EPRI
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Topics:
Electric transients
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Transmission

EPRI EL-4202
Project 2149-1
Final Report
September 1985

Electromagnetic Transients Program (EMTP) Primer

Prepared by
Westinghouse Electric Corporation
Pittsburgh, Pennsylvania

REPORT SUMMARY

SUBJECTS Power system planning / Power system operation

TOPICS Electric transients; Computer simulation; Power systems; Mathematical models; Transmission

AUDIENCE Transmission planners and designers

EPRI-EL--4202

DE86 000060

Electromagnetic Transients Program (EMTP) Primer

Until now, an absence of documentation has made the complex EMTP for transient analyses difficult for new users to apply. This primer, prepared especially for utility engineers, employs case studies to introduce such users to the operation and application of this uniquely efficient software.

BACKGROUND For 15 years, the Bonneville Power Administration (BPA) and other utility and academic groups have been developing and expanding the digital Electromagnetic Transients Program (EMTP). The unusual and flexible program for the inexpensive in-house study of high-speed power system transients quickly received widespread acceptance. But inadequate documentation made the program difficult to learn. An EPRI survey of users and a set of follow-up workshops suggested improvements to make the program easier to apply (report EL-3668). EPRI cosponsored the present effort with the EMTP Development Coordination Group, which includes BPA, the Canadian Electrical Association, Hydro Quebec, Ontario Hydro, the U.S. Bureau of Reclamation, and the Western Area Power Administration.

OBJECTIVE To provide new utility users with introductory and tutorial materials for the Electromagnetic Transients Program.

APPROACH The project group identified the target user as an electrical engineer generally familiar with electrical system transients and computer simulation but not experienced with the EMTP. They decided on a teaching format that employed a series of increasingly sophisticated practical cases. For each case, the primer would describe the problem for analysis, calculate solutions or show field recordings of the situation, explain how to set up the EMTP simulations, and discuss the results. Participants in an August 1984 seminar at the University of Wisconsin Extension had tested the first draft, and the primer was modified accordingly.

RESULTS In testing, the primer's case-study approach proved effective in teaching the intricacies of transient analysis and EMTP use. After introducing the EMTP, the fully illustrated manual explains how to set up a simple case, gives examples of resistance-inductance-capacitance circuits, and presents 11 sample cases of increasing complexity. The cases are keyed to the EMTP input-output formats now in use. When these formats change in future, the primer is to be revised in response.

EPRI PERSPECTIVE

This primer is an important step toward expanded EMTP use, which will decrease the cost and increase the reliability of power system design. Such expanded use would have significance for EPRI research plans as it would enable utilities to make better use of the products of EMTP research now under way. In addition, the primer constitutes a valuable textbook for teaching practical electromagnetic principles and analysis at the university level. The primer does not provide a complete EMTP education—nor was it intended to. Users still must study further and work with the program to become proficient. Additional educational documents now planned are expected to focus further on EMTP application and operation.

PROJECT

RP2149-1
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Electromagnetic Transients Program (EMTP) Primer

EL-4202
Research Project 2149-1

Final Report, September 1985

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ABSTRACT

This document is an outgrowth of a survey and analysis of Electromagnetic Transients Program (EMTP) user needs, in which improved user's documentation was determined to be the single most important enhancement to the EMTP. The Primer is an EMTP training manual for new users. It includes introductory material and eleven sample studies so that the reader can learn by the case study method. The Primer is part of a series of new EMTP user manuals which covers program operation, theory, and application guide lines.

ACKNOWLEDGMENTS

The contractor acknowledges valuable assistance from the Industry Advisors:

Mr. O. J. Garcia	Florida Power & Light Company
Mr. John Kappenman	Minnesota Power & Light Company
Mr. William Torgerson	Puget Sound Power & Light Company

Students and faculty at the August, 1984, EMTP Short Course held at the University of Wisconsin - Extension made many suggestions which led to improvement of the first draft EMTP Primer.

Members of the project team at Westinghouse were Mr. Stephen Mauser, Mr. Thomas McDermott, Mr. Nicholas Abi-Samra, and Mr. Helfried Anderl.

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CONTENTS

Section		Page
S	Summary	S-1
I	Introduction to the EMTP	I-1
II	How to Use this Primer	II-1
III	Setting Up a Simple Case	III-1
IV	Examples of RLC Circuits	IV-1
1	Case 1: Single and Double Frequency Lumped Circuits	1-1
2	Case 2: Transient Recovery Voltage	2-1
3	Case 3: LINE CONSTANTS Calculations	3-1
4	Case 4: Lightning Surge Studies	4-1
5	Case 5: Capacitor Switching	5-1
6	Case 6: Parallel EHV Line Resonance	6-1
7	Case 7: Reclosing of Transmission Lines	7-1
8	Case 8: Surge Arresters	8-1
9	Case 9: Potential Transformer Ferroresonance	9-1
10	Case 10: Subsynchronous Resonance Studies	10-1
11	Case 11: TACS Studies	11-1
12	References	12-1

LIST OF FIGURES

Figure No.		Page
III.1	Fixed-Point Miscellaneous Data	III-3
III.2	Integer Miscellaneous Data	III-4
III.3	Series RLC Branch	III-5
III.4	Branch Cards	III-5
III.5	A Simple Switch	III-6
III.6	Switch Cards	III-6
III.7	Basic Source Types	III-7
III.8	Source Cards	III-7
III.9	Initial Condition Cards	III-8
III.10	Capacitor With Trapped Charge	III-8
III.11	Node Voltage Output Cards	III-9
III.12	Plot Request and Title Cards	III-10
III.13	Plot Specification Cards	III-10
IV.1	Parallel RLC Circuit With Capacitor Discharge	IV-3
IV.2	Response of Parallel RLC Circuit With Capacitor Discharge	IV-3
IV.3	Series RLC Circuit With Step Voltage Input	IV-4
IV.4	Response of Series RLC Circuit With Step Voltage Input	IV-4
IV.5	Capacitor Voltage and Inductor Current for Parallel RLC Circuit Simulation	IV-13
IV.6	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 10$ μsec	IV-14
IV.7	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 4$, $\Delta t = 10$ μsec	IV-15
IV.8	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = .5$, $\Delta t = 10$ μsec	IV-16
IV.9	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = .1$, $\Delta t = 10$ μsec	IV-17
IV.10	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 200$ μsec	IV-18
IV.11	Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 1000$ μsec	IV-19
1.1	Simplified Power Plant One-Line Diagram	1-2
1.2	Simplified Representation for Three-Phase-to-Ground Fault	1-2
1.3	Simplified Equivalent Circuit	1-2
1.4	Circuit Modelled for the Single-Frequency Case	1-4
1.5	Fault Current	1-8

Figure No.		Page
1.6	Circuit Breaker Recovery Voltage.	1-8
1.7	Circuit Modeled for the Double-Frequency Case	1-13
1.8	Double-Frequency Case Node Voltages	1-17
1.9	Circuit Breaker Recovery Voltage.	1-17
2.1	System One-Line Diagram	2-2
2.2	System Reactances and Fault Current Contributions with Reactances in Per Unit on 100 MVA and Base Currents in Per-Unit Amperes. .	2-3
2.3	Connection of the Current Injection Sources	2-6
2.4	Simplified Circuit to Calculate the TRV	2-9
2.5	Circuit Diagram, Node Names, and Data for the System.	2-9
2.6	Voltage Across the Circuit Breaker Terminals "BKR1 A" and "BKR2 A" with Inductive Terminations at Stations 3 and 5. . . .	2-10
2.7	Voltage Across the Circuit Breaker Terminals "BKR1 A" and "BKR2 A" with Transformer-Line Terminations at Stations 3 and 5	2-13
3.1	500-kV Flat Line Configuration.	3-3
3.2	Two 345-kV Lines on the Same Right-of-Way	3-12
3.3	230-kV Flat Line Configuration.	3-15
4.1	Backflash Phenomena for a Single-Phase Line with Shield Wire. . .	4-2
4.2	Tower Top Voltage Neglecting Adjacent Towers.	4-3
4.3	Simplified System for Stroke Terminating at a Tower	4-4
4.4	230-kV Line Configuration	4-5
4.5	Input Lightning Current Surge	4-6
4.6	EMTP Model for a Stroke to Tower.	4-6
4.7	Tower 1 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50.	4-13
4.8	Tower 2 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50.	4-13
4.9	Tower 3 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50.	4-14
4.10	Tower 4 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50.	4-14
4.11	Tower 5 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50.	4-15
4.12	Insulation Stress, T_F = 1, TFR = 50	4-15
4.13	Tower 1 Shield Wire and Coupled Phase Voltages, T_F = 2, TFR = 50.	4-16
4.14	Insulation Stress, T_F = 2, TFR = 50	4-16
4.15	Tower 1 Shield Wire and Coupled Phase Voltages, T_F = 2, TFR = 20.	4-17
4.16	Insulation Stress, T_F = 2, TFR = 20	4-17
5.1	System Model for Capacitor Switch Recovery Voltages	5-11
5.2	Phase B Voltages, Grounded Bank	5-12
5.3	Phase B Recovery Voltage, Grounded Bank	5-12
5.4	Phase C Voltages, Ungrounded Bank	5-13

Figure No.		Page

5.5	Phase C Recovery Voltage, Ungrounded Bank.	5-13
5.6	Phase C Voltages, Ungrounded Bank, Two Poles Hung.	5-14
5.7	Phase C Recovery Voltage, Ungrounded Bank, Two Poles Hung. . . .	5-14
5.8	Phase A Voltages, Ungrounded Bank, One Pole Hung	5-15
5.9	Phase B Voltages, Ungrounded Bank, One Pole Hung	5-15
5.10	Phase C Voltages, Ungrounded Bank, One Pole Hung	5-16
5.11	EMTP Model of Back-to-Back Capacitor Banks with Current-Limiting Reactors	5-16
5.12	Capacitor Bus Voltages While Energizing Step 1	5-17
5.13	Capacitor Step 1 Voltages While Energizing Step 2.	5-18
5.14	Phase B Bus Voltage During Back-to-Back Energization	5-19
5.15	Phase B Step 1 Voltage During Back-to-Back Energization.	5-19
5.16	Phase B Step 2 Voltage During Back-to-Back Energization.	5-20
5.17	Phase B Step 1 Current During Back-to-Back Energization.	5-20
5.18	Phase B Step 2 Current During Back-to-Back Energization.	5-21
5.19	Phase A Bus Voltage During Restrike of Step 1.	5-22
5.20	Phase A Step 1 Voltage During Restrike of Step 1	5-22
6.1	Simplified Diagram of the System Studied	6-1
6.2	System Diagram with the Node Names	6-7
6.3	Voltage at Line 2 Reactor (Node "JUAN2A") Versus Shunt Reactor Size With and Without a Fault at Transposition Point 2 on Line 1.	6-8
6.4	Node Currents In Crest Amperes at Nodes "JUAN1C" and "P1.1 C". .	6-14
6.5	Node Currents In Crest Amperes at Nodes "JUAN1A" and "P1.1 A". .	6-14
7.1	Schematic of One Pole of an EHV Circuit Breaker with a Preinsertion Resistor.	7-2
7.2	Traveling Voltage on the Transmission Line, e", as a Function of the Preinsertion Resistor R	7-2
7.3	Closing Times of the Circuit Breaker Main Contacts	7-3
7.4	Closing Times of the Auxiliary and Main Contacts	7-4
7.5	Uniform Distribution for Selecting the Aiming Point.	7-5
7.6	Typical 500-kV Transmission Tower.	7-5
7.7	Transformer Magnetizing Current.	7-8
7.8	One-Line Diagram of the System Represented	7-10
7.9	System as Represented with Node Names.	7-10
7.10	Fault Clearing, Sending End Voltages	7-13

Figure No.		Page

7.11	Fault Clearing, Receiving End Voltages	7-13
7.12	Case Peaks of the Receiving End Line-to-Ground Voltages with No Surge Reduction Schemes.	7-21
7.13	Case Peaks of the Receiving End Line-to-Ground Voltages with Preinsertion Resistors	7-22
7.14	Case Peaks of the Sending End Line-to-Ground Voltages with No Surge Reduction Schemes	7-23
8.1	Line Overvoltage Profiles.	8-7
8.2	Phase C Voltage at Fourth Metering Point (PNT3) with No Surge Reduction Measures	8-8
8.3	Phase C Voltage at the Receiving End with No Surge Reduction Measures	8-8
8.4	Phase C Voltage at the Fourth Metering Point (PNT3) with Line-End Surge Arresters	8-9
8.5	Phase C Voltage at the Receiving End with Line-End Surge Arresters.	8-9
8.6	Phase B Voltage at the Fourth Metering Point (PNT3) with Preinsertion Resistors	8-10
8.7	Phase B Voltage at the Receiving End with Preinsertion Resistors.	8-10
9.1	Typical Breaker-and-a-Half Substation Arrangement.	9-2
9.2	Simplified Circuit	9-2
9.3	Square Wave Voltage Oscillations of Deenergized Transformer. . .	9-3
9.4	Typical Ferroresonant Voltage Waveform	9-3
9.5	PT Saturation Characteristic	9-11
9.6	Circuit Diagram and Node Names	9-12
9.7	Phase C PT Bus Voltage with No Load Resistors.	9-13
9.8	Phase C Magnetizing Current with No Load Resistors	9-13
9.9	Phase B PT Bus Voltage with 1.5 Ohms in Wye.	9-14
9.10	Phase A PT Bus Voltage with 1.5 Ohms in Wye.	9-14
9.11	Phase C PT Bus Voltage with 1.5 Ohms in Wye.	9-15
9.12	Phase C PT Bus Voltage with 1.0 Ohms in Wye.	9-15
9.13	Phase B PT Bus Voltage with 1.0 Ohms in Delta.	9-16
9.14	Phase B PT Bus Voltage with .5 Ohms in Delta	9-16

Figure No.		Page
10.1	Second IEEE Benchmark System for SSR Studies	10-4
10.2	GEN-LP Shaft Torques for Self-Excitation Cases	10-7
10.3	Static Blocking Filter	10-9
10.4	Filter Parameters for First Mode Damping	10-11
10.5	Torque Amplification with Fault Cleared in 17 Milliseconds . . .	10-16
10.6	Torque Amplification with Fault Cleared in 40 Milliseconds . . .	10-18
10.7	Torque Amplification with Bypass Gaps, Fault Cleared in 17 Milliseconds.	10-19
11.1	EMTP Thyristor Switch Input Format	11-2
11.2	Typical Thyristor and Diode Connections.	11-2
11.3	Thyristor with Snubber and Current-Limiting Reactor.	11-3
11.4	Single-Phase Full-Wave Controlled Rectifier.	11-7
11.5	Flux Linkage Firing Control for a Resistive Load	11-7
11.6	Inductive Load Current	11-8
11.7	TACS Implementation of Flux Linkage Firing Control	11-14
11.8	Source and Load Voltages, $\alpha=90^{o}$, p.f.=1.00	11-16
11.9	Thyristor 1 Flux Linkages, $\alpha=90^{o}$, p.f.=1.00.	11-16
11.10	Thyristor 2 Flux Linkages, $\alpha=90^{o}$, p.f.=1.00.	11-17
11.11	Thyristor Voltages, $\alpha=90^{o}$, p.f.=1.00	11-17
11.12	Thyristor 2 Flux Linkages, $\alpha=30^{o}$, p.f.=1.00.	11-18
11.13	Thyristor Voltages, $\alpha=30^{o}$, p.f.=1.00	11-18
11.14	Load Currents for p.f. = 1.00.	11-19
11.15	Load Currents for p.f. = .71	11-20
11.16	Load Currents for p.f. = .26	11-21
11.17	Load Currents for p.f. = 0.0	11-22

