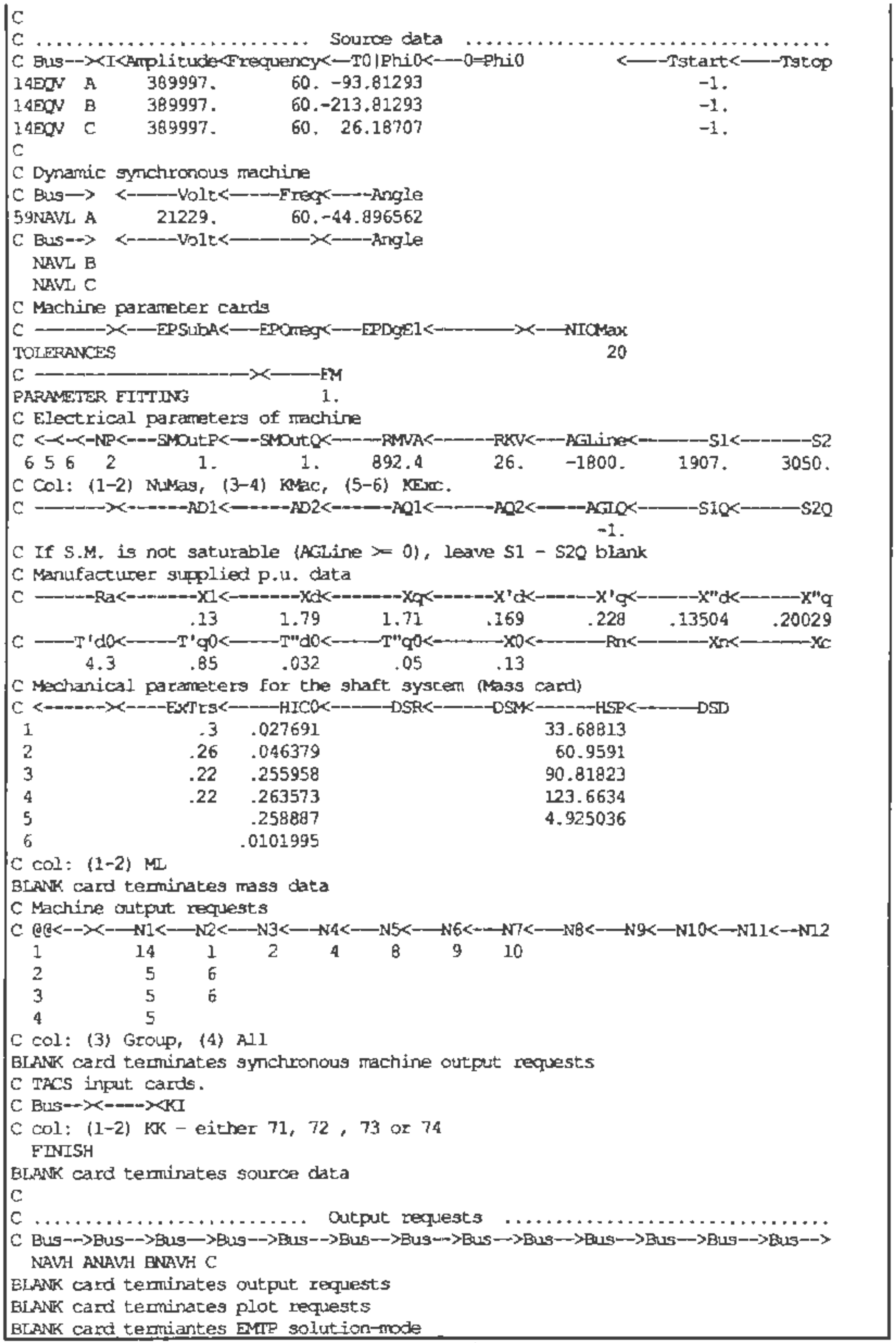


Figure 9-3-1: System studied for SSR extracted from [10] and corresponding to the Navajo Project.

The results obtained for this system are depicted on Figure 9-3-2, that includes saturation effects on the system, and Figure 9-3-3, which is the same case but without saturation. On both cases we can see that the shaft torques, i.e. the difference between the mass torques, widely oscillate due to the SSR between the mechanical system and the electric network. These oscillations are not actually unstable, as their amplitude is ultimately limited. This is because we have not excited a precise resonant frequency, but we are close enough to one of these frequencies to produce large oscillations that eventually will destroy the shafts either of the prime mover or the generator-exciter pair. The same kind of oscillations appear on the mass speeds. Generally, only one of the mechanical modes is excited during SSR. As a result, those specific oscillations associated with the resonant mode are likely to experience large amplitudes. That is to say, large torques will not necessarily develop among every pair of masses. Some portions of the shaft will be subjected to larger proportional stresses than others.

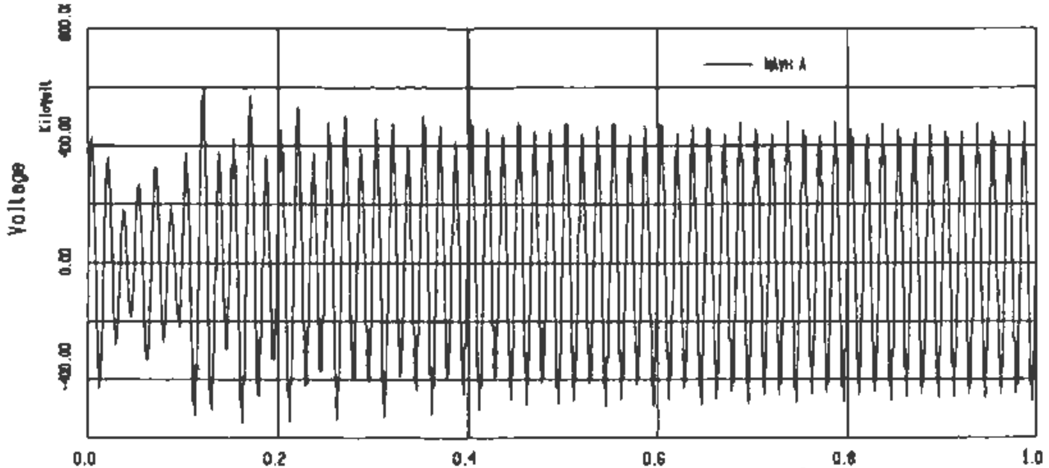
The electric network also experiences large changes on voltages and currents during the SSR oscilations, as do the the field current in the exciter. Saturation tends to increase the field currents for any given level of voltage. As saturation increases, the apparent parameters of the machine are changed. This "detunes" the mechanical and electrical systems, leading to a decrease in the oscillations on the armature currents and shaft torques.

```
C
C Subsynchronous Resonance Benchmark Case
C This is a 6-mass SSR case WITH saturation
C
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  `.0002      1.     60.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
       1       1       1       1       1      -1               1
C --KChg<---Mult<---KChg<---Mult<---KChg<---Mult<---KChg<---Mult<---KChg<---Mult
       5       5      20      20     100     100     500     500    2000    2000
C
C ............................ Circuit data  ...................................
C 3-phase coupled RL branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51NAVH AMCC1 A            162.67      507.51
52NAVH BMCC1 B              6.51      162.97
53NAVH CMCC1 C
C Series RLC branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  MCC1 AMCC2 A                         8285.
  MCC1 BMCC2 B                         8285.
  MCC1 CMCC2 C                         8285.
  MCC2 AEQV  A                   19.52
  MCC2 BEQV  B                   19.52
  MCC2 CEQV  C                   19.52
C Saturable transformer components.
C ----------->Bus3-><----><----I<--PhiBusSt><-Rmag<--------------------------->0
  TRANSFORMER                         TRAN A
C -------current<-----------flux
            9999
C Bus1->Bus2-><----------><---Rk<---Lk<---Nk<--------------------------------->0
 1NAVL ANAVL C                      .1   26.
 2NAVH A                         31.23311.09
C <---------->Bus3-><---------------->BusSt>
  TRANSFORMER TRAN A                  TRAN B
C Bus1->Bus2->
 1NAVL BNAVL A
 2NAVH B
C <---------->Bus3-><---------------->BusSt>
  TRANSFORMER TRAN A                  TRAN C
C Bus1->Bus2->
 1NAVL CNAVL B
 2NAVH C
C Series RLC branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  NAVL A                   2500.        1.13
  NAVL B                   2500.        1.13
  NAVL C                   2500.        1.13
  SWT  AMCC2 A             4830.
  SWT  BMCC2 B             4830.
  SWT  CMCC2 C             4830.
  MCC2 ASWT  A                   13.01
  MCC2 BSWT  B                   13.01
  MCC2 CSWT  C                   13.01
BLANK card terminates circuit data
C
C ............................ Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  SWT  A       .01661667 .09161667
  SWT  B       .01661667 .09161667
  SWT  C       .01661667 .09161667
BLANK card terminates switch data
```