LIST OF TABLES

Table No.		Page
III.1	EMTP Input Deck Structure	III-1
III.2	EMTP Auxiliary Programs	III-2
IV.1	EMTP Input for Parallel RLC Circuit	IV-5
IV.2	EMTP Printed Output for Parallel RLC Circuit	IV-8
IV.3	EMTP Input for Series RLC Circuit	IV-9
IV.4	EMTP Printed Output for Series RLC Circuit	IV-11
IV.5	EMTP Simulations of Series RLC Circuits	IV-12
1.1	Input Data for the Single-Frequency Case	1-4
1.2	Commented Input Data for the Single-Frequency Case	1-7
1.3	Printed Output for Single-Frequency Case	1-9
1.4	Input Data for the Double-Frequency Case	1-15
2.1	Station 1 Representation	2-2
2.2	Station 3 and 5 Representations	2-2
2.3	Transmission Line Representation	2-3
2.4	Input Data for the TRV Case	2-7
2.5	Transformer - Line Terminations at Stations 3 and 5	2-12
3.1	500-kV LINE CONSTANTS Input	3-4
3.2	500-kV LINE CONSTANTS Output	3-7
3.3	500-kV Line Model Parameters	3-11
3.4	345-kV Line Conductor Data	3-12
3.5	345-kV LINE CONSTANTS Input	3-13
3.6	345-kV LINE CONSTANTS Output	3-14
3.7	230-kV LINE CONSTANTS Input	3-17
3.8	230-kV LINE CONSTANTS Output	3-19
3.9	Model Parameter Comparison	3-20
4.1	230-kV Line Surge Impedances	4-5
4.2	EMTP Input for a Stroke to Tower	4-7
4.3	Maximum/Minimum Printout for a Stroke to Tower	4-12
4.4	Backflash Study Results	4-18
4.5	Insulation Strength as a Function of Wavefront	4-18
4.6	Flashover Probability	4-19

Table No.		Page
5.1	Input Data for Capacitor Switch Recovery Voltages.	5-2
5.2	Back-to-Back Capacitor Switching EMTP Input.	5-6
5.3	Switches for Restrike Simulation	5-10
6.1	Matrix Data for the 345-kV Transmission System	6-3
6.2	Input Format for the Pi-Sections	6-3
6.3	Shunt Reactor Ratings	6-4
6.4	Input Data for the Line Resonance Case.	6-5
6.5	Node Voltages in kV With a Line-to-Ground Fault 60 Miles from the Energized End	6-8
6.6	Node Voltages in kV without a Fault on the Line	6-9
6.7	Partial Steady-State Printout	6-10
7.1	Data for the Switched 120-Mile, 500-kV Line	7-6
7.2	Data for the 90-Mile, 500-kV Line	7-6
7.3	Magnetizing Characteristic of the Power Transformer	7-7
7.4	Remote Source Parameters.	7-9
7.5	Input Data for Calculating Trapped Charge	7-11
7.6	Input Data for the 200 Reclosing Operations with preinsertion Resistors	7-15
7.7	Tabulation of Case Peak Receiving End Line-to-Ground Voltages . .	7-18
7.8	Closing Times in Milliseconds which Resulted in the Highest Receiving End Overvoltage	7-25
7.9	Overvoltages at Sending and Receiving Ends in kV (and Per-Unit) .	7-25
8.1	396-kV Metal Oxide Surge Arrester VI Characteristics.	8-2
8.2	Input Data for the Arrester Case.	8-3
8.3	Peak Overvoltage Results in Per-Unit	8-12
9.1	Input Data for the PT Ferroresonance Case	9-7
9.2	PT Saturation Curve	9-9
10.1	TG Electrical Parameters.	10-2
10.2	TG Mechanical Parameters.	10-3
10.3	EMTP Input Data for Self-Excitation Case.	10-5
10.4	EMTP Branch Cards for First Mode Blocking Filter.	10-13
10.5	EMTP Branch and Switch Cards for Series Capacitor Bypass Gaps . .	10-14
11.1	TACS Input Structure.	11-3
11.2	TACS Components	11-4
11.3	Load Impedance Parameters	11-9
11.4	EMTP Input for Single-Phase Full-Wave Rectifier	11-11

SUMMARY

The Electromagnetic Transients Program (EMTP) is a computer program used to simulate electromagnetic, electromechanical, and control system transients on multiphase electric power systems. It was first developed, among many other programs, as a digital computer counterpart to the analog Transient Network Analyzer (TNA). Many other capabilities have been added to the EMTP over a fifteen-year period, and the program has become widely used in the utility industry.

This document is an outgrowth of a survey and analysis of EMTP user needs, in which improved user's documentation was determined to be the single most important enhancement to the EMTP. The Primer is an EMTP training manual for new users. It includes introductory material and eleven sample studies so that the reader can learn by the case study method. The Primer is part of a series of new EMTP user manuals which covers program operation, theory, and application guide lines.

The sample studies in the Primer are intended to involve the user in an active learning process. The cases proceed from simplest to more complicated, and introduce EMTP modeling features one piece at a time. They also illustrate use of the program to conduct engineering studies. Locations of key parameters in the input files are illustrated so the user can more conveniently experiment with the cases.

Each sample study describes the phenomena of interest, illustrates the preparation of input data, and presents selected output. This output is compared to expected results. Use of the output to meet study objectives is also illustrated. Each case concludes with computer running times relative to the other cases, plus suggested areas for further study.

In the Primer's introductory material, Section III describes the general structure and requirements of an EMTP input file. RLC circuit simulations are presented in detail as examples in Section IV. Commands needed to run the EMTP and obtain plots on the user's inhouse computer system are not included in the Primer because these instructions will vary with each installation of the EMTP.

Eleven more detailed sample cases based on practical problems are presented in the main body of the Primer.

- Case 1 introduces single-phase lumped circuits, with applications to single and double frequency transient recovery voltages (TRV) in a power plant.
- Case 2 introduces distributed-parameter transmission lines to simulate circuit breaker TRV's in a substation.
- Case 3 illustrates use of the LINE CONSTANTS auxiliary program to generate EMTP transmission line models used in several of the following studies.
- Case 4 adds a two-phase line model with towers and footings included, to simulate the lightning backflash event.
- Case 5 illustrates three-phase capacitor switching.
- Case 6 uses resonance between parallel, shunt-compensated, EHV lines to illustrate the EMTP's steady-state calculation capabilities.
- Case 7 shows the use of probabilistic switching simulation to conduct electrical line design studies.
- Case 8 introduces surge arrester models in a continuation of the line switching study of Case 7.
- Case 9 uses a non-linear transformer model to simulate ferro-resonance.
- Case 10 introduces the synchronous machine model to study subsynchronous resonance.
- Case 11 illustrates the Transient Analysis of Control Systems (TACS) feature and the thyristor switch model. These features are used in HVDC and SVC studies.

It is suggested that the new user read and work through the sample cases on the inhouse computer system. All new users should study Sections III and IV at least. The other sample cases build on each other. However, if time is limited, sample cases 2 and 3 should provide sufficient background for the user to understand other selected cases of immediate interest.

One the new user has completed EMTP training using this Primer, the Application Guide and Operation Manual are intended to be reference documents for actual engineering studies. The Application Guide will provide information about setting study objectives, selecting EMTP outputs, developing system models, providing generic data when necessary, and interpreting the outputs for various types of studies. The Operation Manual will provide information about EMTP input formats, output formats, and error messages.

Section I

INTRODUCTION TO THE EMTP

The Electromagnetic Transients Program (EMTP) is a computer program used to simulate electromagnetic, electromechanical, and control system transients on multiphase electric power systems. It was first developed, among many other programs, as a digital computer counterpart to the analog Transient Network Analyzer (TNA). Many other capabilities have been added to the EMTP over a fifteen-year period, and the program has become widely used in the utility industry.

The EMTP was developed in the late 1960's by Dr. Hermann Dommel, who brought the program to Bonneville Power Administration (BPA). Since that time, the EMTP has been expanded and distributed under BPA's direction. Some models have been developed inhouse at BPA, but others have been developed by other utilities or by universities. One example is the first synchronous machine model developed at Southern California Edison for use in SSR studies. Another is the detailed silicon carbide surge arrester model developed at Ohio Brass and AEP. Frequency dependent line models, hysteretic iron cores, TACS, and newer machine models have come from universities.

Formal EMTP User's Groups have been established in Japan and Europe. An EMTP Newsletter is published approximately quarterly by Hermann Dommel at the University of British Columbia. There are plans to start an EMTP User's Group in North America. So far, user meetings have taken place at short courses offered by the University of Wisconsin nearly every summer.

Studies involving use of the EMTP have objectives which fall in two general catagories. One is design, which includes insulation coordination, equipment ratings, protective device specification, control system design, etc. The other is solving operating problems such as unexplained outages or equipment failures. A partial list of typical EMTP studies follows:

- Switching Surges
  - Deterministic
  - Probabilistic
  - Single-Pole Switching
  - High-Speed Reclosing

- Capacitor Switching
- Reactor Switching
- Transient Recovery Voltages
- Cable Switching Transients

Lightning Surges
- Backflash
- Induced Surges
- Incoming Surges at Stations

Insulation Coordination
- Overhead Lines
- Outdoor Stations
- Gas-Insulated Substations
- Arrester Duty

Shaft Torsional Stress
- Subsynchronous Resonance
- Switching-Induced

HVDC
- Controls
- Electrical Transients
- Harmonics

Static VAR Compensation
- Controls
- Overvoltages
- Harmonics

Carrier Frequency Propagation
Harmonics
Ferroresonance
Parallel Line Resonance
Motor Starting
Out-of-Phase Synchronization
Islanding or Other Disturbance Events
General Control Systems
Grounding

Alternate Energy Sources

Phase Conductor Transposition

Ground Wire Losses

General Steady-State Analysis of Unbalanced Systems

Series Capacitor Protection

This is only a partial list. One of the EMTP's major advantages is its flexibility in modeling a system, so an experienced user can apply the program to a wide variety of studies.

The user defines a system to be simulated by building up component models. The types of components which can be modeled include:

A. Lumped resistance, inductance, and capacitance. These can be single-phase elements, or they can be multiphase pi sections consisting of symmetrical R, L, and C matrices. These pi sections can be used to model transmission lines and transformers. Typically, the matrices are three-phase, but other configurations are available. For example, a double-circuit line could have six phases, or a single-circuit line with two ground wires retained in the model could have five phases.

B. Traveling wave models to represent overhead lines or cables more accurately than with the pi sections. Several different types are available, including transposed constant parameter, nontransposed constant parameter, and nontransposed frequency dependent. Again, the number of phases need not be restricted to three.

C. Nonlinear impedances:

   1. Nonlinear resistors to represent surge arrester valve blocks.

   2. Nonlinear inductors to represent saturating iron-cored devices.

   3. Time-varying resistances which have been used to simulate circuit breaker arc dynamics.

D. Ideal switches which are used to simulate circuit breaker contacts. Voltage-controlled switches are available to simulate sparkover gaps or flashovers. Diodes and thyristors are available as special switch types. Of the time-controlled switches, some can be dependent on others--for example, the preinsertion resistor auxiliary contact in a circuit breaker. The opening and closing times of switches can also be randomly varied in a probabilistic case.

E. Ideal current and voltage sources which include sinusoids, d.c. and step functions, piecewise linear surges, exponentials, or special user-defined sources.

F. Three-phase synchronous machines which include a complete two-axis model of Park's equations and a lumped mass, spring, and damping mechanical model. Provisions are made for external exciter and governor dynamics.

G. A generalized universal machine model which can represent synchronous machines, although not as efficiently as the model described above. Its primary use is for induction machines, d.c. machines, or synchronous machines which do not have three phases.

H. Control system dynamics which are interfaced to the main electrical network. Measured electrical signals are passed into the Transient Analysis of Control Systems (TACS) part of the program. TACS emulates an analog computer and calculates the control dynamics, and then passes control variables back to the main electrical network.

The EMTP's main COMMON blocks are variably dimensioned so the user can tailor the program size to fit abnormally small or large study systems.

Inputs to the program consist of the calculation time step, length of time to be simulated, and desired outputs, as well as the model data. The lumped branches are defined by resistance in ohms, inductance in millihenries or in ohms at power frequency, and capacitance in microfarads or in micromhos at power frequency. The simplest traveling wave models can be defined by surge impedances, resistance per unit length, wave velocity, and line length for positive and zero sequence. Nonlinear elements are usually specified by current and voltage points for resistors, and current and flux linkage points for inductors. Synchronous machine models use conventional stability data for the electrical side, and parameters in English units for the mechanical side. TACS inputs are specified by transferring information from the control block diagram to card images.

Most of the EMTP's input data requirements are different from, and more extensive than, other programs such as load flow, short circuit, and stability. This is because the program is multiphase, can simulate nonlinear elements, and, in general, uses more detailed models than the other programs. These features are needed to accurately simulate high frequency transients which occur during short time periods. Fortunately, there are auxiliary programs supplied with the EMTP which assist the user in setting up the input data for transmission lines, cables, transformers, surge arresters, and nonlinear inductors.

The primary output from a transient simulation includes plotted bus voltages, branch voltages, branch currents, branch energy dissipation, machine variables, and control system variables. These values can also be printed out as functions of time, but this type of output is often awkward to use. Printed maximum values of the variables and the times at which they occurred are also available.

A steady-state phasor solution is performed before the transient simulation to determine the initial conditions, and this can also be a useful study tool in itself. Branch voltages and currents, bus voltages, power loss, and power flows are determined for the entire network. A frequency scan option is also available which systematically varies the frequency of the sources for the steady-state solution, and plots voltage magnitudes and angles as a function of frequency. This type of output is useful for harmonic studies.

The most success in using the EMTP will be achieved by following a systematic study procedure, especially for new users. A suggested study procedure is outlined below.

1. Define the study objective in terms of an engineering problem to be solved. This may include specifying equipment ratings, determining the cause of an unexplained failure, defining operating procedures, etc.

2. As a natural outgrowth of the study objective, select the outputs to be obtained from the EMTP simulations.

3. Determine the frequency range of the phenomena to be studied, and the types of events and phenomena to be simulated. This will help determine the calculation time step and length of time to be simulated. If case running times will be excessive, consider how to judiciously set up initial conditions or models to focus on the phenomena of interest and minimize the use of computing resources.

4. Based on steps 2 and 3, decide on the extent of the system which must be modeled to accurately represent the phenomena of interest. Also decide which components need the most modeling detail and which can be simplified.

5. Draw a connection diagram of the study system and label the buses.

6. Begin to collect input data for the component models. Often the user must rely on estimated or typical data. In that case, identify model parameters most prone to error so their effect on the results can be determined later. The Application Guide is a source of some typical data.

7. Run the EMTP auxiliary input preparation programs and set up the card image input file.

8. Run a steady-state solution base case to verify the input data and connections between components. Adjust source voltages to obtain the proper initial conditions.

9. Before running transient cases, it is often useful to run a case which proceeds only one time step into the transient simulation. This type of case often uncovers errors not found in the steady-state solution.

10. Estimate the expected simulation results by means of simplified hand calculations, measurements on the system, etc. Compare the expected results to the EMTP results, and explain or resolve any significant differences.

11. Run the cases needed to achieve study objectives. Besides normal parametric variations in the cases, the parameters of critical models might be varied to determine the sensitivity of the results to data uncertainties.

In general, the user should expect valid results from the EMTP. Many problems will occur as a result of the user's system modeling performed in steps 3 through 6. Uncertainty or unavailability of the input data accounts for most of the other problems.

Since the program is multiphase, large study systems will use extensive computing resources. Simulations which use rotating machines, TACS, and thyristor device models are often expensive, as are probabilistic switching cases. Therefore, the user should attempt to simulate no more of the system than is necessary, and no more time than is necessary.

New EMTP users will note many differences compared to other power system computer programs. Input to the EMTP is usually done in physical units rather than per-unit. The values can be scaled to obtain per-unit results, but this often leads to confusion in developing the input files. Sinusoidal source magnitudes are expressed in peak volts or amperes line-to-ground, rather than rms line-to-line. Delta-connected impedances must be multiplied by three to convert the normal per-unit impedance, which is on the line-to-ground base, to the proper line-to-line connected physical value. Transmission line models will exhibit traveling wave behavior rather than lumped pi section behavior. However, at power frequency, the EMTP line models will behave like the lumped models most engineers are familiar with.

Section II

HOW TO USE THIS PRIMER

The sample studies in the remainder of this manual are intended to involve the user in an active learning process. The cases proceed from simplest to more complicated, and introduce EMTP modeling features one piece at a time. They also illustrate use of the program to conduct engineering studies. Locations of key parameters in the input files are illustrated so the user can more conveniently experiment with the cases.

Each sample study describes the phenomena of interest, illustrates the preparation of input data, and presents selected output. This output is compared to expected results. Use of the output to meet study objectives is also illustrated. Each case concludes with computer running times relative to the other cases, plus suggested areas for further study.

It is suggested that the new user read and work through the sample cases on the inhouse computer system. All new users should study Sections III and IV at least. The other sample cases build on each other. However, if time is limited, sample cases 2 and 3 should provide sufficient background for the user to understand other selected cases of immediate interest. Besides running the cases given in the manual, the user is especially encouraged to vary the input parameters and observe their effect on the results.

Section III describes the general structure and requirements of an EMTP input file. RLC circuit simulations are presented in detail as examples in Section IV. Commands needed to run the EMTP and obtain plots on the user's inhouse computer system are not included in the Primer because these instructions will vary with each installation of the EMTP.

Eleven more detailed sample cases based on practical problems are presented in the main body of the Primer.

- Case 1 introduces single-phase lumped circuits, with applications to single and double frequency transient recovery voltages (TRV) in a power plant.
- Case 2 introduces distributed-parameter transmission lines to simulate circuit breaker TRV's in a substation.

- Case 3 illustrates use of the LINE CONSTANTS auxiliary program to generate EMTP transmission line models used in several of the following studies.

- Case 4 adds a two-phase line model with towers and footings included, to simulate the lightning backflash event.

- Case 5 illustrates three-phase capacitor switching.

- Case 6 uses resonance between parallel, shunt-compensated, EHV lines to illustrate the EMTP's steady-state calculation capabilities.

- Case 7 shows the use of probabilistic switching simulation to conduct electrical line design studies.

- Case 8 introduces surge arrester models in a continuation of the line switching study of Case 7.

- Case 9 uses a non-linear transformer model to simulate ferro-resonance.

- Case 10 introduces the synchronous resonance machine model to study subsynchronous resonance.

- Case 11 illustrates the Transient Analysis of Control Systems (TACS) feature and the thyristor switch model. These features are used in HVDC and SVC studies.

One the new user has completed EMTP training using this Primer, the Application Guide and Operation Manual are intended to be reference documents for actual engineering studies. It is still suggested that a systematic study procedure be followed. The Application Guide will provide information about setting study objectives, selecting EMTP outputs, developing system models, providing generic data when necessary, and interpreting the outputs for various types of studies. The Operation Manual will provide information about EMTP input formats, output formats, and error messages.

Section III

SETTING UP A SIMPLE CASE

This section describes the basic structure of an EMTP input deck, with some of the more commonly used input formats. Simple examples consisting of series and parallel resistor-inductor-capacitor (RLC) circuits are presented in Section IV.

Plotted waveforms are the primary useful outputs of EMTP simulations. Procedures for obtaining plots vary with the computer system. The plots included in this document were obtained with a separate postprocessing program which executes after the EMTP, and uses raw plot data stored on disk or tape. This type of plotting program will vary from installation to installation. The EMTP also has provisions for batchmode plotting using CALCOMP software. Many computer systems have this software available, so each case presented in this Primer has sample CALCOMP PLOT cards included in the EMTP input deck as appropriate. The user may have to adjust the plotting procedures according to the graphics software available.

The structure of an EMTP input deck is shown in Table III.1. Most sections are separated by a blank card. For convenience, the user can enter a card image with "BLANK CARD" starting in column 1, which will be interpreted by the EMTP as a blank card. Comment lines can also be added to the input deck by entering a "C-blank" in Columns 1 and 2. Additional comment text can also be added after "BLANK CARD." Comment lines are used extensively in the sample cases in this Primer. The EMTP prints these lines in the record of input data, but otherwise ignores them.

TABLE III.1

EMTP Input Deck Structure

```
BEGIN NEW DATA CASE (one line)
Special Request Cards
Fixed-point Miscellaneous Data Card
Integer Miscellaneous Data Card
TACS Function Cards
     BLANK CARD
TACS Source Cards
     BLANK CARD
TACS Supplemental Variable and Device Cards
     BLANK CARD
TACS Output Request Cards
     BLANK CARD
TACS Initial Condition Cards
     BLANK CARD
```

TABLE III.1 (Cont'd)

EMTP Input Deck Structure

Cards for Branches, Transformers, Cables, and Transmission Lines
    BLANK CARD
Switch Cards
    BLANK CARD
Source Cards
    BLANK CARD
Initial Condition Cards
Node Voltage Output Request Cards
    BLANK CARD
CALCOMP PLOT Request Cards
    BLANK CARD
    BLANK CARD (Ends the case)

TABLE III.2

EMTP Auxiliary Programs

LINE CONSTANTS - Calculates EMTP input data for overhead transmission lines.

CABLE CONSTANTS - Calculates EMTP input data for cables, or for overhead transmission lines.

JMARTI SETUP, SEMLYEN SETUP, HAUER SETUP, WEIGHT - These programs calculate data for various frequency-dependent line models in the EMTP. Thier use is covered in the Application Guide.

XFORMER, TRELEG, BCTRAN - These programs calculate impedance matrix models for transformers from short-circuit test data. Their use is covered in the Application Guide.

SATURATION - Gains access to the following three subprograms:
- CONVERT - Calculates data for transformer core saturation models.
- HYSDAT - Calculates data for hysteretic iron core models.
- ARRDAT - Calculates data for nonlinear arrester models.

Note that the TACS input comes before the electrical network input. TACS will not be covered until the last sample case of this Primer. Cases which do not include TACS simply delete the five sections of TACS cards from the input deck, along with the five associated BLANK CARDs.

Only one of the special request cards will be covered in this Primer, namely the LINE CONSTANTS program. This card transfers control to a subprogram within the EMTP called LINE CONSTANTS. This subprogram calculates EMTP input data for overhead transmission lines using conductor and tower geometry data. The LINE CONSTANTS program has its own input structure, different from Table III.1, which will be covered later. The subprograms available through special request cards are listed in Table III.2.

There are several other features of the EMTP which are available through the special request cards.

The input formats of those cards which are needed to simulate a simple RLC circuit transient will now be described in the order in which they appear in Table III.1. The input formats are described according to FORTRAN notation. For example, E8.0 indicates a right-justified real number in exponential format, to fill a total of 8 columns including leading blanks. Similarly, I8 is a right-justified 8-column integer, and A6 is a six-character alphanumeric name. The notation 8X signifies eight blank columns.

BEGIN NEW DATA CASE: This card always precedes an input deck.

Fixed-Point Miscellaneous Data: This card contains seven real number parameters to be entered in fields eight columns wide. Only the four parameters shown in Figure III.1 will be used.

DELTAT	TMAX	XOPT	COPT
E8.0	E8.0	E8.0	E8.0

FIGURE III.1. Fixed-Point Miscellaneous Data

DELTAT is the time step used in the simulation. It must always be greater than zero.

TMAX is the length of time in seconds to be simulated. It can be equal to or less than zero, in which case the EMTP performs a steady-state solution of the initial conditions only, and does not perform a transient simulation.

XOPT is the power frequency for purposes of inductance specification. If it is zero or blank, all inductances are entered in millihenries. If it is 60.0, for example, all inductances are entered as reactive ohms at 60 Hertz.

COPT is the power frequency for purposes of capacitance specification. If it is zero or blank, all capacitances are entered in microfarads. If it is 60.0, for example, all capacitances are entered as microohms at 60 Hertz.

Integer Miscellaneous Data Card: This card contains up to ten integer parameters, which are entered right-justified in fields eight columns wide. Only seven parameters as shown in Figure III.2 will be used in this Primer.

IOUT	IPLOT	IDOUBL	KSSOUT	MAXOUT		ICAT	NENERG
I8	I8	I8	I8	I8	8X	I8	I8

FIGURE III.2. Integer Miscellaneous Data

IOUT - This parameter specifies the rate at which output variables are printed during the simulation. If IOUT is zero or one, each time step is printed. If IOUT = k, then every kth time step is printed. IOUT should always be either blank or equal to an odd number. Even numbers will permit numerical oscillations to exist which the user cannot detect in the output. As an alternative, the user may specify a very large IOUT to avoid time step printed output. The use would then rely on plotted output.

IPLOT - This parameter specifies the rate at which output variables are plotted during the simulation in exactly the same way that IOUT controls printed output. IPLOT should also be either blank or equal to an odd number.

IDOUBL - Setting IDOUBL equal to one will cause a network topology listing to be printed out. It is useful in checking branch and switch connections when setting up a case.

KSSOUT - Setting KSSOUT equal to one will cause a complete steady-state voltage and current solution to be printed for each branch in the network. KSSOUT equal to two causes only switch and source steady-state solutions to be printed. KSSOUT equal to three causes switch, source, and requested output variable steady-state solutions to be printed.

MAXOUT - Setting MAXOUT equal to one will cause the EMTP to print the maximum values attained by each output variable during the transient simulation.

ICAT - Setting ICAT equal to one causes all plot data generated by the EMTP to be saved on disk for future plotting by a separate program.

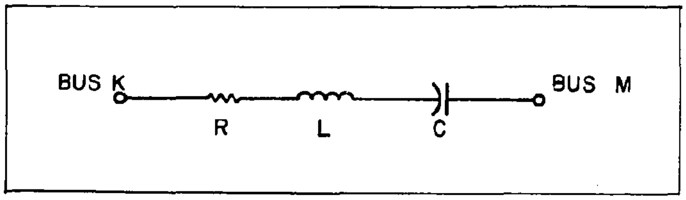


FIGURE III.3. Series RLC Branch

	BUS K	BUS M		R	L	C		BRANCH OUTPUT
2X	A6	A6	12X	E6.0	E6.0	E6.0	35X	I1

FIGURE III.4. Branch Cards

NENERG - Setting NENERG greater than zero causes a probabilistic switching simulation to be performed. This feature is covered later in this Primer, and in the Application Guide.

Branch Cards: Only the single-phase, lumped-parameter branches shown in Figure III.3 are used in the RLC circuit examples. The parameters are punched in fields six columns wide. Since the precision is limited by the number of columns in the input fields, inductances specified in ohms or millihenries and capacitances specified in micromhos or microfarads are usually the optimum scaled units. Resistances are input in ohms. Branch current and voltage output variables are specified on these cards, while node voltage outputs are specified near the end of the EMTP input deck as shown in Table III.2. Figure III.4 shows the branch card input format.

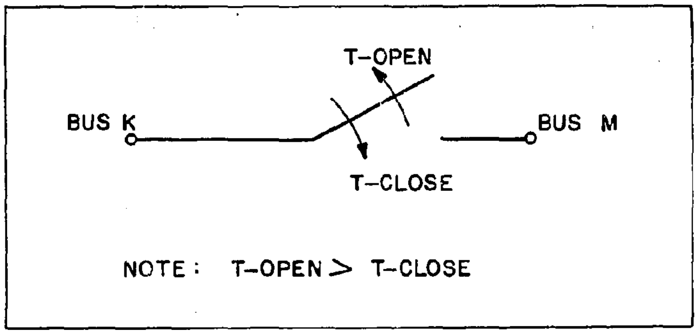


FIGURE III.5. A Simple Switch

	BUS K	BUS M	T-CLOSE	T-OPEN		BRANCH OUTPUT
2X	A6	A6	E10.0	E10.0	45X	I1

FIGURE III.6. Switch Cards

This format is for single-phase branches which do not use the reference branch feature. BUS K and BUS M are the six-character node names on the user's schematic of the system. Care should be taken to assign unique node names. The parameters R, L, and C are the resistance, inductance, and capacitance (in series) of the branch. One of these parameters must be non-zero. If either BUS K or BUS M is left blank, the branch is assumed to be connected from a node to ground. BRANCH OUTPUT is a single integer which requests branch variable output. We will use a 1 to request inductor current outputs. Other options include a 2 to have the branch differential voltage output, a 3 to have both branch current and voltage output, and a 4 to have branch power and energy output.

Switch Cards: The format of these cards is similar to the branch cards, except that switch closing and opening times are specified rather than R, L, and C. The EMTP switch models perform one close-open operation during the simulation. The input format for the switch depicted in Figure III.5 is shown in Figure III.6.

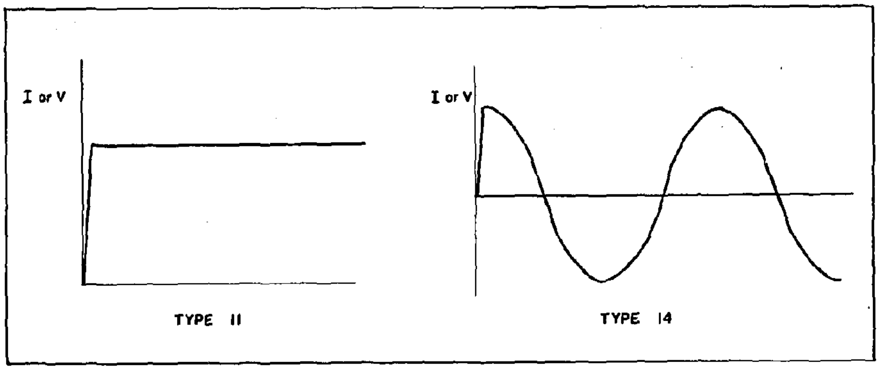


FIGURE III.7. Basic Source Types

TYPE	BUS	V OR I	AMPLITUDE	FREQUENCY	PHASE ANGLE
I2	A6	I2	E10.0	E10.0	E10.0

FIGURE III.8. Source Cards

The switch is connected between nodes BUS K and BUS M, one of which may be left blank to indicate a switch to ground. T-CLOSE and T-OPEN are specified in seconds. A negative T-CLOSE may be used to indicate a switch which is already closed in the steady state. If T-OPEN is left blank or is assigned a value greater than TMAX, the switch will never open during the simulation. Branch current and voltage outputs may also be requested for switches in the same way as for branches.

Source Cards: A variety of source types are available in the EMTP. Step functions and cosine functions shown in Figure III.7 are often used. The sources can be either node voltages to ground or currents injected at the node. Input formats are shown in Figure III.8.

TYPE is a two-digit integer, 11=step function
14=cosine function.

BUS is the node name where the source is connected.

V OR I is a two-digit integer, blank=voltage source
-1=current source.

AMPLITUDE is the current or voltage level of the step, or the amplitude in peak units line-to-ground of the cosine wave.