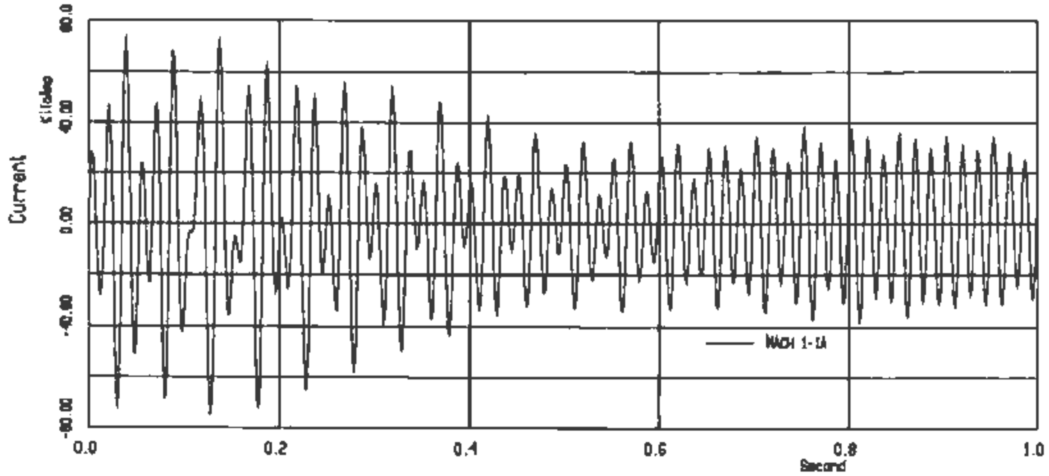


```
C
C ............................ Source data  ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14EQV  A     389997.       60. -93.81293                           -1.
14EQV  B     389997.       60.-213.81293                           -1.
14EQV  C     389997.       60.  26.18707                           -1.
C
C Dynamic synchronous machine
C Bus-->  <-----Volt<-----Freq<----Angle
59NAVL A      21229.       60.-44.896562
C Bus-->  <-----Volt<--------><----Angle
  NAVL B
  NAVL C
C Machine parameter cards
C -------><---EPSubA<---EPOmeg<---EPDgEl<--------><---NIOMax
TOLERANCES                                                20
C ---------------------><-----FM
PARAMETER FITTING             1.
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 6 5 6   2        1.        1.     892.4       26.    -1800.     1907.     3050.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc.
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q
                                                         -1.
C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Manufacturer supplied p.u. data
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
               .13      1.79      1.71      .169      .228    .13504    .20029
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
       4.3       .85      .032       .05       .13
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HIC0<------DSR<------DSM<------HSP<------DSD
 1                .3   .027691                    33.68813
 2               .26   .046379                     60.9591
 3               .22   .255958                    90.81823
 4               .22   .263573                    123.6634
 5                     .258887                    4.925036
 6                    .0101995
C col: (1-2) ML
BLANK card terminates mass data
C Machine output requests
C @@<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  1         14     1     2     4     8     9    10
  2          5     6
  3          5     6
  4          5
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C TACS input cards.
C Bus--><----><KI
C col: (1-2) KK - either 71, 72 , 73 or 74
  FINISH
BLANK card terminates source data
C
C ...........................  Output requests  ................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  NAVH ANAVH BNAVH C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card termiantes EMTP solution-mode
```

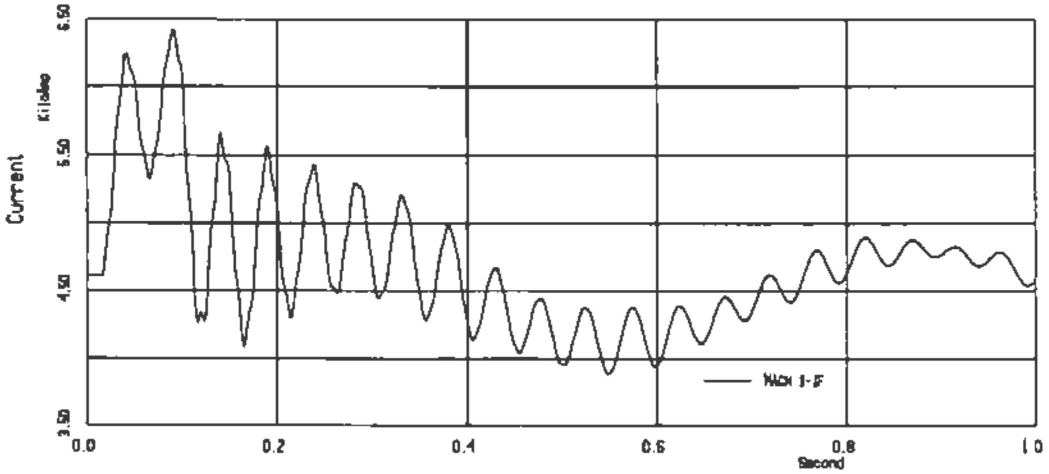
(a) Input data.



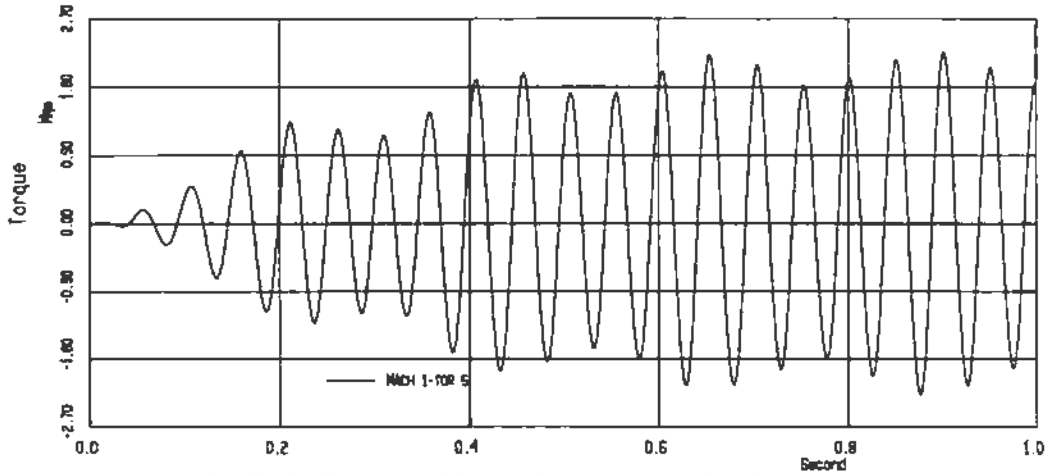
(b) Voltage on phase *a*.



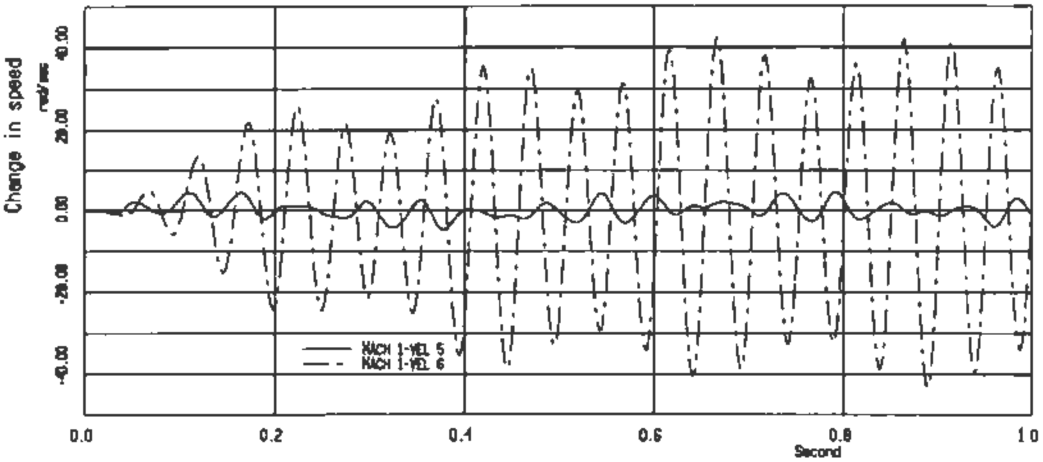
(c) Current on phase *a*.



(d) Field current.



(d) Shaft Torque. Notice large torque develops.



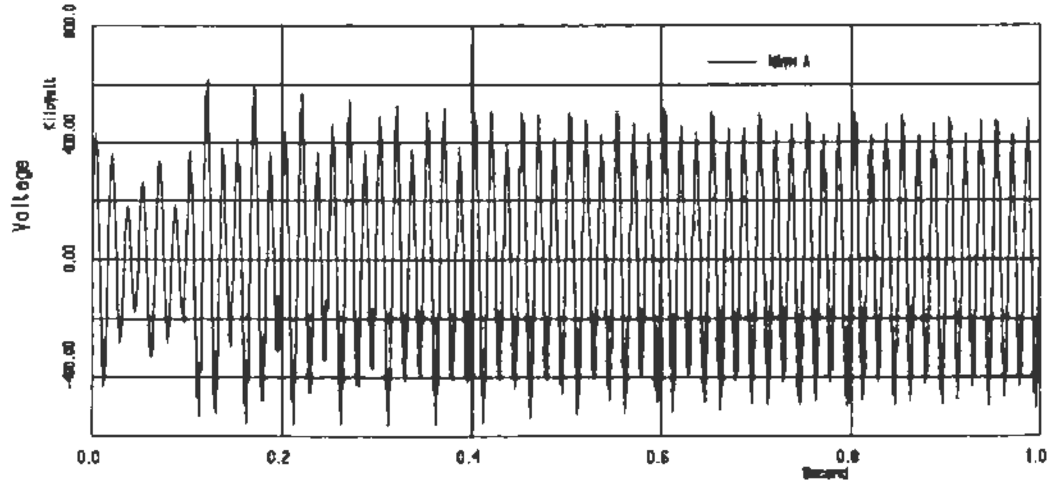
(e) Speed variation at masses 5 and 6.

Figure 9-3-2: SSR study for the benchmark case shown in Figure 9-3-1. Saturation has been considered in this case.