FREQUENCY is the frequency in Hertz of a cosine function (blank for step function).

PHASE ANGLE is the phase angle in degrees of the cosine function (blank for step function).

IDENT	BUS K	V
I2	A6	E15.8

IDENT	BUS K	BUS M	I	V
I2	A6	A6	E15.8	E15.8

FIGURE III.9. Initial Condition Cards

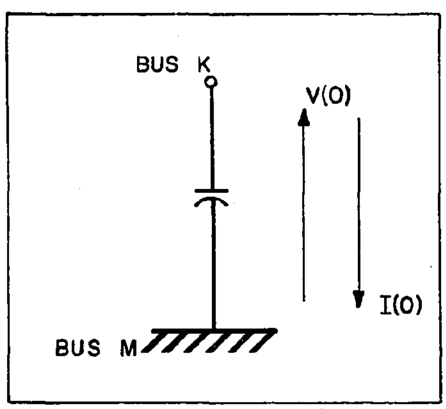


FIGURE III.10. Capacitor With Trapped Charge

These EMTP sources will become active in the first time step of the transient simulation. However, the Operation Manual describes how to specify sources as being active in the pre-transient steady state.

Initial Condition Cards: These are commonly used to specify trapped charges on capacitors. For each capacitor, one card is used to specify the initial node voltage at each terminal and another card is used to specify the initial voltage and current in the capacitance itself. The formats for those cards are shown in Figure III.9, with the parameters to be specified shown on Figure III.10. In this example, the BUS M terminal of the capacitor is grounded, so a node voltage card is not required for BUS M.

IDENT=2 for the node voltage card (first one in Figure III.9).
IDENT=3 for the branch current and voltage card (second one in Figure III.9).
BUS=node name of a capacitor terminal.
BUS K and BUS M are the node names of the capacitor branch terminals.
V=trapped voltage on the capacitor.
I=0 for a capacitor with a d.c. trapped charge.

Node Voltage Output Cards: These cards immediately follow the initial condition cards (if any). As opposed to branch currents and voltages, these cards specify the output of node voltages to ground.

A single card can be used with a "1" in Column 2 to request all node voltages to be output. In this case, DO NOT use the BLANK CARD which normally terminates the node voltage output cards.

To select individual node voltages to be output, use the format in Figure III.11. Each card contains node names of the output voltages. More than one node voltage output card may be used if there are more than 13 voltages to be output. However, there is an upper limit on the number of output variables which varies from installation to installation.

	BUS 1	BUS 2	....	BUS 13
2X	A6	A6		A6

FIGURE III.11. Node Voltage Output Cards

On each card, BUS 1 must be non-blank.

Plot Request Cards: The cards for batch-mode plots fall in two general groups. The first group specifies line printer or Calcomp plots, together with the plot title. These cards are shown in Figure III.12.

Plot Request Card

2X CALCOMP PLOT or PRINTER PLOT

Case Title Card

I2 Alpha Format (up to 78 characters)

FIGURE III.12. Plot Request and Title Cards

CALCOMP PLOT may not be operational at each installation, but PRINTER PLOT will always produce plots in the EMTP printout using alphanumeric characters. For that reason, these plots are harder to use than CALCOMP PLOTs. Whichever type is used, the specification of each individual plot is made using the format shown in Figure III.13.

FLAG	TYPE	UNITS	UPI	ORIG	END		BUS 1	BUS 2	BUS 3	BUS 4
I2	I1	I1	E3.0	E4.0	E4.0	9X	A6	A6	A6	A6

FIGURE III.13. Plot Specification Cards

FLAG is always equal to 1 in Column 2.
TYPE=4 for a node voltage plot.
=8 for a branch voltage plot.
=9 for a branch current plot.
UNITS=3 for a time scale in seconds.
=4 for a time scale in milliseconds.
=5 for a time scale in microseconds.
UPI is the number of UNITS per inch.
ORIG is the beginning time (in UNITS) of the plot.
END is the ending time (in UNITS) of the plot.

In most cases, UPI, ORIG, and END should be chosen to get a total time-scale length of 10 to 12 inches. UPI should be a convenient scaling division, since the grid lines are drawn one per inch.

If a node voltage plot is being made, up to four different node voltages may be plotted on the same graph as indicated in Figure III.13. If a branch voltage or current plot is being made, BUS 1 and BUS 2 are the branch node names as specified in the EMTP simulation. BUS 3 and BUS 4 may contain node names for a second branch variable to be plotted on the same graph.

Section IV

EXAMPLES OF RLC CIRCUITS

Series and parallel RLC circuits are analyzed in Reference (1). Usually, the transient response of the circuit can be predicted by knowing the initial and final states of the circuit, and three basic parameters which govern the transition from the initial state to the final state.

The initial and final states of the circuit are defined by the energy stored in the capacitance and inductance, or in other words, the voltage across the capacitance and the current through the inductance. If the initial and/or final states are d.c., then the capacitor current and the voltage across the inductor are both zero. This makes it easy to calculate the initial and final conditions. The current and voltage of the resistor are determined by the capacitor voltage and inductor current. For both the capacitor voltage and the inductor current, one of three general relations between the initial and final states will usually hold true:

1. Variable changes from a zero initial value to a non-zero final value.
2. Variable changes from a non-zero initial value to a zero final value.
3. Variable starts and ends at a zero value, but undergoes transient variations between the initial and final state.

In each case, the variable will overshoot the ultimate final value and gradually settle in to a steady state. The maximum overshoot for the first two cases, in the absence of resistive damping, will be equal to the difference between initial and final values. The minimum overshoot, with excessive resistive damping, will be zero.

The transition between the initial and final states is governed by three circuit parameters, namely, the undamped natural frequency f_0, the surge impedance Z, and the time constant T. These parameters are calculated as follows:

$$f_o = 1/(2\pi\sqrt{LC}) \quad \text{(IV-1)}$$

$$Z = \sqrt{L/C} \quad \text{(IV-2)}$$

$$T = L/R \text{ for series RLC circuits} \quad \text{(IV-3)}$$

$$= RC \text{ for parallel RLC circuits}$$

The damping is conveniently expressed in dimensionless form in terms of a ratio between the resistance and surge impedance.

$$\lambda = Z/R \text{ for series RLC circuits} \quad \text{(IV-4)}$$

$$\eta = R/Z \text{ for parallel RLC circuits} \quad \text{(IV-5)}$$

Note that η^2 is equal to the parallel circuit time constant divided by the series circuit time constant. There is a duality between the series and parallel RLC circuits. The parameters λ and η are also known as the quality factor or "Q" of a circuit.

The transient response will be oscillatory if λ or η is greater than 0.5, with a frequency approximately equal to f_o. The transient response will be non-oscillatory, or overdamped, if λ or η is less than 0.5. The case of λ or η equal to 0.5 is called critically damped. If λ or η is infinite, no damping exists at all.

The first case simulated is a parallel RLC circuit with a switch between the capacitor and the rest of the circuit, as shown in Figure IV.1. The capacitor has an initial d.c. voltage which discharges through the resistance and inductance after the switch closes. Therefore, the capacitor voltage starts from a non-zero initial value and reaches a final value of zero. The inductor current is initially zero and is also zero in the final state. However, the peak inductor current for infinite η (no damping) is given by $I = V_c(0)/Z$. The predicted responses of the circuit are shown in Figure IV.2 for the undamped and critically damped cases.

The second case simulated involves a series RLC circuit which is energized by a battery as shown in Figure IV.3. The initial capacitor voltage and inductor current are both zero. Since the final capacitor current in a d.c. circuit must be zero, the final inductor current is also zero. Since that means there is no voltage drop across the resistance or inductance in the final state, the final capacitor voltage is equal to the battery voltage. The predicted responses of the

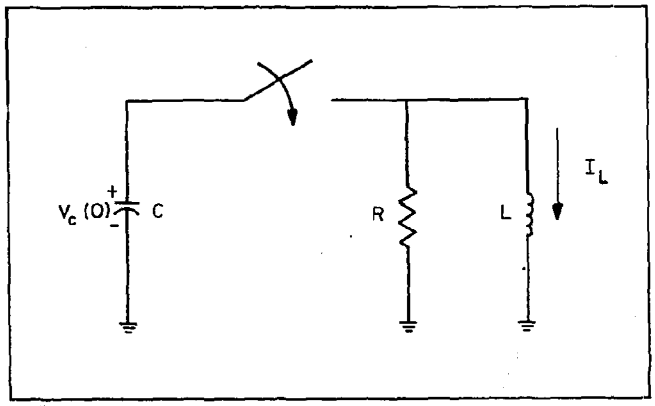


FIGURE IV.1. Parallel RLC Circuit With Capacitor Discharge

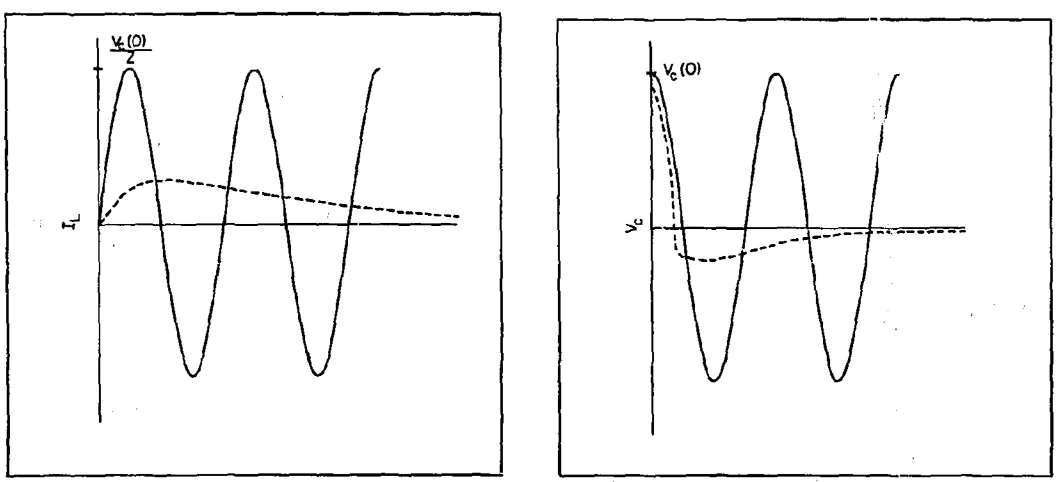


FIGURE IV.2. Response of Parallel RLC Circuit With Capacitor Discharge

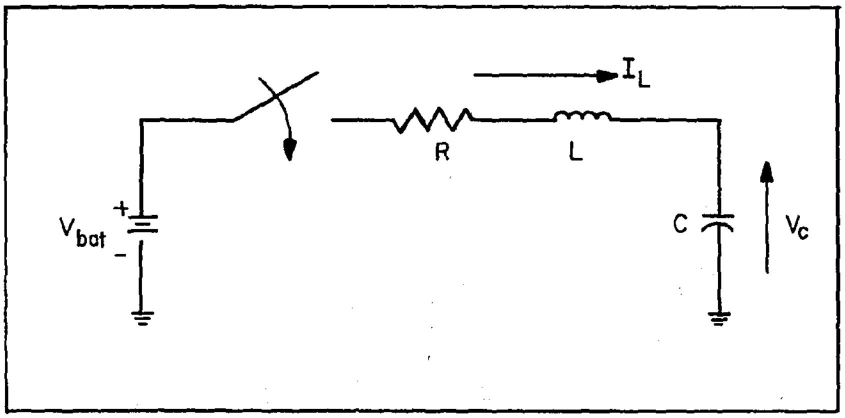


FIGURE IV.3. Series RLC Circuit With Step Voltage Input

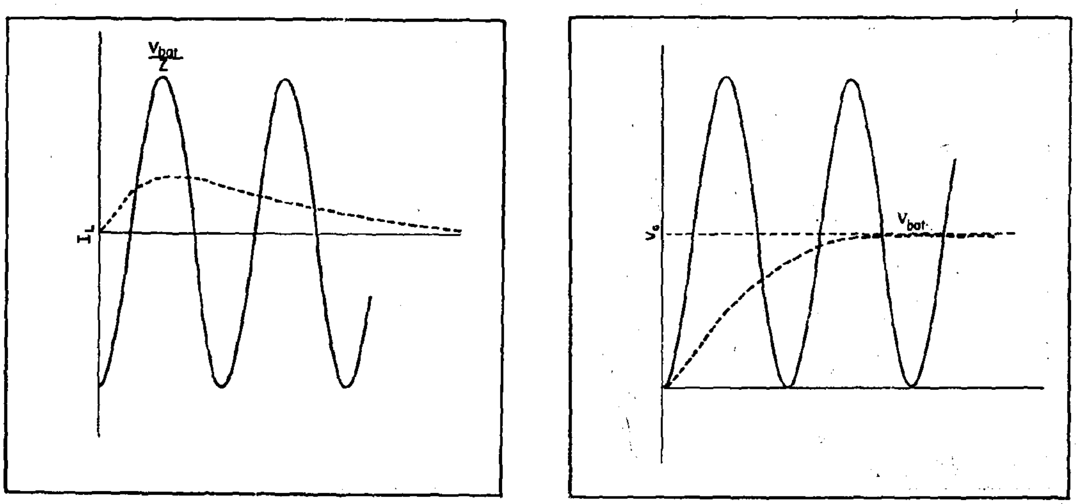


FIGURE IV.4. Response of Series RLC Circuit With Step Voltage Input circuit are shown in Figure IV.4 for the undamped and critically damped cases. The peak inductor current for the undamped case is given by $I = V_{battery}/Z$.

Table IV.1 shows the EMTP input file for the simulation of a parallel RLC circuit transient similar to that depicted in Figures IV.1. and IV.2. The initial capacitor voltage before the switch closes is one volt due to a trapped charge. The capacitor voltage and the inductor current will be plotted. The circuit parameters are R = 632.46 ohms, L = 5 millihenries, and C = 5 microfarads. Therefore,

$$Z = \sqrt{\frac{L}{C}} = \sqrt{\frac{5 \times 10^{-3}}{5 \times 10^{-6}}} = 31.62 \text{ ohms}$$

$$f_0 = \frac{1}{2\pi \sqrt{LC}} = \frac{1}{6.28 \sqrt{25} \times 10^{-9}} = 1007 \text{ Hz}$$

$$\eta = \frac{R}{Z} = \frac{632.46}{31.62} = 20$$

TABLE IV.1

EMTP Input for Parallel RLC Circuit

```
BEGIN NEW DATA CASE
  10.E-6  10.E-3
   20000       1       1       1       1
  SWITCH                  632.46
  SWITCH                              5.
  CAP                                       5.
BLANK CARD ENDING BRANCHES
  CAP   SWITCH     .0005         1.
BLANK CARD ENDING SWITCHES
BLANK CARD ENDING SOURCES
 2CAP                1.0
 3CAP                      0.             1.0
C END OF INITIAL CONDITIONS
  CAP
BLANK CARD ENDING NODE VOLTAGE OUTPUT
  CALCOMP PLOT
 2 PARALLEL RLC CIRCUIT WITH CAPACITOR DISCHARGING
 1941.0    10.0         SWITCH
 1441.0    10.0         CAP
BLANK CARD ENDING PLOTS
BLANK CARD ENDING THE CASE
```

The capacitor voltage should start at one volt and reach zero volts via a lightly damped oscillation of approximately 1000 Hz. The inductor current should start and end at zero amps, but will undergo a similar 1000-Hz transient. The peak inductor current should be slightly less than $V_c(0)/Z$, or .0316 amps, due to the resistive damping. Because of the resistive damping, the overshoot of capacitor voltage should not quite reach minus one volt.

Line 1 of the EMTP input in Table IV.1 is the BEGIN NEW DATA CASE card. On line 2, the time step and the maximum time to be simulated have been chosen. Since the expected transient frequency is 1000 Hz, the T_{max} of 10 milliseconds will allow 10 cycles of the oscillation to be simulated. Since the period of oscillation is 1000 microseconds, the chosen time step will produce 100 time steps per cycle of oscillation. The absence of power frequency input on line 2 indicates that inductances and capacitances will be input in millihenries and microfarads.

Line 3 contains the integer miscellaneous data. The first parameter, IOUT, effectively specifies no printed output because there will only be 1000 time steps simulated. However, the IPLOT parameter specifies that every point will be plotted. The next three parameters, IDOUBL, KSSOUT, and MAXOUT request a network connection table, steady-state printout, and printout of maximum and minimum values reached during the simulation.

Line 4 is a branch card specifying a 632.46-ohm resistance from node SWITCH to ground. Line 5 specifies a 5-millihenry inductance from node SWITCH to ground The "1" in column 80 requests output of the current in this inductance. Line 6 specifies a 5-microfarad capacitance from node CAP to ground. A switch defined on Line 8 connects the two nodes SWITCH and CAP. It closes after .0005 seconds and opens after 1 second (which is after the simulation ends). There are no sources in this simulation.

Line 11 specifies an initial voltage of one volt at node CAP. Line 12 specifies an initial current of zero and branch voltage of one volt for the branch from node CAP to ground. Together, these cards specify the trapped charge on the capacitor. Line 13 requests output of the voltage to ground at node CAP.

Line 15 requests batch-node CALCOMP plots, each captioned with the title on Line 16. Line 17 requests a plot of the branch current from node SWITCH to ground. The time axis units will be milliseconds. The total time axis length is 10 milliseconds, with 1 millisecond per division. Vertical axis scaling is left to the program. Line 18 requests a plot of the node voltage from CAP to ground. The next two lines end the plots and shut off the EMTP.

Printed output is shown in Table IV.2. The steady-state solution printout is bypassed because there are no sources active in the steady state. The network connection printout contains three lines. The first line indicates three branches connected to node SWITCH. Two are connected to node TERRA (or ground), namely the resistance and inductance. The other, connected to node CAP, is the switch. The next line indicates two branches connected to node CAP. The first, to node TERRA, is the capacitance. The second, to node SWITCH, is the switch. The third line indicates three branches connected to ground. The first two, connected to node SWITCH, are the resistance and inductance. The third one, connected to node CAP, is the capacitance. Therefore, each branch has two entries in the connectivity table, one for each terminal.

The time step printout consists only of the first and last step because IOUT was specified very high. The first variable is the capacitor voltage, and the second is the inductor current. The actual switch closing time is included in the time step printout.

The second part of Table IV.2 is the maximum and minimum value printout. It shows that the capacitor voltage reached -.924867 volts on the initial overshoot, which is not quite -1.0 volts, as expected. The peak inductor current was .0304091 amps, which is not quite .0316 amps, again as expected.

The plotted capacitor voltage and inductor current are shown in Figure IV.5. They display lightly damped 1000 Hz oscillations which are settling into the predicted final values.

TABLE IV.2

EMTP Printed Output for Parallel RLC Circuit

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CRAY TRANSLATION, PRODUCED BY THE WESTINGHOUSE ELECTRIC CORPORATION, AST DIVISION.
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =   03/22/85  17:00:19   ANY PLOTS BEAR THE SAME FIGURES.
FOR INFORMATION, CONSULT THE 840-PAGE EMTP RULE BOOK DATED   MARCH,   1983.   PROGRAM VERSION = "M35."
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS  96419  INTEGER WORDS.    602   600   600   150  4000
   104  5400 15000   100   150   150   150    8    8   50    9    4   24  8000  1000   100   100  4000    9  1500    50
-----------------------------------------------+--------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA 1 INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
-----------------------------------------------+--------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.              1BEGIN NEW DATA CASE
MISC. DATA.     0.100E-04   0.100E-01   0.000E+00 1  10.E-6  10.E-3
MISC. DATA. 20000    1  1  1  1  0  0  0  0  0    1  20000       1       1       1       1
SERIES R-L-C.     0.632E+03  0.000E+00  0.000E+00 1  SWITCH                632.46
SERIES R-L-C.     0.000E+00  0.500E+01  0.000E+00 1  SWITCH                          5.
SERIES R-L-C.     0.000E+00  0.000E+00  0.500E+01 1  CAP                                   5
BLANK CARD TERMINATING BRANCH CARDS.              1BLANK CARD ENDING BRANCHES
SWITCH.    0.50E-03  0.10E+01  0.00E+00  0.00E+00 1  CAP    SWITCH     .0005        1.
BLANK CARD TERMINATING SWITCH CARDS.              1BLANK CARD ENDING SWITCHES
BLANK CARD TERMINATING SOURCE CARDS.              1BLANK CARD ENDING SOURCES

LIST OF INPUT ELEMENTS CONNECTED TO EACH BUS.
         1) ONLY THE PHYSICAL CONNECTIONS OF MULTIPHASE LINES ARE SHOWN (CAPACITIVE AND INDUCTIVE COUPLING IGNORED)
         2) REPEATED ENTRIES IMPLY PARALLEL CONNECTIONS
         3) SOURCES ARE OMITTED, ALTHOUGH SWITCHES ARE INCLUDED;
         4) U.M. USAGE PRODUCES EXTRA, INTERNALLY-DEFINED NODES "UM????" (1ST 2 LETTERS "UM").
FROM BUS NAME 1 NAMES OF ALL ADJACENT BUSSES
--------------+--------------------------------------------------------------------------------------------------
        SWITCH1TERRA *TERRA *CAP   *
        CAP   1TERRA *SWITCH*
        TERRA 1SWITCH*SWITCH*CAP   *
--------------+--------------------------------------------------------------------------------------------------

NODE VOLT INIT COND.  0.100E+01  0.000E+00    0.0 1 2CAP            1.0
LINEAR I.      0.0000E+00  0.1000E+01  0.0000E+00 1 3CAP                    0.          1.0
COMMENT CARD.                                     1C END OF INITIAL CONDITIONS
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.        1  CAP
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT.  1BLANK CARD ENDING NODE VOLTAGE OUTPUT

COLUMN HEADINGS FOR THE   2  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
  FIRST   1  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)\
   NEXT   0  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)\
   NEXT   1  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)\
   NEXT   0  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY\
  FINAL   0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING\
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

 STEP    TIME        CAP          SWITCH
                                  TERRA
    0 0.000000 0.100000E+01 0.000000E+00
***                                                         SWITCH  "CAP   "  TO  "SWITCH"  CLOSED AFTER  0.510000E-03 SEC.
 1000 0.010000-0.214509E+00-0.181309E-02

MAXIMA AND MINIMA WHICH OCCURRED DURING THE SIMULATION FOLLOW.   THE ORDER AND COLUMN POSITIONING ARE THE
SAME AS FOR THE REGULAR PRINTED OUTPUT VS. TIME.
VARIABLE MAXIMA %
               0.100000E+01 0.304031E-01
TIMES OF MAXIMA %
               0.300000E-04 0.760000E-03
VARIABLE MINIMA %
              -0.924867E+00-0.281067E-01
TIMES OF MINIMA %
               0.100000E-02 0.126000E-02
```

Table IV.3 shows the input file for an EMTP simulation of a series RLC circuit transient similar to that depicted in Figures IV.3 and IV.4. The values of L and C are unchanged, but now R = 1.5811 ohms. The values of Z and f_0 are unchanged, but now for a series circuit we have:

$$\lambda = \frac{Z}{R} = \frac{31.62}{1.5811} = 20$$

The damping characteristics should be similar to the ones in Figure IV.5 because of the duality between series and parallel RLC circuits.

In this simulation, a battery source will simply be turned on at time zero to energize the circuit. The initial capacitor voltage starts at zero and will finish at one volt, with a peak value on the overshoot slightly less than two volts. The inductor current starts and ends at zero, but reaches a peak value slightly less than V_{bat}/Z, or .0316 amps.

TABLE IV.3

EMTP Input for Series RLC Circuit

```
BEGIN NEW DATA CASE
  10.E-6  10.E-3
   20000       1        1        1        1
  SOURCECAP                  1.5811    5.
  CAP                                            5.
BLANK CARD ENDING BRANCHES
BLANK CARD ENDING SWITCHES
11SOURCE            1.
BLANK CARD ENDING SOURCES
  CAP
BLANK CARD ENDING NODE VOLTAGE OUTPUT
  CALCOMP PLOT
 2 SERIES RLC CIRCUIT WITH STEP VOLTAGE INPUT
 1941.0   '10.0           SOURCECAP
 1441.0    10.0           CAP
BLANK CARD ENDING PLOTS
BLANK CARD ENDING THE CASE
```

Line 4 of the input file in Table IV.3 specifies a series RLC branch between nodes SOURCE and CAP, with R = 1.5811 ohms, L = 5 millihenries, and C = 0. The "1" in column 80 requests output of the inductor current. To obtain an output of the capacitor voltage, a separate branch from node CAP to ground is specified on Line 5. There are no switches, but a one-volt d.c. source from node SOURCE to ground is specified on line 8. It will be turned on at time zero. Line 10 requests output of the capacitor voltage from node CAP to ground. The plotting cards are similar to those in Table IV.1, except that the plotted branch current is from node SOURCE to node CAP.

Table IV.4 presents the printed output from this simulation. Once again the steady-state printout is omitted because there are no power frequency sources. Note that the d.c. source is not included in the connectivity table. The peak capacitor voltage is 1.92395 volts, which is slightly less than 2.0 volts, as expected. The peak inductor current is .0304092 amps, nearly identical to the peak value from the parallel RLC circuit case. The plotted capacitor voltage and inductor current are presented in Figure IV.6, and both display lightly damped 1000 Hz oscillations.

The damping in a series RLC circuit can be increased by increasing the value of R, which reduces λ. The case was repeated with λ values of 4, .5, and .1. The results are plotted in Figures IV.7, IV.8, and IV.9. A summary of the case input parameters is shown in Table IV.5.

The case of $\lambda = 4$ displays much more damping, but the transient is still oscillatory. The peak capacitor voltage and inductor current are both reduced. With $\lambda = .5$, the oscillation is critically damped. There is no capacitor voltage overshoot, and the voltage approaches its final value exponentially. The inductor current follows a double exponential with sharply-reduced peak value. When $\lambda = .1$, both the capacitor voltage and inductor current take longer to reach their final values due to the lengthened circuit time constant.

TABLE IV.4

EMTP Printed Output for Series RLC Circuit

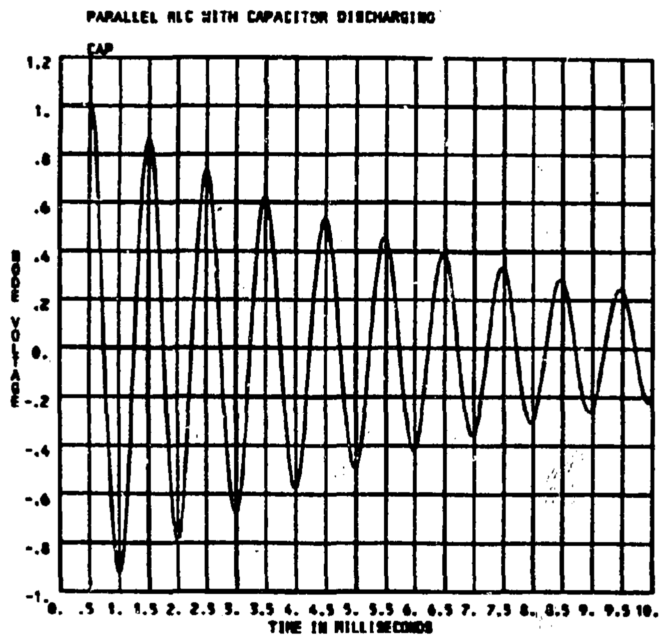
```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CRAY TRANSLATION. PRODUCED BY THE WESTINGHOUSE ELECTRIC CORPORATION, AST DIVISION.
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =   03/25/85  16:31:30   ANY PLOTS BEAR THE SAME FIGURES.
FOR INFORMATION, CONSULT THE 840-PAGE EMTP RULE BOOK DATED   MARCH.   1983.   PROGRAM VERSION = "M35."
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF    /LABEL/   EQUALS  96419  INTEGER WORDS.      602    600    600    150  4000
   104  5400 15000    100    150    150    150     8     8    50     9     4    24  8000  1000   100   100  4000     9  1500    50
----------------------------------------------+-----------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA 1 INPUT DATA CARD IMAGES PRINTED BELOW. ALL 80 COLUMNS. CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
----------------------------------------------+-----------------------------------------------------------------------------------
MARKER CARD PRECEDING NEW DATA CASE.            |BEGIN NEW DATA CASE
MISC. DATA.     0.100E-04   0.100E-01  .000E+00 |  10.E-6   10.E-3
MISC. DATA. 20000   1   1   1   1   0   0   0   |  20000       1         1         1         1
SERIES R-L-C.    0.158E+01  0.500E+01 0.000E+00 |  SOURCECAP                  1.5811    5.
SERIES R-L-C.    0.000E+00  0.000E+00 0.500E+01 |  CAP                                           5.
BLANK CARD TERMINATING BRANCH CARDS.            |BLANK CARD ENDING BRANCHES
BLANK CARD TERMINATING SWITCH CARDS.            |BLANK CARD ENDING SWITCHES
SOURCE.    0.10E+01  0.00E+00  0.00E+00  0.00E+00 |11SOURCE          1.
BLANK CARD TERMINATING SOURCE CARDS.            |BLANK CARD ENDING SOURCES

LIST OF INPUT ELEMENTS CONNECTED TO EACH BUS.
        1) ONLY THE PHYSICAL CONNECTIONS OF MULTIPHASE LINES ARE SHOWN (CAPACITIVE AND INDUCTIVE COUPLING IGNORED)
        2) REPEATED ENTRIES IMPLY PARALLEL CONNECTIONS
        3) SOURCES ARE OMITTED, ALTHOUGH SWITCHES ARE INCLUDED;
        4) U.M. USAGE PRODUCES EXTRA, INTERNALLY-DEFINED NODES "UM????" (1ST 2 LETTERS "UM").
FROM BUS NAME 1 NAMES OF ALL ADJACENT BUSSES
--------------+----------------------------------------------------------------------------------------------------
       SOURCE |CAP    *
       CAP    |TERRA  *SOURCE*
       TERRA  |CAP    *
--------------+----------------------------------------------------------------------------------------------------

CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.        |  CAP
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT.  |BLANK CARD ENDING NODE VOLTAGE OUTPUT

COLUMN HEADINGS FOR THE    2  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
  FIRST    1  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)\
   NEXT    0  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)\
   NEXT    1  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)\
   NEXT    0  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY\
  FINAL    0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING\
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

 STEP      TIME         CAP            SOURCE
                                       CAP
    0  0.000000  0.000000E+00  0.000000E+00
 1000  0.010000  0.804031E+00  0.218249E-02