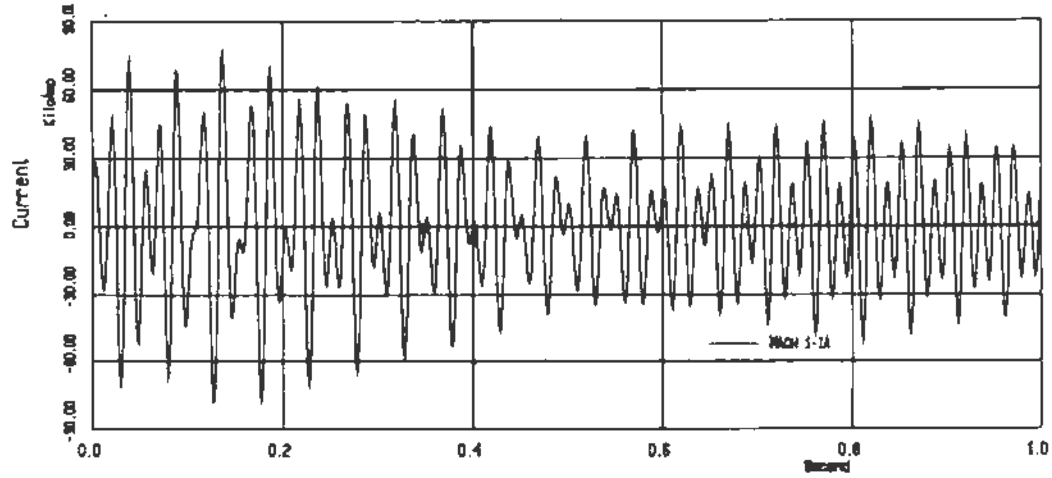
```
C SubSynchronous Resonance Benchmark Model.
C This is a 6-mass SSR case with a synchronous machine WITHOUT saturation
BEGIN NEW DATA CASE
C ..........................  Miscellaneous data ............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   .0002      1.     60.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
       1       1       1       0       1      -1               1
C --KChg<---Mult<---KChg<---Mult<---KChg<---Mult<---KChg<---Mult<---KChg<---Mult
       5       5      20      20     100     100     500     500    2000    2000
C
C ..........................  Circuit data  .................................
C 3-phase coupled RL branch
C Bus1->Bus2->Bus3->Bus4-><----R<---------L
51NAVH AMCC1 A            162.67      507.51
52NAVH BMCC1 B              6.51      162.97
53NAVH CMCC1 C
C Series RLC branch
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  MCC1 AMCC2 A                         8285.
  MCC1 BMCC2 B                         8285.
  MCC1 CMCC2 C                         8285.
  MCC2 AEQV  A                   19.52
  MCC2 BEQV  B                   19.52
  MCC2 CEQV  C                   19.52
C Saturable transformer components
C ---------->Bus3-><----><-----I<--PhiBusSt><-Rmag<---------------------------->O
  TRANSFORMER                         TRAN A
C --------current<-----------flux
            9999
C Bus1->Bus2-><-----------><---Rk<---Lk<---Nk<-------------------------------->O
 1NAVL ANAVL C                      .1   26.
 2NAVH A                         31.23311.09
C <---------->Bus3-><--------------->BusSt>
  TRANSFORMER TRAN A                  TRAN B
C Bus1->Bus2->
 1NAVL BNAVL A
 2NAVH B
C <---------->Bus3-><--------------->BusSt>
  TRANSFORMER TRAN A                  TRAN C
C Bus1->Bus2->
 1NAVL CNAVL B
 2NAVH C
C Series RLC branch
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  NAVL A                   2500.        1.13
  NAVL B                   2500.        1.13
  NAVL C                   2500.        1.13
  SWT  AMCC2 A             4830.
  SWT  BMCC2 B             4830.
  SWT  CMCC2 C             4830.
  MCC2 ASWT  A                   13.01
  MCC2 BSWT  B                   13.01
  MCC2 CSWT  C                   13.01
BLANK card terminates circuit data
C
C ..........................  Switch data  ..................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  SWT  A       .01661667 .09161667
  SWT  B       .01661667 .09161667
  SWT  C       .01661667 .09161667
BLANK card terminates switch data
C
C ..........................  Source data  ..................................
```

```
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14EQV  A   389997.       60. -93.81293                           -1.
14EQV  B   389997.       60.-213.81293                           -1.
14EQV  C   389997.       60.  26.18707                           -1.
C Dynamic synchronous machine
C Bus-->  <-----Volt<-----Freq<----Angle
59NAVL A    21229.       60.-44.896562
C Bus-->  <-----Volt<--------><----Angle
  NAVL B
  NAVL C
C Machine parameter cards
C ---------------------><-----FM
PARAMETER FITTING             1.
C Electrical parameters of machine
C <-<-<-NP<---SMOutP<---SMOutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 6 5 6   2        1.        1.     892.4       26.    +1800.     1907.     3050.
C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q
                                                         +1.
C If S.M. is not saturable (AGLine >= 0), leave S1 - S2Q blank
C Manufacturer supplied p.u. data
C ------Ra<-------Xl<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
                 .13      1.79      1.71      .169      .228    .13504    .20029
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
       4.3       .85      .032       .05       .13
C Mechanical parameters for the shaft system (Mass card)
C <------><----ExTrs<-----HICO<------DSR<------DSM<------HSP<------DSD
 1                .3   .027691                      33.68813
 2               .26   .046379                       60.9591
 3               .22   .255958                      90.81823
 4               .22   .263573                      123.6634
 5                     .258887                      4.925036
 6                    .0101995
C col: (1-2) ML
BLANK card terminates mass data
C Machine output requests
C @@<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12
  1         14     1     2     4     8     9    10
  2          5     6
  3          5     6
  4          5
C col: (3) Group, (4) All
BLANK card terminates synchronous machine output requests
C TACS input cards.
C Bus--><----><KI
C col: (1-2) KK - either 71, 72 , 73 or 74
  FINISH
BLANK card terminates source data
C
C ..............................  Output requests  .............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  NAVH ANAVH BNAVH C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

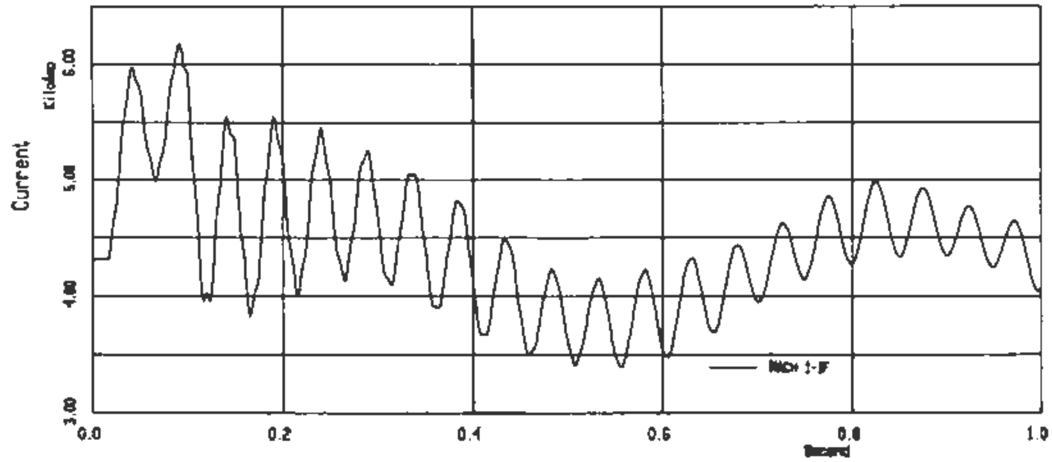
(a) Input data.



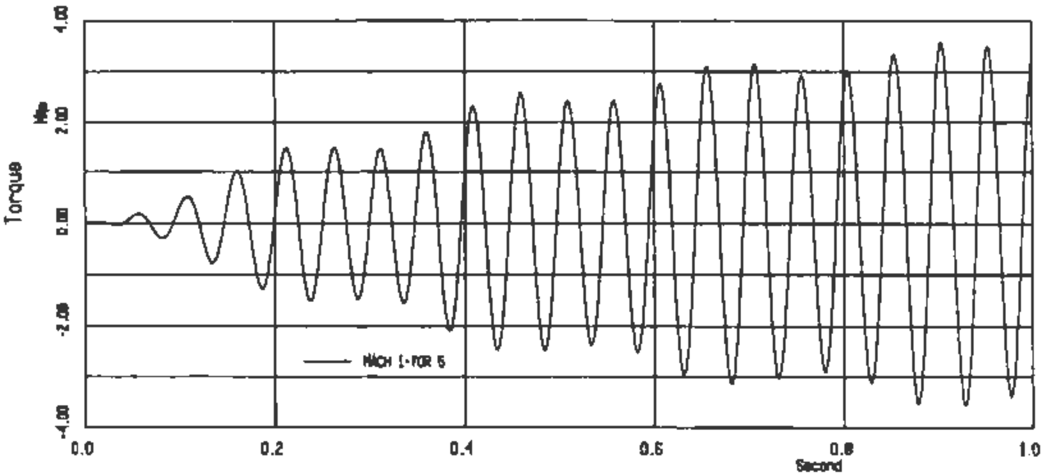
(b) Voltage on phase *a*.



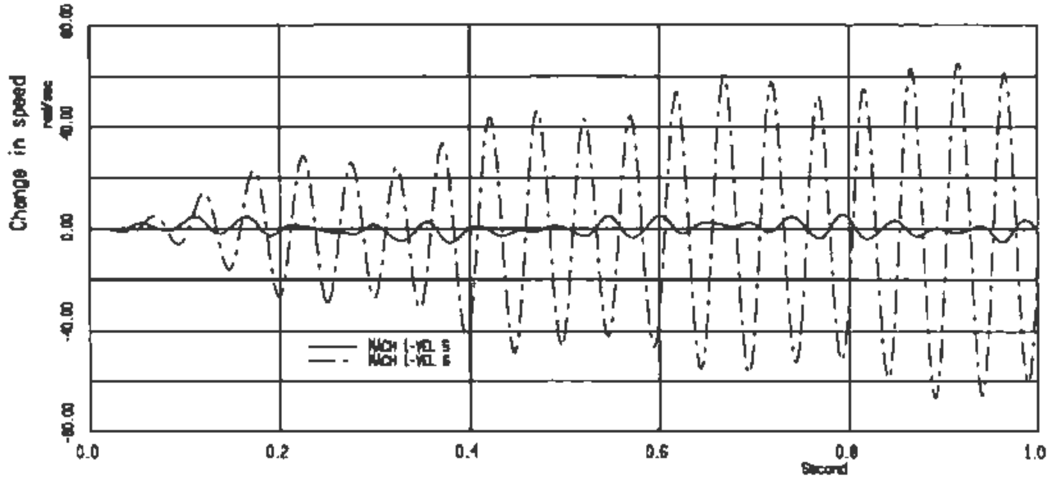
(c) Current on phase *a*.



(d) Field current.



(e) Shaft Torque. Notice that the torque reaches a higher peak than in the "saturation considered" case.



(f) Speed variation at masses 5 and 6.

Figure 9-3-3: SSR study for the benchmark case shown in Figure 9-3-1. Saturation has been ignored in this case.

9.4 SSR Damping Schemes

Several countermeasures have been developed during the years in order to avoid or solve the SSR problem. We discuss briefly some of them.

SSR can be reduced by filtering and damping techniques to detune the electric network from the mechanical system. A short description of some techniques to accomplish detuning follows:

- Static Blocking Filter: A static blocking filter, tuned at subsyn-chronous frequencies, is inserted in series with the generator step-up transformer winding. This isolates the machine from the system at resonant frequencies.

- Line Filter: A reactor is connected in parallel with the series capacitor in the compensated line. The reactor is properly sized so that interacts with the capacitor to block the SSR currents.

- Bypass Damping Filter: This filter, a resistor in series with a parallel connection of a capacitor and an inductor, is added in shunt to the series capacitors in each phase of the transmission line. It is tuned so that the SSR currents in the network do not flow through the series capacitor, i.e. short circuits the capacitor at SSR frequencies.

- Dynamic Filter: Is an active device connected in series with the generator to eliminate the subsynchronous voltage generated by the machine. This isolates the SSR voltages produced in the generator from the electric network.

- Dynamic Stabilizer: A Thyristor Controlled Reactor is connected at the generator terminals with an appropriate firing circuit to detect the mechanical oscillations in the rotor. At SSR frequencies the TCR is activated to detune the generator from the network.

- Excitation System Damper: This device modulates the exciter output when torsional oscillations appear in the rotor.

Another way of preventing SSR is by means of special relays and detecting instruments. The most commonly used are:

- Torsional Motion Relay: This is a relay that disconnects the machine whenever large torsional oscillations are detected on the shafts.

- Armature Current SSR Relay: This relay detects subsynchronous frequencies in the armature current, opening the breakers when such frequencies appear on the terminal current.

- Torsional Monitor: This device monitors vibrations in the machine shafts, without taking any corrective action. It is up to the operator to determine, based on the information given by this instrument, the procedures to be followed to avoid permanent damage to the mechanical system.