MAXIMA AND MINIMA WHICH OCCURRED DURING THE SIMULATION FOLLOW.   THE ORDER AND COLUMN POSITIONING ARE THE
SAME AS FOR THE REGULAR PRINTED OUTPUT VS. TIME.
VARIABLE MAXIMA %
                  0.192395E+01 0.304092E-01
TIMES OF MAXIMA %
                  0.500000E-03 0.250000E-03
VARIABLE MINIMA %
                  0.000000E+00-0.281068E-01
TIMES OF MINIMA %
                  0.000000E+00 0.750000E-03
```

Two other cases were run with $\lambda = 20$ and longer time steps, as indicated in Table IV.5. The results for a time step of 200 microseconds are shown in Figure IV.10. There are 5 time steps per cycle of oscillation. The correct frequency and damping rate are indicated, but the peak values are significantly less than the correct values plotted in Figure IV.6. When the time step is further increased to 1000 microseconds, there is one time step per cycle of oscillation. The results plotted in Figure IV.11 bear little similarity to the true nature of the phenomena. However, the simulation is numerically stable, and both variables will eventually settle in to the correct final values. These cases illustrate the importance of selecting an appropriate time step to obtain accurate results.

TABLE IV.5

EMTP Simulations of Series RLC Circuits

Figure Number	R [ohms]	L [mH]	C [μF]	Z [ohms]	f_0 [Hz]	λ	Δt [μ-sec]
IV.6	1.5811	5.0	5.0	31.62	1007	20	10
IV.7	7.9057	5.0	5.0	31.62	1007	4	10
IV.8	63.246	5.0	5.0	31.62	1007	.5	10
IV.9	316.23	5.0	5.0	31.62	1007	.1	10
IV.10	1.5811	5.0	5.0	31.62	1007	20	200
IV.11	1.5811	5.0	5.0	31.62	1007	20	1000



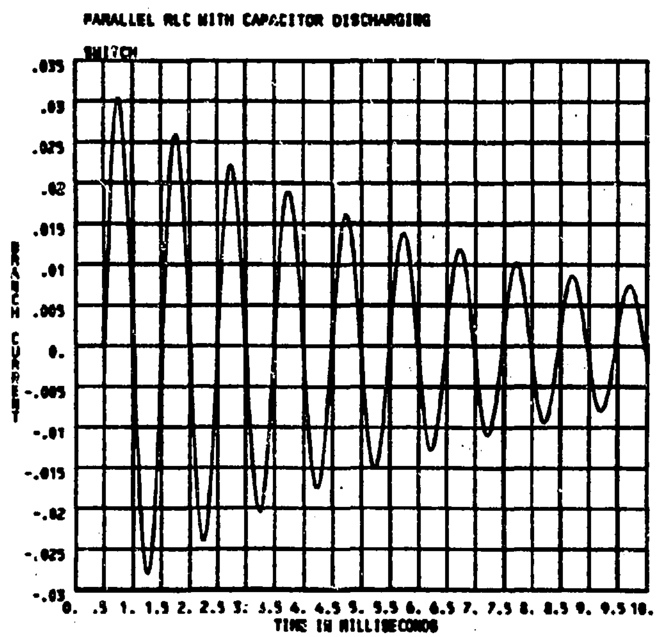
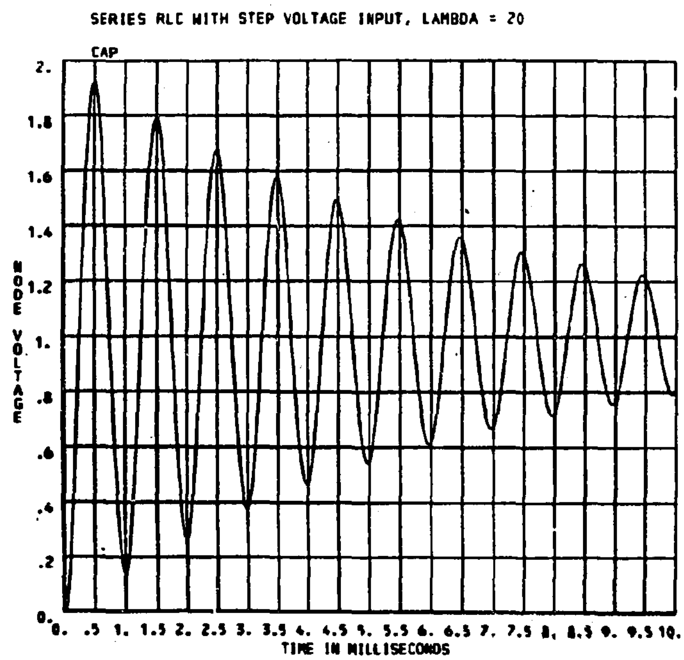


FIGURE IV.5. Capacitor Voltage and Inductor Current for Parallel RLC Circuit Simulation



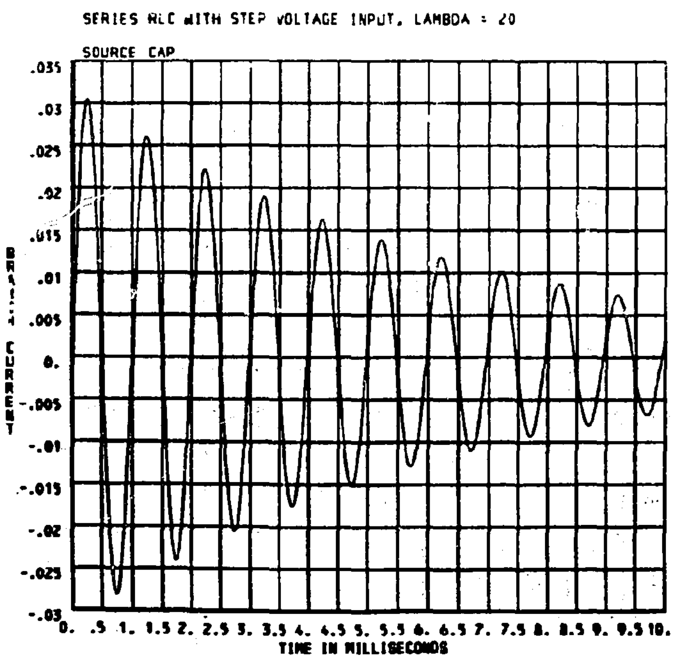
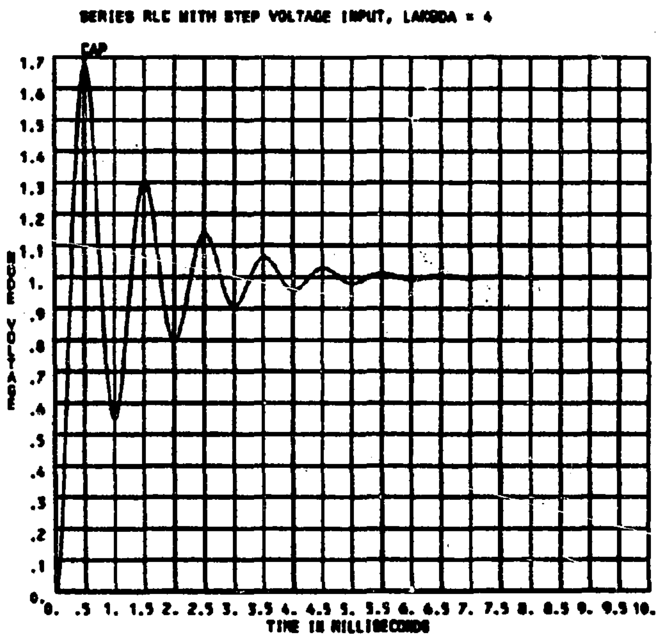


FIGURE IV.6. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 10$ μsec



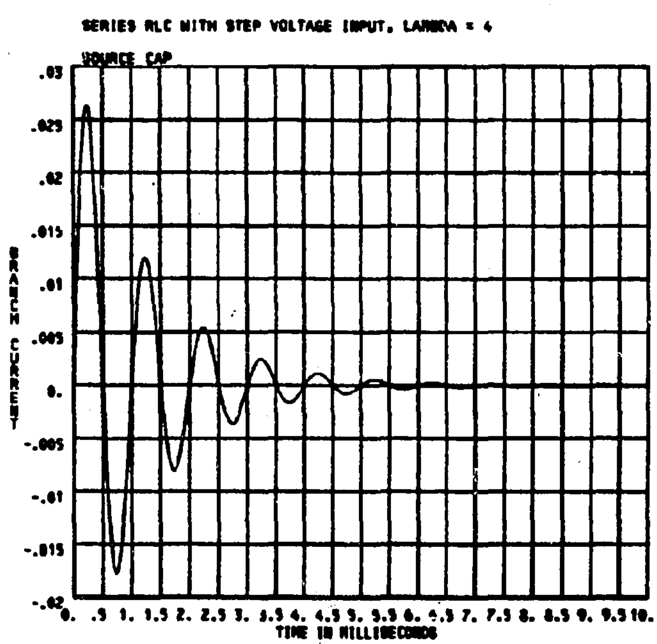
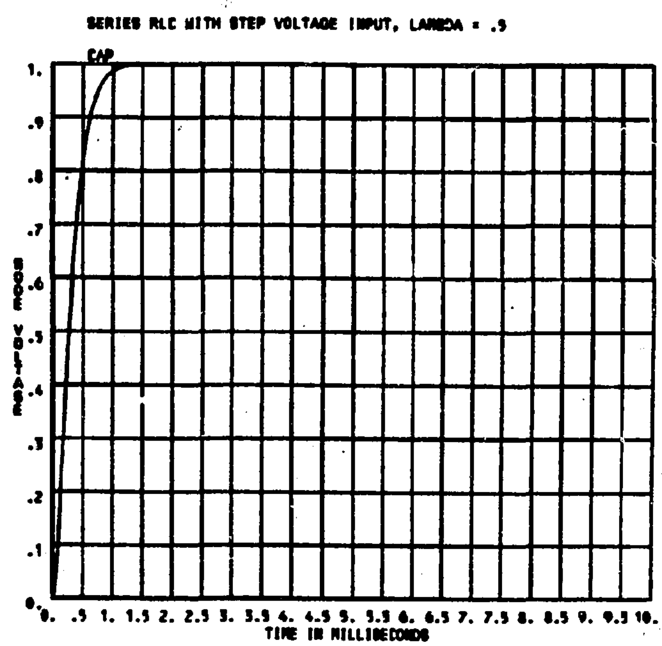


FIGURE IV.7. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 4$, $\Delta t = 10$ μsec



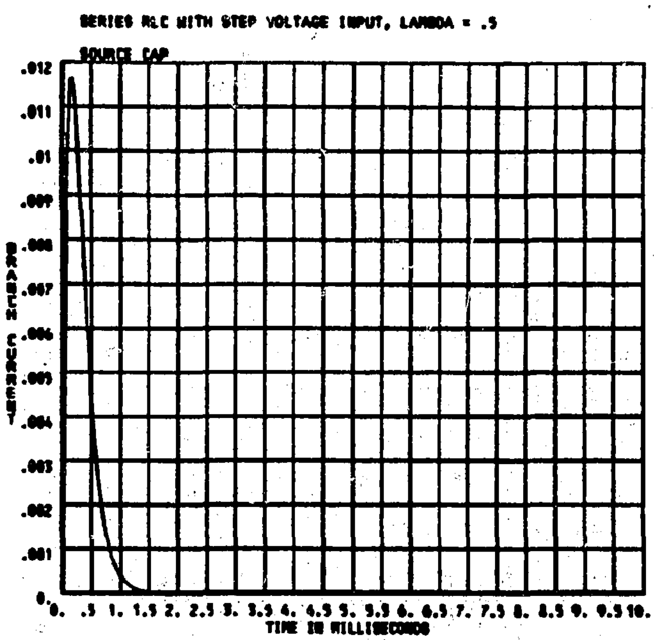


FIGURE IV.8. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = .5$, $\Delta t = 10\ \mu sec$

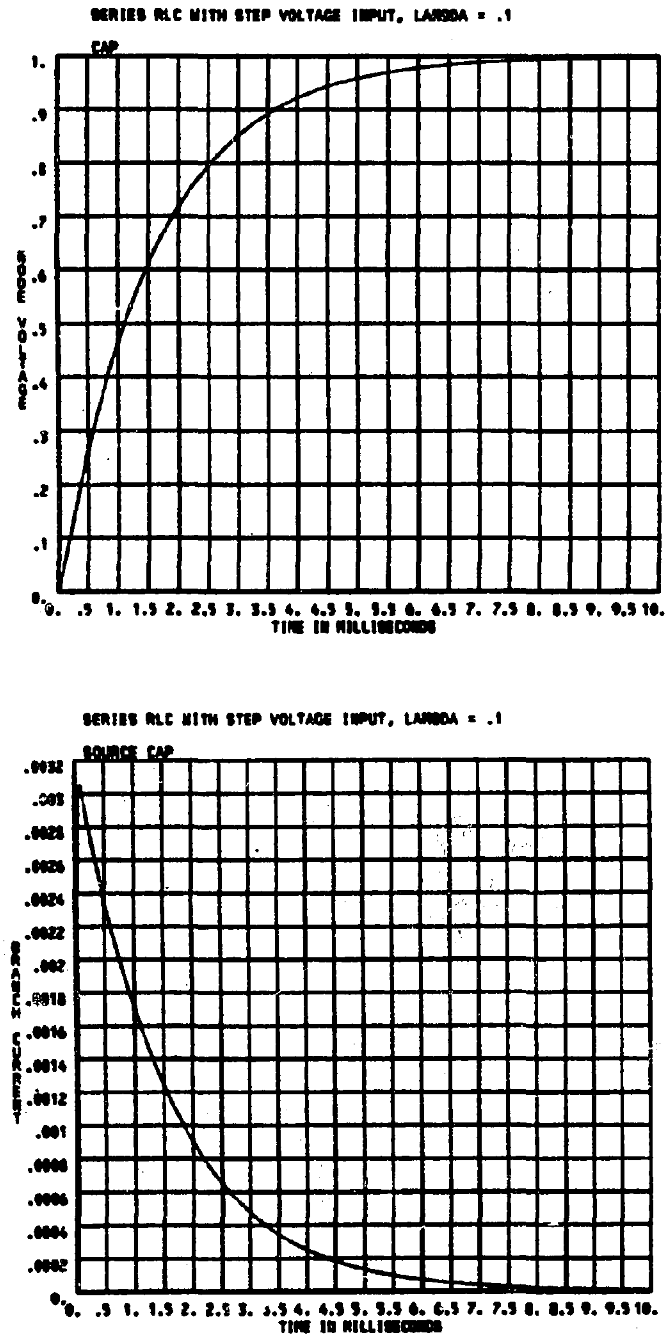
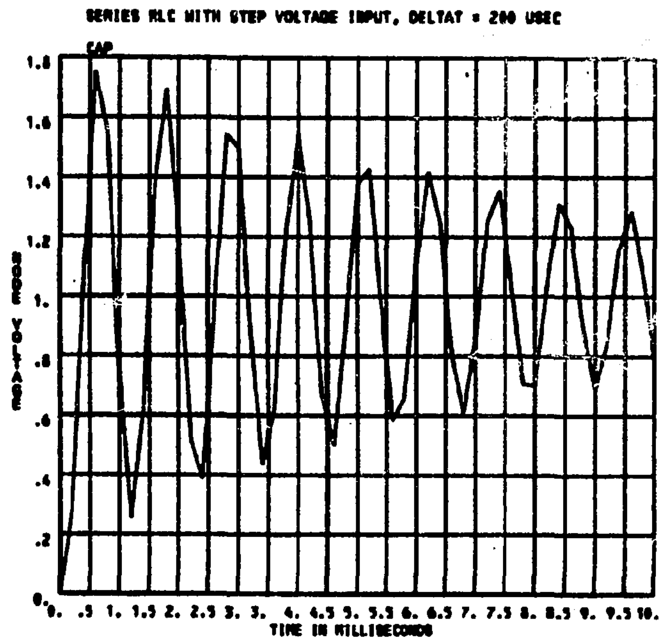


FIGURE IV.9. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = .1$, $\Delta t = 10\ \mu sec$



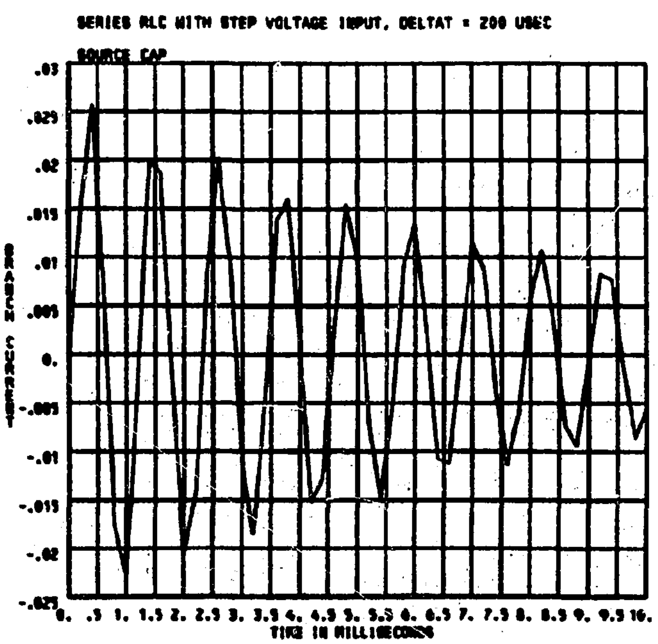
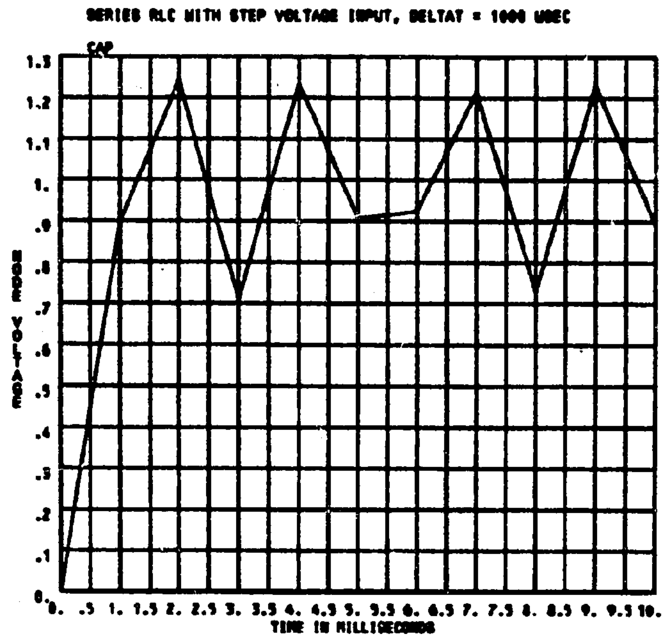


FIGURE IV.10. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 200$ μsec



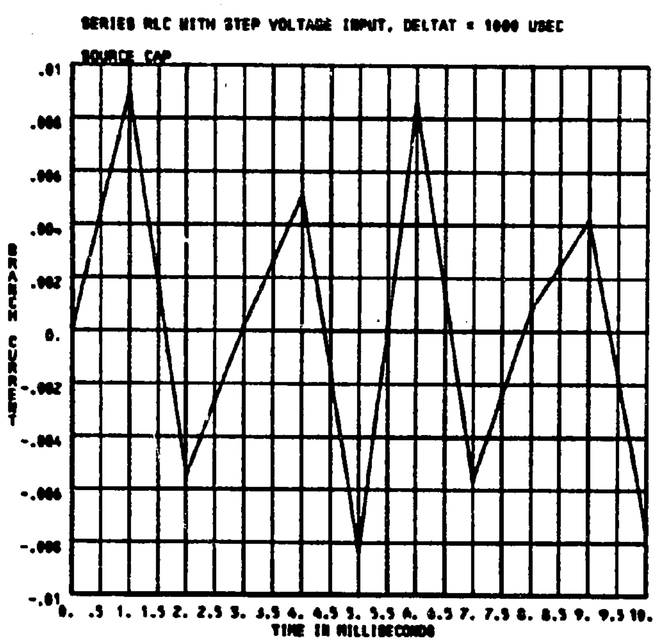


FIGURE IV.11. Capacitor Voltage and Inductor Current for Series RLC Circuit Simulation, $\lambda = 20$, $\Delta t = 1000$ μsec

Section 1

CASE 1: SINGLE AND DOUBLE FREQUENCY LUMPED CIRCUITS

This sample case applies the simple single-phase lumped parameter circuits introduced in Section IV to a practical power system problem. It illustrates simplification of the model to obtain still-valid results. The results are easily verified by hand calculations.

Two auxiliary voltage levels, 13.8 kV and 4.16 kV, are used in a power plant, as shown in Figure 1.1. Assume that the circuit breaker to the main auxiliary transformer is open, and, therefore, the auxiliary buses are supplied only through the startup transformer. The following fault conditions are considered: Fault "A" is a three-phase-to-ground fault on the 13.8-kV bus, and Fault "B" is a three-phase-to-ground fault on the low side of the 13.8/4.16-kV transformer. The faults would be cleared by Breakers A and B, respectively.

In order for the circuit breakers to interrupt successfully, the fault current and the recovery voltage (voltage across the breaker contacts after interruption) have to be within the rated capability of the circuit breakers. The objective of these cases is to calculate the transient recovery voltage (TRV) across Circuit Breakers A and B, respectively.

The intent of these cases is to familiarize the reader with the use of the EMTP program by simulating simple circuits with lumped elements. Only lumped inductive and capacitive elements, a switch, and a voltage source are represented. Also, the output and plotting requests are kept as simple as possible. These problems can probably be solved easier by hand calculation, but they give practice in setting up simple input files. It is not the intent of these cases to familiarize the readers with Transient Recovery Voltage (TRV), which can be done by studying References (2) and (3). The data selected for the various components are realistic typical values in order to get reasonable results.

A simplified system representation for a three-phase-to-ground fault on the terminals of Breaker A is shown in Figure 1.2. This system is further simplified for the EMTP cases.

The key element is the representation of the transformer. C_H is the high-side capacitance, C_{HL} is the capacitance between the high and low windings, and C_L is the low-side capacitance.

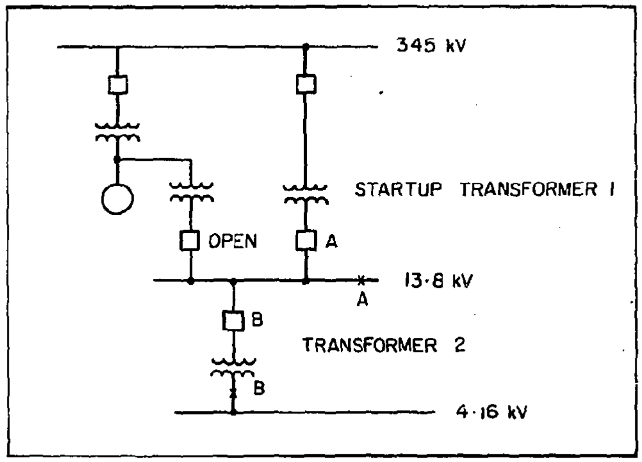


FIGURE 1.1. Simplified Power Plant One-Line Diagram

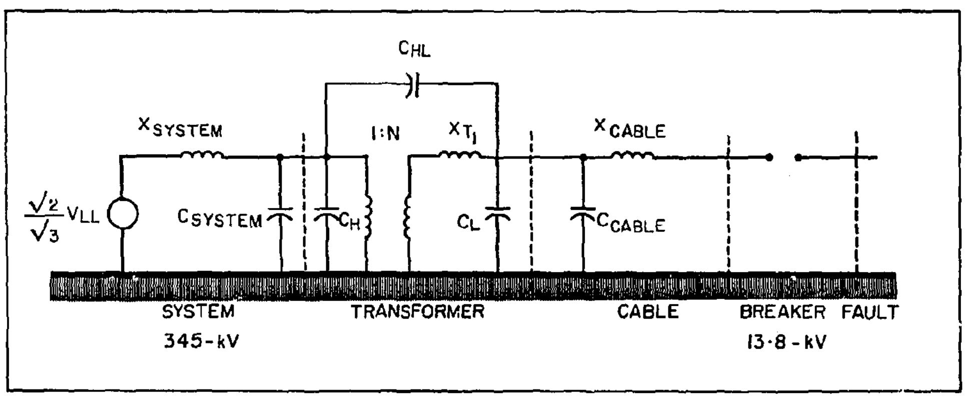


FIGURE 1.2. Simplified Representation For Three-Phase-To-Ground Fault

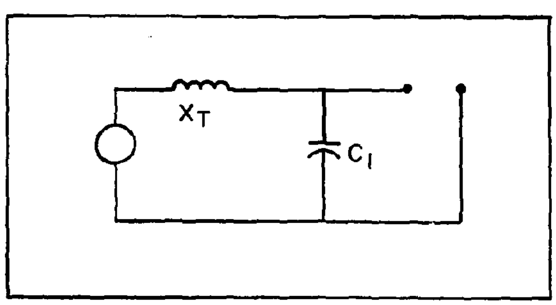


FIGURE 1.3. Simplified Equivalent Circuit

For a relatively stiff 345-kV system, the transformer leakage inductance and secondary capacitance will dominate any high frequency transients which occur on the 13.8-kV system because the low X_{system} effectively shorts out C_H. Therefore, the equivalent circuit can be simplified as shown in Figure 1.3. C_1 represents the transformer secondary capacitance, C_L, in parallel with the cable capacitance, C_{cable}. This circuit produces a circuit breaker TRV with a (1-cosine) shape.

The following system characteristics are assumed:

System:	X_1 = .02 p.u. (on 100 MVA)
Transformer 1:	345/13.8 kV; 60 MVA; 7% Impedance; wye/wye connected X_{T_1} = .117 p.u. (on 100 MVA) or L_1 = .589 mH at 13.8 kV C_L = .02 μF
Cable:	C_{cable} = .09 μF (15-kV class, 1000 feet 3/c belted paper-insulated cable) X_{cable} ignored $C_1 = C_L + C_{cable}$ = .11 μF
Fault:	Represented by a .1 Ω resistance split on each side of the circuit breaker

The natural frequency of the L-C circuit can be calculated as:

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{(.589 \times 10^{-3})(.11 \times 10^{-6})}} = 19{,}772 \text{ Hz} \tag{1-1}$$

The TRV will have a (1-cosine) shape with a time to crest of 1/2f or 25.3 μs.

Since no damping was included in the circuit, the peak of the recovery voltage will be 2 per-unit ($2 \times 13.8 \times \sqrt{2}/\sqrt{3}$) or 22.54 kV.

Figure 1.4 shows the circuit as represented in the EMTP. Since a three-phase grounded fault is represented, only a single-phase representation is necessary. The figure also gives the names which were assigned to the nodes. The user might find it convenient to use mnemonic combinations of letters and numbers to identify the nodes. This can become very important when complicated circuits are studied.

The node names selected stand for:

TRAN1H	--	Transformer 1 - high side
TRAN1L	--	Transformer 1 - low side
BKR 1	--	Circuit Breaker A, Contact 1
BKR 2	--	Circuit Breaker A, Contact 2

Table 1.1 gives the basic input data for the case. Table 1.2 shows the same input data, but several comment lines have been added. The purpose of the many comment lines is to make it easier for a beginning EMTP user to interpret the input data and to be able to create simple input files without consulting any other manual.

This input file gives all column headings in abbreviated form, and it also gives the column numbers for each entry. The user might find it helpful to identify the file with a short case description at the beginning of the file.

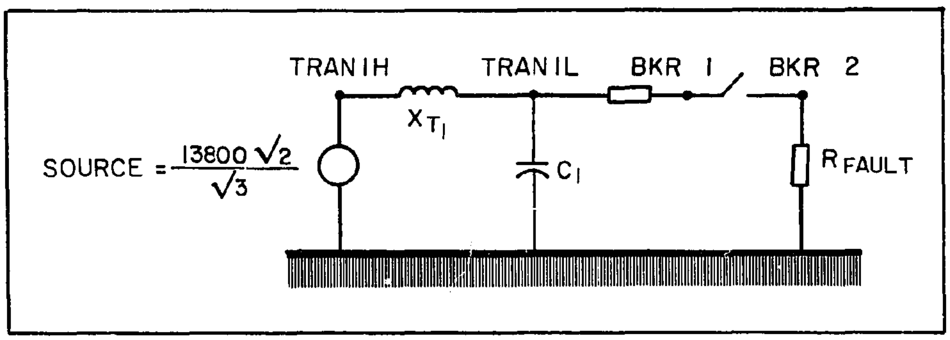


FIGURE 1.4. Circuit Modelled For the Single-Frequency Case

TABLE 1.1

<u>Input Data for the Single-Frequency Case</u>