SSR can also be avoided by tripping lines with series compensation when a fault, already known to produce subsynchronous resonant frequencies, occurs in the system. This procedure isolates the generator from the series capacitors. Unit tripping is another way of reducing shaft torques. Both techniques imply that the system conditions which produce SSR and the tripping scheme have already been determine from previous studies.

Modifications to the prime mover and/or generator can also reduce, or avoid, the problems induced by SSR. Shafts and masses of the turbine-generator pair can be altered in order to change the resonant frequencies of the system for specific network configurations. This approach has the problem that any future changes to the network could also shift the resonant points. Connecting series reactances at the generator terminals for detuning the resonant frequencies is another way to avoid SSR. Another technique is to introduce pole-face amortisseur windings to reduce the subsynchronous voltages induced in the armature windings of the generator, although this is only suitable for new machines

The interested reader is referred to [2] for more details on these techniques.

9.5 References

[1] IEEE SSR Task Force, Dynamic System Performance Working Group on PSE Committee, "First Benchmark Model for Computer Simulation of Subsynchronous Resonance," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, Sept/Oct 1977, pp. 1565-1572.

[2] IEEE SSR Working Group of the System Dynamic Performance Subcommittee PSE Committee, "Countermeasures to Subsynchronous Resonance Problems," IEEE Symposium on Countermeasures for SSR, 81TH0086-9-PWR, July 30, 1981, pp. 4-12.

SECTION 10

INDUCTION MOTORS AND OTHER MACHINES

The EMTP offers extensive additional machine modelling capabilities. Most of these are contained within the "universal machine" component. The universal machine is quite flexible but not quite as easy to use as the synchronous machine. The universal machine is based on the idea that any machine can be represented by first describing its windings as a set of mutually coupled coils. In this section we illustrate the use of the induction motor model of the EMTP for the purpose of performing a motor starting current calculation. We omit the mathematics of the model and concentrate entirely on the use of the model.

10.1 Induction Motor Modelling

As in the case of the synchronous machine, a frequent problem in representation of machines is the conversion of data from readily available measurements to the values of the internal parameters used by the models. Induction motors in the EMTP can be represented using the universal machine model. The universal machine requires knowledge of a few quantities for proper operation. The model is based on the "two-axis" theory of machines, in which we represent "direct" and "quadrature" axis quantities. In order for the EMTP to operate, it needs to construct its internal mathematical model. This internal model ultimately requires knowledge of the following quantities:

- Armature and rotor resistances for each winding.
- Magnetization reactance of the magnetic circuit for the d and q axis, which are usually the same for a symmetric three-phase induction motor.
- Leakage reactance of each coil in the d-q equivalent circuits. The power side is represented as one coil for each axis, while the excitation side is simulated by as many coils as the user wants to define. Saturation is introduced as part of the leakage reactances. Each coil is assumed linked by the common flux in addition to its own flux.
- Moment of inertia of the motor shaft.
- Any externally applied mechanical torques or load torques.

The universal machine model of the EMTP can represent mechanical characteristics in detail. Mechanical torques can be controlled by means of TACS blocks. The dynamics of the shaft can also be represented, but the user mus create an electric circuit analog of the mechanical shaft system. That is, construct an electric circuit that behaves like the mechanical shaft system.

There are two ways in which we can apply specify these parameters to the EMTP. The first way is to enter their values directly. The second is to enter "nameplate data" for the motor and let the EMTP take care of the internal conversion. We illustrate here both options but note that the second option (entering of nameplate data) is only at the prototype stage and was not tested. Instead, we report on its use by others. Thus, a direct comparison was not possible.

As far as solution techniques, two options exist. The equations for the machine can be fully integrated and solved simultaneously with the network equation using compensation, or they can be solved by a "prediction" technique, where at every time step the network solution uses predicted rather than actual values for the machine variables. The pros and cons of these two alternative ways of incorporating the machine model into the rest of the network are:

- The compensation based approach is likely to be more accurate, particularly when saturation is considered.
- The prediction based approach is likely to be faster.
- The compensation based approach is less likely to result in numerical problems, including possible numerical instabilities.
- The compensation based approach limits the use to a single machine in any portion of the system not separated by at least one time step delay (such as a distributed line). The prediction based approach lets the user specify as many machines as desired in any portion of the system. This is because the EMTP can only deal with a limited number of nonlinearities and time varying elements in any disconnected portion of the system.

Users are free to select among these two approaches to machine internal representation.

10.2 A Motor Starting Study Setup

The example shown in Figures 10-2-2 and 10-2-3 is based on an 11000 HP (8.2 MW) induction motor given in reference [1], with certain assumptions about the mechanical system (not all the mechanical system data was available from the paper). The case to be studied is the cold start-up of a fully loaded induction motor using the universal machine model of the EMTP. The first test uses input given in terms of the machine nameplate data; a processor inside the EMTP transforms these data to a set of resistances and inductances needed by the universal machine. This model could not be tested at this time, but is included here because we expect that it will be operational in the near future. A detailed explanation of the way the transformation from nameplate data to internal data is done can be found in [1]. The nameplate data for this induction motor is:

$P_{rated} = 11,000$ HP
$V_{terminal} = 6.6$ kV

Full Load Specifications
$\eta = 0.985$
$\cos\phi = 0.906$
$S = 0.00622$

Starting Specifications
$I_{start_1} = 8*I_{rated}$ (at V_{rated})
$I_{start_2} = 6.03*I_{rated}$ (at $0.758\ V_{rated}$)
$T_{start} = 1.47*T_{rated}$ (at V_{rated})

$T_{max} = 3.5*T_{rated}$
Design Ratio = 0.55

The mechanical system was simulated based on the assumption that the load can be represented by a mass with damping D_L and inertia J_L, attached to the motor by a stiff shaft ($K = \infty$). On the other hand the machine rotor is simulated by another mass with damping D_M and inertia J_M. This mechanical system can be represented by a electric circuit as shown in Figure 10-2-1. The switch is used to guarantee that the mechanical circuit is energized at the same time as the terminals of the motor.

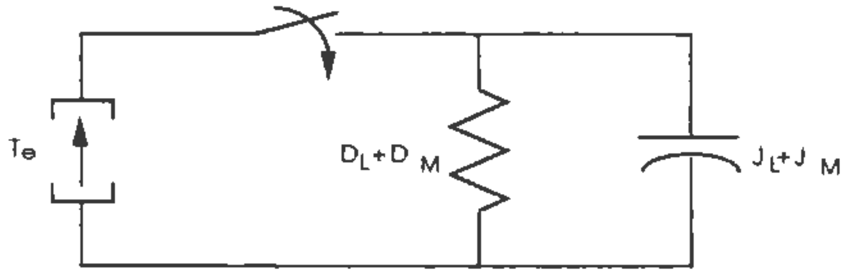


Figure 10-2-1: Modelling of the mechanical system as an electric circuit. The masses representing the load and the rotor can be lumped into one by assuming that the shaft is stiff. The electromagnetic torque T_e is represented as a current source, and the speed of the rotor-load pair is the nodal voltage.

```
C Cold start-up of an Induction Motor using type 40 Induction Machine model.
C The information given to the EMTP is the NEMA standard data printed in the
C machine plate.  This data is transformed by an internal processor to standard
C data needed by the type 19 U.M. model for a 3-phase doubly-fed Induction Motor
C (U.M. type 4).
C
C This example is extracted from:
C    G.J. Rogers and D. Shirmohammadi, "Induction Machine Modelling for
C    Electromagnetic Transient Program," IEEE Trans. on Energy Conversion,
C    Vol. EC-2, No. 4, Dec. 1987.
C
BEGIN NEW DATA CASE
C Universal machine table space allocation
C ------------------->, I, J, K, L
ABSOLUTE U.M. DIMENSIONS, 20, 3, 20, 20
C
C ..........................  Miscellaneous data ............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   2.E-3    14.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      81       1                                               1
C TACS data
TACS HYBRID
C Node_V
90BUSA                     60.
91BKRA                     60.
90IM                        0.
C RMS value
88Vt_A  66+BUSA                                      60.
88It_A  66+BKRA                                      60.
C Slip
88Slip   =1 - IM/(377/2)
C TACS output requests
33Vt_A  It_A  Slip
BLANK card terminates TACS data
C
C ..........................  Circuit data  .................................
C Ideal voltage sources always loaded
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                    0
  SRCA                        1.
  SRCB        SRCA
  SRCC        SRCA
C Small resistance connected at the rotor terminals
  BUSRA                    1.E-5
  BUSRB       BUSRA
  BUSRC       BUSRA
C Source impedances
  SRCA  BKRA               0.005    1.
  SRCB  BKRB  SRCA  BKRA
  SRCC  BKRC  SRCA  BKRA
C Mechanical system represented as an electric network
C    C = J*1E6   R = 1/D   L =1/K*1E3
  IMP                                   1.2E9
  IMP                     4.3E-3
BLANK card terminates circuit data
C
C ..........................  Switch data  ..................................
C Bus-->Bus--><---Tclose<---Topen<-------Ie                                     0
  BKRA  BUSA         0.2      9999.        0                                   1
  BKRB  BUSB         0.2      9999.        0                                   0
  BKRC  BUSC         0.2      9999.        0                                   0
  IM    IMP          0.2      9999.        0                                   1
BLANK card terminates switch data
C
```