```
BEGIN NEW DATA CASE
  2.0E-6 300.E-6       0       0
       5       1       1       1       0       0       0       1
  TRAN1HTRAN1L                  .58900
  TRAN1L                              .11000
  TRAN1LBKR  1            .05000
  BKR  2                  .05000
  BKR  1BKR  2      -1.0    1.0E-6                                             3
BLANK CARD TERMINATING BRANCH CARDS
BLANK CARD TERMINATING SWITCH CARDS
14TRAN1H      11267.      60.0     -25.0                              -1.0
BLANK CARD TERMINATING SOURCE CARDS
  TRAN1HBKR  1BKR  2
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT REQUESTS
  CALCOMP PLOT                 2
 2 EXAMPLE 1 - SINGLE FREQUENCY LUMPED CIRCUIT
 14525.     300.        TRAN1H
 14525.     300.        BKR  1
 14525.     300.        BKR  2
 18525.     300.        BKR  1BKR  2
 19525.     300.        BKR  2BKR  1
BLANK CARD TERMINATING PLOT REQUESTS
BLANK CARD TERMINATING THE CASE
```

The calculation time step was chosen to be 2 microseconds. Since the circuit's natural frequency is 19,772 Hz, there will be approximately 25 time steps per oscillation period of 51 microseconds. The time step should be chosen with the highest expected transient frequency in mind.

Large time steps will not lead to numerical instability, but will tend to filter out or alias the higher frequency transients, possibly yielding misleading results.

Branches and other elements connected to ground only list the BUS 1 node, and the BUS 2 node remains blank. For example, the capacitance, C_1, of .11 μF is connected from TRAN1L to ground. The input data for BUS 1 and BUS 2 read "TRAN1L" "   ".

The results are shown in Figures 1.5 and 1.6. Figure 1.5 shows the sinusoidal fault current which has a ramp shape prior to current zero. The circuit breaker opens at time t = 34 μs. The TRV across the breaker (nodes "BKR 1" to "BKR 2") starts to build up after time t = 34 μs. The observed values of peak voltage and frequency for the TRV compare well with the previously calculated values. Since no supply-side resistance was represented, the TRV is an undamped oscillation.

Hand calculations predicted a 2 per-unit peak TRV, but the result in Figure 1.6 shows 20.5 kV, which is only 1.82 per-unit. The reduction occurs because the fault current is not interrupted at a peak in the source voltage. The simulated fault resistance of .1 ohms causes the fault current to not be purely inductive, which in turn means that the source voltage is approximately 25 degrees before a peak when current zero occurs.

The source voltage phase angle in Table 1.2 was chosen to be -25 degrees because the fault current lags the voltage by 65.8 degrees. It is made active in the steady-state by specifying T-START equal to -1.0 seconds in columns 61-70. The choice of phase angle means that a current zero occurs shortly after time zero in the simulation.

In order to familiarize the reader with the output of the EMTP program, the complete printout of the single frequency case is shown in Table 1.3. First, the input data is printed out. On the right-hand side are the card images of the data, and on the left is an "interpretation" of the input data. When an input value is in an incorrect column, the interpretation of the number is different from the entry on the right. The interpretation should be checked to ensure that all data entries were read correctly.

If a "1" is placed on the second miscellaneous card's column 24, the network connections are printed out. All branch and switch connections to each bus are printed. This serves as a very good check that all the branches are connected to the correct nodes.

A steady-state printout was requested by putting a "1" in column 32 on the second misellaneous data card. For each node, the node voltage is given in rectangular and in polar form. For each branch, the current (rectangular and polar) and the power flow (P and Q) are given.

A printout of each fifth time step was requested (columns 1-8, second comment card). The printout lists the time when a circuit breaker closes or opens. In most cases a printout of the data points is not necessary, especially when a CALCOMP plot is requested. If CALCOMP software is not available, line printer plots can be made using the same plot request input, except that the keyword becomes PRINTER PLOT rather than CALCOMP PLOT. These line printer plots are usually awkward to use. As another alternative, the raw plot data can be dumped into a file for later plotting by an in-house program. The plot data dump is requested by placing a 1 in column 64 of the second miscellaneous data card, underneath the description, "dump into disk," in Table 1.2. In these cases, the CALCOMP PLOT request cards were commented out, and the plots were made with a separate postprocessing program.

TABLE 1.2

Commented Input Data For the Single-Frequency Case