```
C ...........................Source data  .....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <----Tstart<----Tstop
14SRCA      5388.877      60.0       0.0                          -1.     9999.
14SRCB      5388.877      60.0    -120.0                          -1.     9999.
14SRCC      5388.877      60.0     120.0                          -1.     9999.
C
C Universal machine
C
C Miscellaneous universal machine data
19
C col: (1-2) source type 19:  universal machine
C            <
             0
C col: (1) InPU (blank means SI units), (2) InitUM (1 means initialize machine)
C      (15) IComp (0 means use compensation, 1 means use prediction)
BLANK card terminates miscellaneous universal machine data
C
C Induction machine data (type 40 source - nameplate data is used)
C Phase a, b and c data
C Bus-->  <-----Slip<-----Freq
40BUSA          100.       60.
C col: (1-2) JType
C Bus-->
  BUSB
  BUSC
C Design ratio (Optional)
C ----------------><----FMin
DESIGN RATIO            0.55
C
C Nameplate rating data
C Full load rating
C ----PFLd<-----VFLd<----PFFLd<----EFFLd<-----SFLd
   -11000.     6600.     0.906     0.985  0.00622
C Starting information (in pu)
C ----CSta<-----TRat<-----VRed<-----CRed
       8.      1.47     0.758      6.03
C Leakage saturation data (in pu)
C ----CSat<----TQMax
       2.       3.5
C
C Mechanical parameters
C        <----HInitBus-->
 2          60000. IM
C col: (1-2) NP
C
C Induction machine output requests
C  I I I I I I
C <S<R<E<N<A<Q
 1 1 1 1 1 1
C col: (1-2) IP
BLANK card terminates universal machine data
BLANK card terminates source data
C
C ..............................  Output requests  ..........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUSA  BUSB  BUSC  IM
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

Figure 10-2-2: Input data for the simulation of a cold start-up of a fully loaded 11000 HP, 6.6 kV induction motor using a universal machine. type 40 model, including saturation. EMTP Version 1 does not recognize this model.

We could not run this case in Version 1.0 of the EMTP (Apollo Version), because the program did not recognize the universal machine type 40.

The second alternative to the representation of the induction motor requires explicit calculation of the machine inductances, and the use of the "induction motor" mode of the universal machine (universal machine type 4). The results for this case are illustrated in Figure 10-2-3 which uses universal machine type 4 model without considering saturation. For this type of universal machine, all the impedances have to be given explicitly to the program. When only the nameplate data of the machine is known the data must be converted from nameplate data. These converted data are also given in reference [1], and can be transformed to the required form for universal machine type 4 model by assuming the base values of 8.2 MW and 6.6 kV . Details of the conversion process are given in [1]. The results of this conversion are:

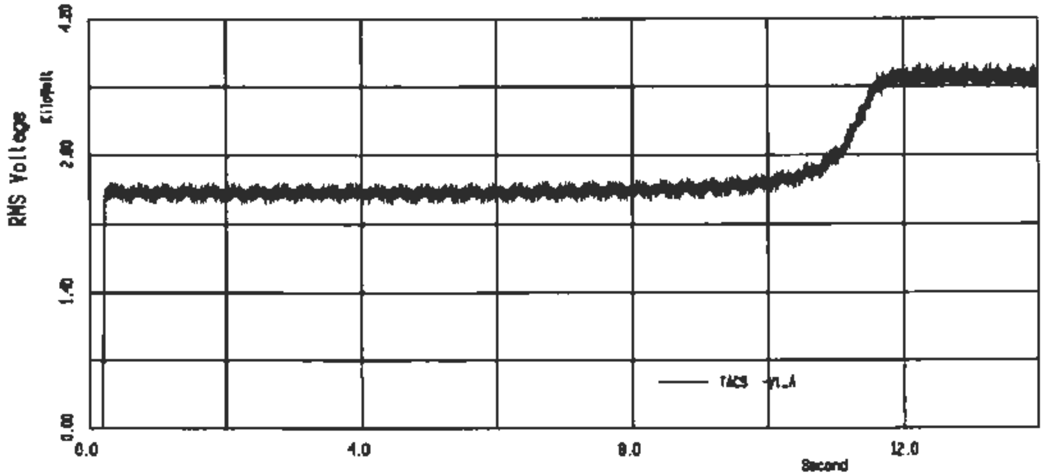
$$L_{md} = L_{mq} = 0.04413 \text{ H}$$
$$r_s = 0.02453 \ \Omega$$
$$L_{1d} = 0.0009132 \text{ H}$$
$$r_r = 0.10948 \ \Omega$$
$$L_{1q} = 0.0009130 \text{ H}$$

The resulting plots depicted in Figure 10-3-4 correspond closely to those in Figure 10-3-3 and are what we expected for a cold start-up of a rather large induction motor. The terminal current shows a large value when the motor is energized, and after several seconds it settles down to its steady-state value. The voltage shows a drop from its rated value due to the source impedance and the large start-up line current. The electromagnetic torque shows an initial oscillation that is typical of the start-up of any induction motor, then it increases steadily until it reaches its maximum just before the rotor gets to its rated speed. When this speed is attained, all the machine variables attain their steady-state value. This motor has very large time constants due to its size, therefore, and it takes a long time (about 12 seconds) to reach steady state operation.

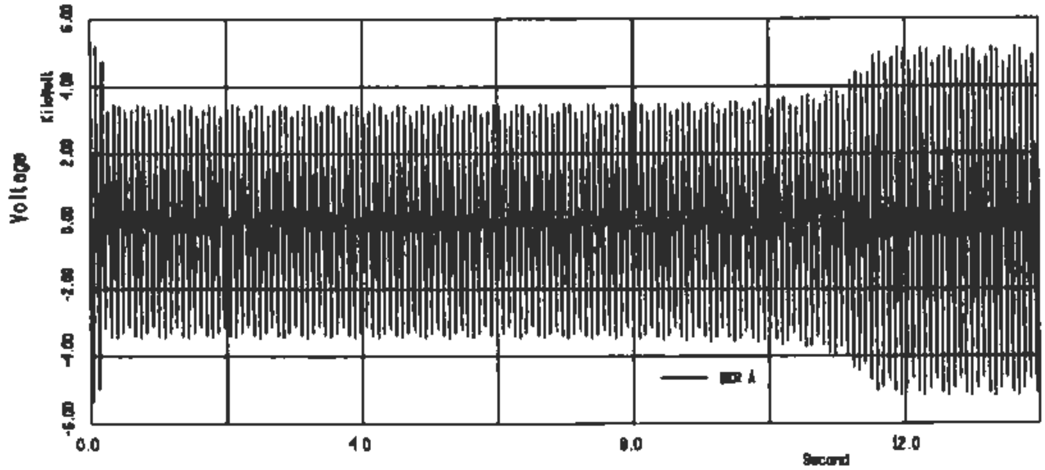
```
C Cold start-up of an Induction Motor using type 4 Induction Machine model.
C The input date are impedances according to rules given in EMTP Rule Book,
C i.e. in the following order:
C       - d,q mutual inductances,
C       - 0,d,q leakage inductances for stator (in this order),
C       - d,q,0 leakage inductances for rotor (in this order).
C
C This example is extracted from:
C    G.J. Rogers and D. Shirmohammadi, "Induction Machine Modelling for
C    Electromagnetic Transient Program," IEEE Trans. on Energy Conversion,
C    Vol. EC-2, No. 4, Dec. 1987.
C
BEGIN NEW DATA CASE
C ............................  Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   2.E-3     14.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      81       1                                               1
C
C TACS data
TACS HYBRID
C Node_V
90BUSA                     60.
91BKRA                     60.
90IM                        0.
C RMS value
88Vt_A  66+BUSA                                      60.
88It_A  66+BKRA                                      60.
C
C Slip
88Slip    =1 - IM/(377/2)
C
C TACS output requests
33Vt_A  It_A  Slip
BLANK card terminates TACS data
C
C ..........................  Circuit data  ..................................
C Ideal voltage sources always loaded
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C                                    0
  SRCA                        1.
  SRCB        SRCA
  SRCC        SRCA
C Small resistances connected at the rotor terminals
  BUSRA                    1.E-5
  BUSRB       BUSRA
  BUSRC       BUSRA
C Source impedances
  SRCA  BKRA               0.005    1.
  SRCB  BKRB  SRCA  BKRA
  SRCC  BKRC  SRCA  BKRA
C Mechanical system represented as an electric network
C    C = J*1E6   R = 1/D   L = 1/K*1E3
  IMP                                  1.2E9
  IMP                     4.3E-3
BLANK card terminates circuit data
C
C ..........................  Switch data  ...................................
C Bus-->Bus--><---Tclose<---Topen<-------Ie                                     0
  BKRA  BUSA         0.2     9999.         0                                    1
  BKRB  BUSB         0.2     9999.         0                                    0
  BKRC  BUSC         0.2     9999.         0                                    0
  IM    IMP          0.2     9999.         0                                    1
BLANK card terminates switch data
C
```

```
C ...........................Source data  ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14SRCA      5388.877      60.0       0.0                            -1.     9999.
14SRCB      5388.877      60.0    -120.0                            -1.     9999.
14SRCC      5388.877      60.0     120.0                            -1.     9999.
C
C Universal machine
C Miscellaneous universal machine
19
C col: (1-2) source type 19:  universal machine
C             <
              0
C col: (1) InPU (blank means SI units), (2) InitUM (1 means initialize machine)
C      (15) IComp (0 means use compensation, 1 means use prediction)
BLANK card terminates miscellaneous universal machine data
C
C Machine table data
C <-<-<<<MNode>TACS-><-<-----------Rj<--------DCoef<--------EpsoM<----------Freq
 4    111IM          2
C col: (1-2) JType, (3-4) NCLD, (5-6) NCLQ, (7) TQOut, (8) OMOut, (9) THOut,
C      (22-23) NPPair
C
C Initial speed, unsaturated d-axis inductance, saturated inductance and point
C -------OMegM<---------LMUD<<---------LMSD<--------FlxSD<--------FlxRD
           0.0     0.044130 0
C col: (29) JSatD (Blank if saturation is to be ignored)
C
C Initial position, unsaturated q-axis inductance, saturated inductance and point
C ------ThetaM<---------LMUQ<<---------LMSQ<--------FlxSQ<--------FlxRQ
           0.0     0.044130 0
C col: (29) JSatQ (Blank if saturation is to be ignored)
C
C Coil table data
C -------Resis<---------LLeakBus1->Bus2->XTACS><<----------Cur
C Armature
       0.02453    0.0009132 BUSA                0           0.0
       0.02453    0.0009132 BUSB                0           0.0
       0.02453    0.0009132 BUSC                0           0.0
C Rotor
       0.10948    0.0009130 BUSRB               0           0.0
       0.10948    0.0009130 BUSRC               0           0.0
       0.10948    0.0009130 BUSRA               0           0.0
C col: (47) CurOut (1 if you want to output this coil current)
BLANK card terminates universal machine data
BLANK card terminates source data
C
C .............................  Output requests  ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BKRA  BKRB  BKRC  IM
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

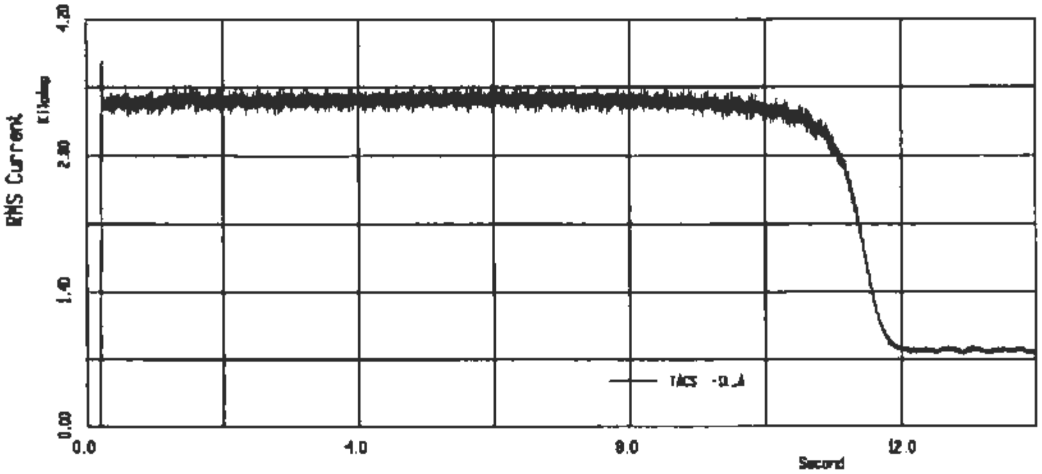
(a) Input data.



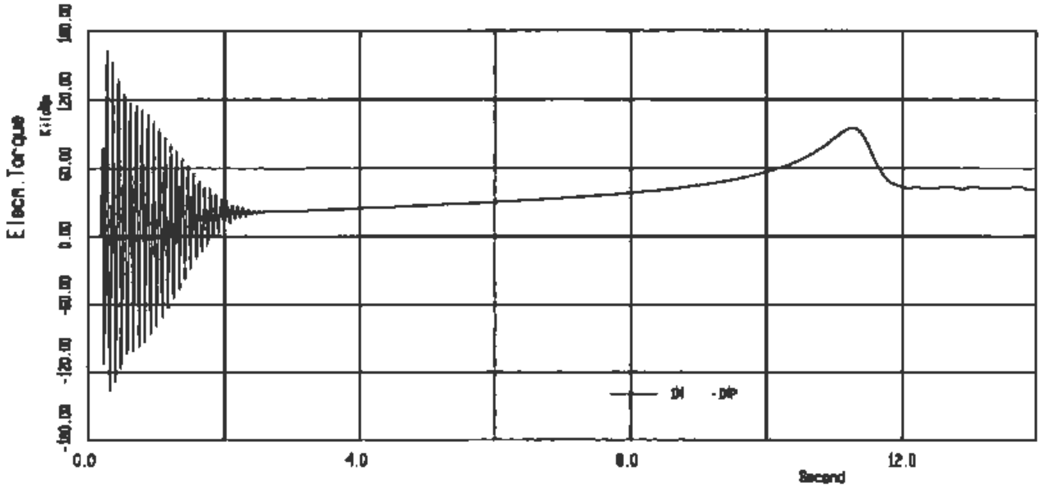
(b) Terminal RMS voltage. Ripples are due to the TACS RMS meter design and the time step used for the simulation.



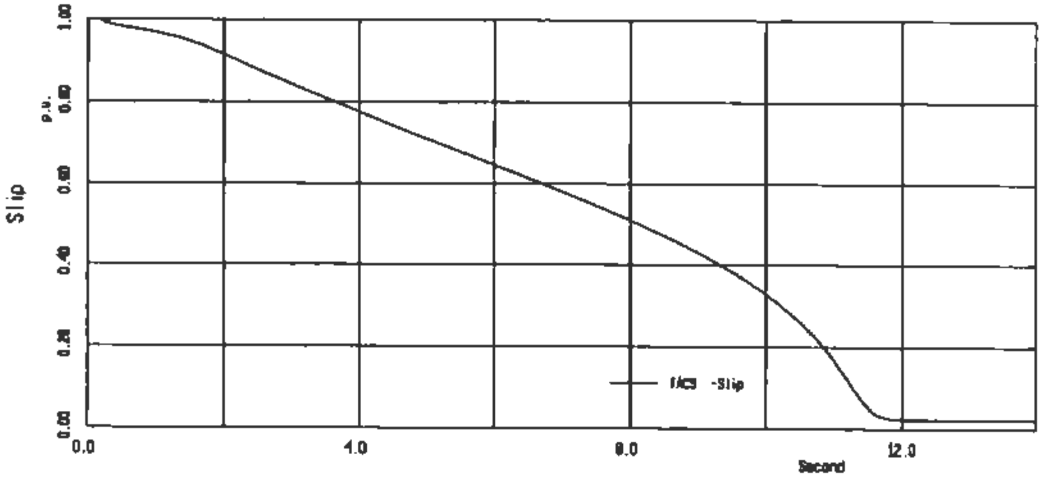
(c) Phase voltage.



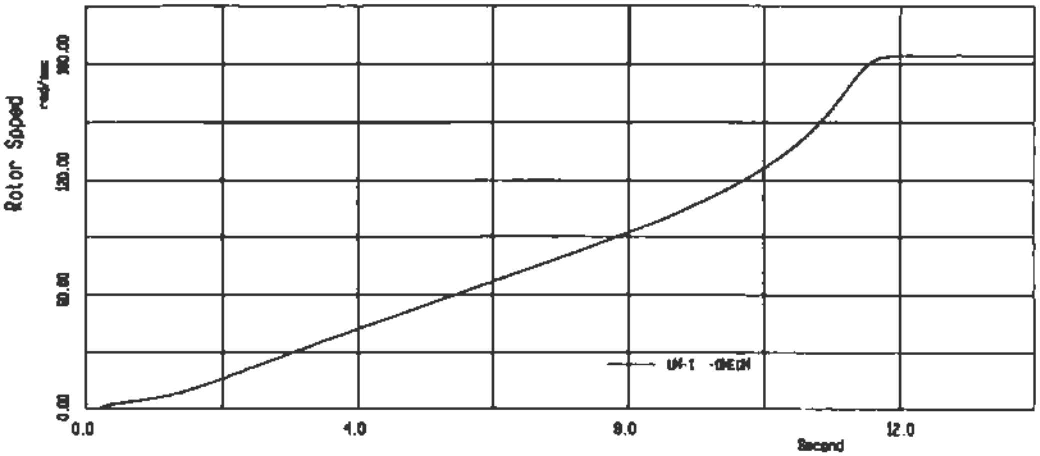
(d) Terminal RMS current. Ripples are due to the TACS RMS meter design and the time step used for the simulation.



(e) Electromagnetic torque.



(f) Slip.



(g) Rotor speed.

Figure 10-3-3: Cold start-up of a full loaded 11000 HP, 6.6 kV induction motor simulated with a universal machine type 4 model. Saturation is not included in this analysis.

10.4 References

[1] G. J. Rogers and D.Shirmohammadi, "Induction Machine Modelling for Electromagnetic Transient Program," IEEE Trans. on Energy Conversion, Vol. EC-2, No. 4, December 1987.

APPENDIX A

TEMPLATES

This appendix contains templates useful for the preparation of input data and understanding the organization of data for most of the EMTP capabilities described in this workbook. The short templates provided in this sectrion are practical and concise. You must first select the desired template from the following list, then locate and use this template.

The following templates are included in this section:

- Template for general EMTP case studies.
- Template for ideal transformer (type `18` source).
- Template for single-phase two-winding staurable transformer.
- Template for single-phase N-winding staurable transformer.
- Template for three-phase Δ-Δ connected saturable transformer.
- Template for three-phase Δ-Y connected saturable transformer.
- Template for three-phase Y-Δ connected saturable transformer.
- Template for three-phase Y-Y connected saturable transformer.
- Template for `XFORMER` study.
- Template for `TRELEG` study.
- Template for `BCTRAN` study.
- Template for `CONVERT` study.
- Template for `HYSDAT` study.
- Template for pseudo-nonlinear reactance (type `98` branch).
- Template for pseudo-nonlinear hysteretic reactance (type `96` branch).
- Template for using `BCTRAN` `[R]` and `[L]` matrices.
- Template for using `BCTRAN` `[R]` and $[L]^{-1}$ matrices.
- Template for synchronous machine (type `59` source).
- Template for universal machine (type `19` source).
- Template for induction machine (type `19` source, UM type `40`).

All of these templates are provided in the diskette that accompanies this workbook.

```
C Template for general EMTP case studies.
C
BEGIN NEW DATA CASE
C .......................... Miscellaneous data ................................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart

C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup

C
C .......................... Circuit data ......................................
C Distributed parameter line
C Bus1->Bus2->Bus3->Bus4-><---R'<---L'<---C'<--len 0 0 0                       O
-
C
C RLC branch
C Bus1->Bus2->Bus3->Bus4-><----R<-----L<-----C                                  O

C Mutually-copuled branches (zero and positive sequence)
C Bus-->Bus-->            <----R<----------L
51
52
53
C Mutully-coupled branches
C Bus1->Bus2->Bus3->Bus4-><----R<-----L<-----C<-----R<-----L<-----C<-----R<-----L<-----C
51
52
53
BLANK card terminates circuit data
C
C .......................... Switch data .......................................
C Bus1->Bus2-><---Tclose<----Topen<-------Ie                                    O

BLANK card terminates switch data
C
C .......................... Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop

BLANK card terminates source data
C
C .......................... Output requests ...................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->

BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

```
C IDEAL TRANSFORMER (type 18 source) -- Ideal transformer belongs to source
C data group.
C
C                    +------+   x Voltage source
C             k -----|      |---+---(~)--- j
C                    | 1:n  |
C             m -----|      |----- l
C                    +------+
C
C Busj->  <Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14              .001       60.        0.                        9999.     9999.
C Busl->  <----RatioBusk->Busm->Busx->
18                              INode
C Busx is the internal node x, must be unique for each transformer.
C Contarary to the Rule Book, the amplitude and frequency must be non-zero.
C However, a value of Tstart > Tmax will prohibit the voltage source becomes
C active.
```

```
C SINGLE-PHASE TWO-WINDING SATURABLE TRANSFORMER -- Saturable transformer
C belongs to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ---------->Bus3->       <--Iss<PhissBusTo><-Rmag                             O
  TRANSFORMER
C -------current<----------flux

          9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                   O
 1HIGH
 2LOW
```

```
C SINGLE-PHASE N-WINDING SATURABLE TRANSFORMER -- Saturable transformer belongs
C to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ---------->Bus3->       <--Iss<PhissBusTo><-Rmag                             O
  TRANSFORMER
C -------current<----------flux

          9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                   O
 1BUS1
 2BUS2
 3BUS3
 4BUS4
```

```
C 3-PHASE SATURABLE TRANSFORMER (delta-delta connected) --  Saturable
C transformer belongs to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ----------->Bus3->      <--Iss<PhissBusTo><-Rmag                              0
  TRANSFORMER                         INTAB
C -------current<-----------flux

            9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                    0
 1LOWA  LOWB
 2HIGHA HIGHB
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTAB                   INTBC
C Bus1->Bus2->
 1LOWB  LOWC
 2HIGHB HIGHC
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTAB                   INTCA
C Bus1->Bus2->
 1LOWC  LOWA
 2HIGHC HIGHA
```

```
C 3-PHASE SATURABLE TRANSFORMER (delta-Y connected) --  Saturable transformer
C belongs to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ----------->Bus3->      <--Iss<PhissBusTo><-Rmag                              0
  TRANSFORMER                         INTAB
C -------current<-----------flux

            9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                    0
 1LOWA  LOWB
 2HIGHA
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTAB                   INTBC
C Bus1->Bus2->
 1LOWB  LOWC
 2HIGHB
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTAB                   INTCA
C Bus1->Bus2->
 1LOWC  LOWA
 2HIGHC
```

```
C 3-PHASE SATURABLE TRANSFORMER (Y-delta connected) --  Saturable transformer
C belongs to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ----------->Bus3->      <--Iss<PhissBusTo><-Rmag                             0
  TRANSFORMER                         INTA
C -------current<-----------flux

            9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                   0
 1LOWA
 2HIGHA HIGHB
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTA                    INTB
C Bus1->Bus2->
 1LOWB
 2HIGHB HIGHC
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTA                    INTC
C Bus1->Bus2->
 1LOWC
 2HIGHC HIGHA
```

```
C 3-PHASE SATURABLE TRANSFORMER (Y-Y connected) --  Saturable transformer
C belongs to circuit data group.
C
C BusTo is a name for internal bus at the top of the magnetization branch which
C uniquely identifies the transformer.
C ----------->Bus3->      <--Iss<PhissBusTo><-Rmag                             0
  TRANSFORMER                         INTA
C -------current<-----------flux

            9999
C Bus1->Bus2->            <---Rk<---Lk<---Nk                                   0
 1LOWA
 2HIGHA
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTA                    INTB
C Bus1->Bus2->
 1LOWB
 2HIGHB
C ----------->Bus3->                  BusTo>
  TRANSFORMER INTA                    INTC
C Bus1->Bus2->
 1LOWC
 2HIGHC
```

```
C XFORMER -- Calculates [R] and [L] matrices for single-phase two-winding and
C three-winding transformers.
C
BEGIN NEW DATA CASE
C XFORMER card---------------------><-N
XFORMER
C
C Branch card (Optional)
C        High (51)  Medium (52)   Low (53)
C ----->Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
BRANCH
C
C Electrical parameters
C ---CMagn<----PBCur    <-IPunch
                               0
C col: (1) NW, (2-10) CMagn
C
C Winding data
C ---Volt1<--PLoss12<----ZSC12<----PBZ12

C ---Volt2<--PLoss13<----ZSC13<----PBZ13

C ---Volt3<--PLoss23<----ZSC23<----PBZ23

C Repeat from branch card for additional cases
BLANK card terminates XFORMER data
BLANK card terminates EMTP solution-mode
```

```
C TRELEG -- Calculates [R] and [L] matrices for single-phase and three-phase
C transformers.
C
BEGIN NEW DATA CASE
C XFORMER card--------------------><-N
XFORMER                             33.
C
C Branch card (Optional)
C        High (51)  Medium (52)   Low (53)
C ------>Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->
BRANCH
C Data for all classes starts at column 2.
C
C Electrical parameters (class #1)
C N<-<--------Freq<--------SBVA

C col: (2-3) N, (4-5) NDelta
C
C Class #2 (present only if  NDelta = 2)
C ------TPKMR<-------TPKMX

C -

C col: (2-3) IDT
C ------TZKMR<-------TZKMX

C
C Measurement data (class #3)
C   # of cards = (N-1)*N/2 + 1     for NDelta < 2
C                (N-1)(N-2)/2 + 1      NDelta = 2
C I<J<---------TPR<---------TPX<---------TZR<---------TZX

C col: (2-3) I
BLANK card terminates measurement data
C
C Output units (class #4)
C -

C col: (2-3) KZOut
C Winding data (class #5)
C   # of cards = N+1
C J < <--------VRj<----------RjNAi-->NBi-->NAi1->NBi1->NAi2->NBi2->

C col: (2-3) J, (5) INDD
BLANK card terminates winding data
C
C Magnetizing impedance specifier (class #6)
C -

C col: (2-3) NT
C
C Magnetizing impedance (class #7)
C   # of cards = 1  for NT <> 1
C               N      NT  = 1
C -------XPos<-------XZero

BLANK card terminates magnetizing impedance
C
C Repeat from branch card for additional cases
BLANK card terminates TRELEG data
BLANK card terminates EMTP solution-mode
```

```
C BCTRAN -- Calculates [R] and inverse of [L] matrices for single-phase and
C three-phase transformers.
C
BEGIN NEW DATA CASE
C XFORMER card----------------------><-N
XFORMER                              44.
C Excitation data                                        N     I
C                                                                        P I   P
C              pos       pos        pos      zero      zero       zero   h T I r
C     Freq    I         $        Loss       I         S        Loss      a e P i
C              excit     rating     excit    excit     rating     excit  s s u n
C <---------<---------<---------<---------<---------<---------<---------<e<t<t<t

C col: (1-2) N
C
C Winding data
C   # of cards = N                   Winding k
C                        Phase 1     Phase 2     Phase 3
C k<-Vkrating<-------Rk Bus1->Bus2->Bus1->Bus2->Bus1->Bus2->

C col: (1-3) k
C
C Short circuit test data
C   # of cards = N(N-1)/2                              I
C                                                      D I
C                  pos     pos        zero     zero    e L
C  k    P         Z       S          Z        S        l o
C        ik        ik      rating     ik       rating  t s
C <-<---------<---------<---------<---------<---------<a<s

C col: (1-2) i
BLANK card terminates short circuit test data
BLANK card terminates BCTRAN data
BLANK card terminates EMTP solution-mode
```

```
C CONVERT (Vrms vs. Irms) -- Convert RMS voltage-current saturation curves into
C flux-current curves.
C
BEGIN NEW DATA CASE
SATURATION
C --Freq<--VBase<--PBase<-IPunch<-KThird
                               0
C ------Irms(pu)<-------Vrms(pu)

           9999.
C Begin with the point closest to the origin (excluding origin) and then move
C continuously away from origin.
BLANK card terminates CONVERT data
BLANK card terminates EMTP solution-mode
```

```
C CONVERT (Current vs. incremental inductance) --  Convert current-incremental
C inductance curves into flux-current curves.
C
BEGIN NEW DATA CASE
SATURATION
C --Freq<--VBase<--PBase<-IPunch<-KThird
     -1.                       0
C ------------ik<-------------Lk

           9999.
C ik must be monotone increasing.  Lk must be greater than zero.
BLANK card terminates CONVERT data
BLANK card terminates EMTP solution-mode
```

```
C HYSDAT -- Generate flux-current curves for specifying major hysteresis loop
C characteristic in type-96 branch.
C
BEGIN NEW DATA CASE
SATURATION
C --Freq
     88.
C -Itype<--Level<-Ipunch
       1               0
C -Cusat<-FlxSat

BLANK card terminates hysteresis curve requests
BLANK card terminates HYDAT data
BLANK card terminate EMTP solution-mode
```

```
C PSEUDO-NONLINEAR REACTOR (type 98 element) - Pseudononlinear reactor belongs
C to circuit data group.
C
C Bus1->Bus2->Bus3->Bus4-><--iss<Phiss                                          O
96
C -------Current<-----------Flux

           9999.
C
C Specify current and flux in monotone increasing order.  The origin is an
C implicit point.  Usually, the first point equals to (iss, Phiss) in order to
C provide continuity between steady-state and transient solution at time zero.
C Note that Phiss and iss are used to define the slope of the curve for
C steady-state solution.
```

```
C PSEUDO-NONLINEAR HYSTERETIC REACTOR (type 96 element) - Pseudo-nonlinear
c hysteretic reactor belongs to circuit data group.
C
C Bus1->Bus2->Bus3->Bus4-><--iss<Phiss<PhiRe                                    O
96
C -------Current<-----------Flux

           9999.
C
C Specify iss = 8888. for EMTP to calculate iss and Phiss.
C The current flux curve must specify the bottom half of the hysteresis loop.
C The first point specifies the point after negative saturation point.  Then
C the other points are specified in order, up to and including the first
C point after the positive saturation point.
```

```
C USE RL - Uses BCTRAN [R] and [L] matrices in EMTP study.  USE RL is belong
C to branch data group.
C
C Bus1->
  USE RL
$VINTAGE, 1
C Bus1->Bus2->            <--------------R<--------------L

$VINTAGE, 0
```

```
C USE AB - Uses BCTRAN [R] and inverse of [L] matrices in EMTP study.  USE AB
C is belong to branch data group.
C
C Bus1->
  USE AB
$VINTAGE, 1
C Bus1->Bus2->            <--------------A<--------------B

$VINTAGE, 0
C
C Note:  Column A corresponds to the inverse of [L] matrix and B corresponds to
C the [R] matrix.
```

```
C DYNAMIC SYNCHRONOUS MACHINE - Synchronous machine belongs to source data
C group.
C
C Terminal connection for phase a
C Bus-->  <-----Volt<-----Freq<----Angle
59
C Connection for phase b and c (leave column 1-2 blank)
C Bus-->  <-----Volt<--------><----Angle


C Machine parameter cards (Optional)
C   Only non-blank fields redefine the default parameters
C -------><---EPSubA<---EPOmeg<---EPDgEl<------------------------------><---NIOMax
TOLERANCES
C ----------------------><-----FM
PARAMETER FITTING
C ----------------->
DELTA CONNECTION
C
C Electrical parameters of machine
C <-<-<-NP<----SMOutP<----SMOutQ<------RMVA<-------RKV<---AGLine<--------S1<-------S2

C Col: (1-2) NuMas, (3-4) KMac, (5-6) KExc
C -------><-------AD1<-------AD2<-------AQ1<-------AQ2<------AGLQ<-------S1Q<------S2Q

C If S.M. is not saturable (AGLine >= 0) leave S1 - S2Q blank
C
C Manufacturer supplied p.u. data (if parameter fitting is used)
C -------Ra<--------Xl<--------Xd<--------Xq<-------X'd<-------X'q<-------X"d<-------X"q

C ----T'd0<------T'q0<------T"d0<------T"q0<--------X0<--------Rn<--------Xn<-------Xc

C Per unit inductance and resistance matrices (no parameter fitting is used)
C -------Xf<-------Xaf<------Xfkd<--------Xd<------Xakd<-------Xkd<--------Xl

C -------Xg<-------Xag<------Xgkq<--------Xq<------Xakq<-------Xkq

C -------X0<--------Ra<--------Rf<-------Rkd<--------Rg<-------Rkq<--------Rn<-------Xn

C
C Mechanical parameters for the shaft system (mass data)
C <------><----ExTrs<-----HICO<------DSR<------DSM<-------HSP<-------DSD

C col: (1-2) ML
C Repeat this card for masses specified by NuMas
C
C Old style synchronous machine output requests
C @@@@@@@@@@<---Angles<----Speed<-Torques

C col: (1) JPAR, (2) JMIC, (3) JIdq0, (4) JFI, (5) JD2, (6) JQ1, (7) JQ2,
C      (8) JFV, (9) JETM, (10) JETE, (11) JIABC, (12) JSAT
C If the "old style" output is begin used, remove the blank card that terminates
C mass cards, otherwise, remove the "old style" output card.
BLANK card teminates mass data
C
C Synchronous machine output requests
C @@<--><---N1<---N2<---N3<---N4<---N5<---N6<---N7<---N8<---N9<--N10<--N11<--N12

C col: (3) Group, (4) All
C Repeat this card for each output group as necessary
BLANK card terminates synchronous machine output requests
C
C TACS input data
C Bus--><----><KI
```

```
C col: (1-2) KK - either 71, 72, 73 or 74
  FINISH PART
  FINISH
C Terminate TACS input by special terminator card FINISH PART or FINISH.  If
C there is more than one dynamic synchonous machine connected to the same bus,
C use FINISH PART to indicate the S.M. data is only partially completed.
C Repeat from "machine parameters" card and terminate with for each S.M. data
C as mentioned aboved. Terminate the last (or the only) S.M. machine with the
C card FINISH.
```

```
C UNIVERSAL MACHINE - Universal machine belongs to source data.
C
C Miscellaneous universal machine
19
C col: (1-2) source type
C             <

C col: (1) InPU, (2) InitUM, (15) IComp
BLANK card terminates miscellaneous universal machine data
C
C Machine table data
C <-<-<<<MNode>TACS-><-<------------Rj<--------DCoef<--------EpsoM<---------Freq

C col: (1-2) JType, (3-4) NCLD, (5-6) NCLQ, (7) TQOut, (8) OMOut, (9) THOut,
C       (22-23) NPPair
C ---------OMegM<---------LMUD<<--------LMSD<--------FlxSD<--------FlxRD

C col: (29) JSatD
C --------ThetaM<---------LMUQ<<--------LMSQ<--------FlxSQ<--------FlxRQ

C col: (29) JSatQ
C
C Steady state initialization (includes next two cards only if InitUM = 1)
C --------AmplUM<-------AnglUMBusF->BusM->

C --                                BusM-><-------DistRF

C col: (1-4) More
C
C Coil table data
C ---------Resis<--------LLeakBus1->Bus2->XTACS><<----------Cur

C col: (47) CurOut
C
C Include other universal machines here.
BLANK card terminates universal machine data
```

```
C INDUCTION MACHINE (TYPE 40 SOURCE) - Induction machine is part of the
C universal machine model and it belongs to source data group.
C
C THE FOLLOWING DATA SHOULD BE PLACE AFTER "BEGIN NEW DATA CASE" CARD
C Universal machine table space allocation
C -------------------->, I, J, K, L
ABSOLUTE U.M. DIMENSIONS,  ,  ,  ,
C
C THE FOLLOWING DATA SHOULD BE PLACE IN SOURCE DATA GROUP
C Miscellaneous universal machine data
19
C col: (1-2) source type
C             <

C col: (1) InPU, (2) InitUM, (15) IComp
BLANK card terminates miscellaneous universal machine data
C
C Induction machine data (type 40 source)
C
C Phase a, b and c data
C Bus-->  <-----Slip<-----Freq
40
C col: (1-2) JType
C Bus-->


C
C Design ratio (Optional)
C --------------><----FMin
DESIGN RATIO
C
C Nameplate rating data
C
C Full load rating
C ----PFLd<-----VFLd<----PFFLd<----EFFLd<-----SFLd

C Starting information (in pu)
C ----CSta<-----TRat<-----VRed<-----CRed

C Leakage saturation data (in pu)
C -----CSat<-----TQMax

C
C Saturation data (Optional)
C ----->  <-----VLin<----VFlat<-----CLin<-----CFlat
MAGNETIC
C
C Mechanical parameters
C          <----HInitBus-->

C col: (1-2) NP
C
C Induction machine output requests
C  I I I I I I
C <S<R<E<N<A<Q

C col: (1-2) IP
C Voltage request (includes only if IQ = 1)
C ---VLTQ1<-----VLTQ2<-----VLTQ3<-----VLTQ4<-----VLTQ5<-----VLTQ6<-----VLTQ7<-----VLTQ8

C
C Include other induction machine or other universal machine here.
BLANK card terminates universal machine data
```

EMTP

Electric Power Research Institute (EPRI)

Associate Members of the EMTP Research with EPRI

Electricite de France
American Electric Power Service Corporation

Members of the EMTP Development Coordination Group

Bonneville Power Administration

Canadian Electrical Association-Utility Members

Hydro Quebec

Ontario Hydro

Western Area Power Administration

United States Bureau of Reclamation

Associate Members of the EMTP Development Coordination Group

ASEA-Brown Boveri

Central Research Institute
of the Electric Power Industry in Japan