```
C FILE NAME: "SING.OSC.". FAULT ON THE 13.8 KV BUS. SINGLE OSCILLATION TRV
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     1-8    9-16   17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C                  F(HZ)   F(HZ)
  2.0E-6 300.E-6       0       0
C
C SECOND MISCELLANEOUS DATA CARD
C     1-8    9-16   17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT     PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  ENERG.   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
       5       1       1       1       0       0       0       1
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.                 (OUTPUT IN COLUMN 80)
C                  BRANCH           MH    UF                                    I=  1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                                    V=  2
C                                                                               I,V 3
C                                                                               P,E 4
  TRAN1HTRAN1L                      .58900
  TRAN1L                                  .11000
  TRAN1LBKR  1                .05000
  BKR  2                      .05000
BLANK CARD TERMINATING BRANCH CARDS
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24     25-34     35-44     45-54     55-64     65-74
C                                                    (OUTPUT OPTION IN COLUMN 80)
C   NODE NAMES                          IE FLASHOVER   SPECIAL   REFERENCE
C                 TIME TO   TIME TO     OR   VOLTAGE   REQUEST SWITCH-NAME
C   BUS1  BUS2      CLOSE      OPEN   NSTEP               WORD  BUS5  BUS6
  BKR  1BKR  2       -1.0    1.0E-6                                                 3
BLANK CARD TERMINATING SWITCH CARDS
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17.(E.G. 11-13 ARE RAMP FUNCTIONS. 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE. -1=CURRENT SOURCE
C    3-8        11-20     21-30     31-40     41-50     51-60     61-70     71-80
C   NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1   TIME-T1   T-START    T-STOP
C   NAME                  IN HZ      DEGR             SECONDS   SECONDS   SECONDS
14TRAN1H       11267.      60.0     -25.0                           -1.0
BLANK CARD TERMINATING SOURCE CARD
C NODE VOLTAGE OUTPUT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C   BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  TRAN1HBKR  1BKR  2
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT

C PLOTTING OF THE RESULTS
  CALCOMP PLOT                2
C (CASE TITLE UP TO 78 CHARACTERS)
 2 EXAMPLE 1 - SINGLE FREQUENCY LUMPED CIRCUIT
C COLUMN 2,    "1"
C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
C COLUMN 4, UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C                       UP TO  4 NODE NAMES FOR               49-64           65-80
C                             NODE VOLTAGE PLOTS
C                       UP TO  2 PAIRS OF  NODE               GRAPH   VERTICAL AXIS
C                       NAMES FOR  BRANCH  OR               HEADING         HEADING
C                                   SWITCH PLOTS                LABEL           LABEL
C                       1ST  ELEMENT 2ND ELEMENT
C                        25-30 31-36 37-42 43-48
C                         BUS1  BUS2  BUS3  BUS4
 14525.    300.           TRAN1H
 14525.    300.           BKR  1
 14525.    300.           BKR  2
 18525.    300.           BKR  1BKR  2
 19525.    300.           BKR  2BKR  1
BLANK CARD TERMINATING PLOTTING
BLANK CARD TERMINATING THE CASE
```

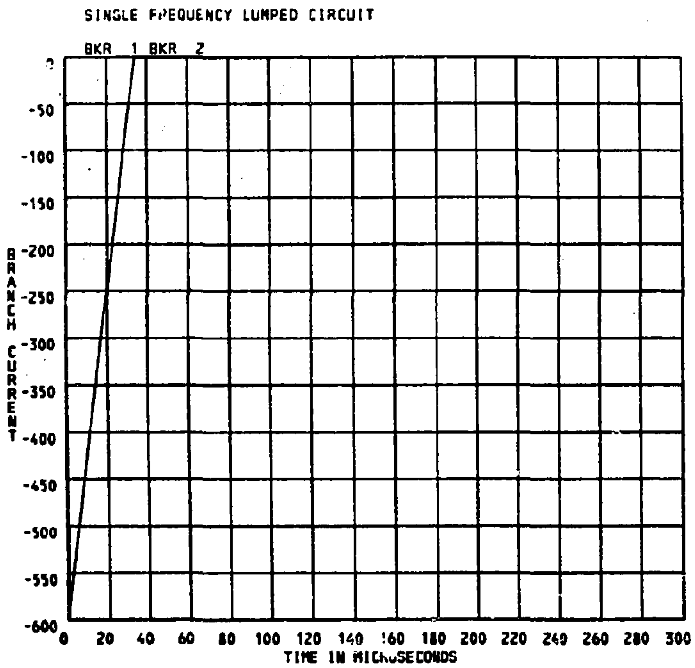


FIGURE 1.5. Fault Current

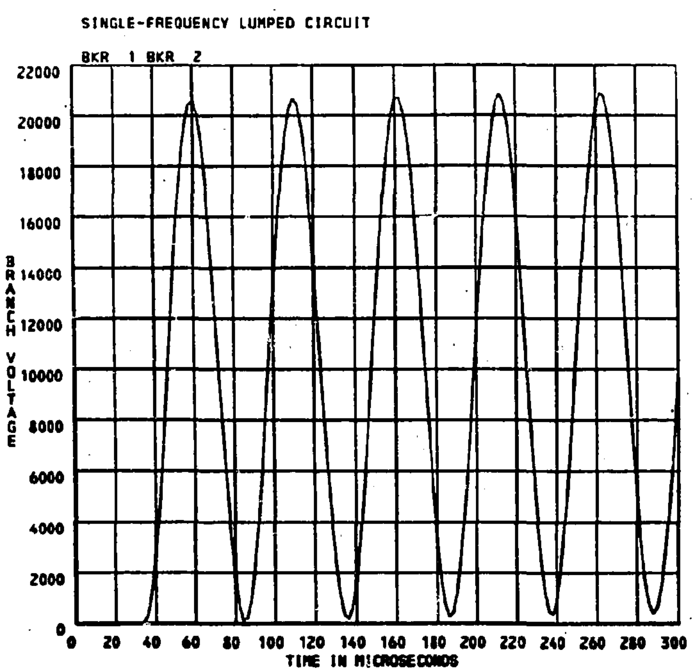


FIGURE 1.6. Circuit Breaker Recovery Voltage

TABLE 1.3

Printed Output For Single-Frequency Case

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CRAY TRANSLATION, PRODUCED BY THE WESTINGHOUSE ELECTRIC CORPORATION, AST DIVISION.
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =   04/04/85  07:29:38    ANY PLOTS BEAR THE SAME FIGURES.
FOR INFORMATION, CONSULT THE 840-PAGE EMTP RULE BOOK DATED    MARCH,    1983.   PROGRAM VERSION = "M35."
INDEPENDENT LIST LIMITS FOLLOW.    TOTAL LENGTH OF     /LABEL/    EQUALS  96419  INTEGER WORDS.       602    600    600    150  4000
    104  5400 15000    100    150    150    150    8     8     50     9     4    24  8000  1000    100    100  4000     9  1500    50
--------------------------------------------------+--------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
--------------------------------------------------+--------------------------------------------------------------------------------
COMMENT CARD.                                     1C FILE NAME: "SING.OSC.", FAULT ON THE 13.8 KV BUS, SINGLE OSCILLATION TRV
MARKER CARD PRECEDING NEW DATA CASE.              1BEGIN NEW DATA CASE
COMMENT CARD.                                     1C FIRST MISCELLANEOUS DATA CARD:
COMMENT CARD.                                     1C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     1C    1-8     9-16    17-24    25-32
COMMENT CARD.                                     1C T-STEP   T-MAX    X-OPT    C-OPT
COMMENT CARD.                                     1C SECNDS SECONDS     O=MH     O=UF
COMMENT CARD.                                     1C                   F(HZ)    F(HZ)
MISC. DATA.      0.200E-05  0.300E-03  0.000E+00  1  2.0E-6 300.E-6      0        0
COMMENT CARD.                                     1C
COMMENT CARD.                                     1C SECOND MISCELLANEOUS DATA CARD
COMMENT CARD.                                     1C    1-8     9-16    17-24    25-32    33-40    41-48    49-56    57-64    65-72    73-80
COMMENT CARD.                                     1C  PRINT     PLOT NETWORK    PR.SS   PR.MAX    I PUN    PUNCH     DUMP    MULT. DIAGNOS
COMMENT CARD.                                     1C O=EACH   O=EACH    O= NO    O= NO    O= NO    O= NO    O= NO     INTO   ENERG.    PRINT
COMMENT CARD.                                     1C K=K-TH   K=K-TH    1=YES    1=YES    1=YES    1=YES    1=YES    DISK  STUDIES     O=NO
MISC. DATA.     5    1   1   1   0   0   0   1   0   0  1       5        1        1        1        0        0        0        1
COMMENT CARD.                                     1C
COMMENT CARD.                                     1C BRANCHES
COMMENT CARD.                                     1C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     1C    3-8   9-14  15-20  21-26  27-32  33-38  39-44
COMMENT CARD.                                     1C   NODE NAMES    REFERENCE   RES.   IND.   CAP.                    (OUTPUT IN COLUMN 80)
COMMENT CARD.                                     1C                    BRANCH           MH     UF                                        I=   1
COMMENT CARD.                                     1C   BUS1   BUS2   BUS3   BUS4    OHM    OHM   UMHO                                       V=   2
COMMENT CARD.                                     1C                                                                                     I,V  3
COMMENT CARD.                                     1C                                                                                     P,E  4
SERIES R-L-C.    0.000E+00  0.589E+00  0.000E+00  1  TRAN1HTRAN1L               .58900
SERIES R-L-C.    0.000E+00  0.000E+00  0.110E+00  1  TRAN1L                            .11000
SERIES R-L-C.    0.500E-01  0.000E+00  0.000E+00  1  TRAN1LBKR   1           .05000
SERIES R-L-C.    0.500E-01  0.000E+00  0.000E+00  1  BKR   2                 .05000
BLANK CARD TERMINATING BRANCH CARDS.              1BLANK CARD TERMINATING BRANCH CARDS
COMMENT CARD.                                     1C SWITCH CARDS
COMMENT CARD.                                     1C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     1C    3-8   9-14        15-24      25-34      35-44     45-54      55-64     65-74
COMMENT CARD.                                     1C                                                       (OUTPUT OPTION IN COLUMN 80)
COMMENT CARD.                                     1C   NODE NAMES                                      IE FLASHOVER   SPECIAL    REFERENCE
COMMENT CARD.                                     1C                     TIME TO    TIME TO            OR    VOLTAGE   REQUEST SWITCH-NAME
COMMENT CARD.                                     1C   BUS1   BUS2        CLOSE       OPEN     NSTEP                      WORD   BUS5   BUS6
SWITCH.    -0.10E+01  0.10E-05  0.00E+00  0.00E+00  1  BKR   1BKR   2         -1.0     1.0E-6                                                   3
BLANK CARD TERMINATING SWITCH CARDS.              1BLANK CARD TERMINATING SWITCH CARDS
COMMENT CARD.                                     1C SOURCE CARDS
COMMENT CARD.                                     1C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     1C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
COMMENT CARD.                                     1C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
COMMENT CARD.                                     1C    3-8        11-20      21-30      31-40      41-50      51-60      61-70      71-80
COMMENT CARD.                                     1C   NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1    TIME-T1    T-START     T-STOP
COMMENT CARD.                                     1C   NAME                  IN HZ       DEGR               SECONDS    SECONDS    SECONDS
SOURCE.     0.11E+05  0.60E+02 -0.25E+02 -0.10E+01  114TRAN1H         11267.       60.0      -25.0                                   -1.0
BLANK CARD TERMINATING SOURCE CARDS.              1BLANK CARD TERMINATING SOURCE CARD

LIST OF INPUT ELEMENTS CONNECTED TO EACH BUS.
        1) ONLY THE PHYSICAL CONNECTIONS OF MULTIPHASE LINES ARE SHOWN (CAPACITIVE AND INDUCTIVE COUPLING IGNORED)
        2) REPEATED ENTRIES IMPLY PARALLEL CONNECTIONS
        3) SOURCES ARE OMITTED, ALTHOUGH SWITCHES ARE INCLUDED;
        4) U.M. USAGE PRODUCES EXTRA, INTERNALLY-DEFINED NODES "UM????" (1ST 2 LETTERS "UM").
```

TABLE 1.3 (Cont'd)

Printed Output For Single-Frequency Case

```
FROM BUS NAME : NAMES OF ALL ADJACENT BUSSES
--------------+-------------------------------------------------------------------------------------------------
        TRAN1H:TRAN1L*
        TRAN1L:TERRA *TRAN1H*BKR   1*
        BKR   1:TRAN1L*BKR  2*
        BKR   2:TERRA *BKR  1*
        TERRA :TRAN1L*BKR  2*
--------------+-------------------------------------------------------------------------------------------------


SINUSOIDAL STEADY STATE SOLUTION, BRANCH BY BRANCH.  ALL FLOWS ARE AWAY FROM BUS, AND REAL PART, MAGNITUDE, OR P
IS PRINTED ABOVE THE IMAGINARY PART, THE ANGLE, OR Q.   FIRST SOLUTION FREQUENCY =   0.6000000000E+02   HERTZ.
 BUS K                                  NODE VOLTAGE                       BRANCH CURRENT              POWER FLOW      POWER LOSS
           BUS M       RECTANGULAR          POLAR         RECTANGULAR            POLAR                  P AND Q         P AND Q

TRAN1H                0.1021137E+05   0.1126700E+05    -0.6099410E+03   0.4626606E+05         0.1070274E+09   0.4768372E-06
                     -0.4761640E+04        -25.0000    -0.4626204E+05        -90.7554         0.2376516E+09   0.2376520E+09

          TRAN1L     -0.6101329E+02   0.4626606E+04     0.6099410E+03   0.4626606E+05        -0.1070274E+09
                     -0.4626204E+04        -90.7556     0.4626204E+05         89.2446         0.4438323E+03

TRAN1L               -0.6101329E+02   0.4626606E+04     0.1918442E+00   0.1918608E+00         0.0000000E+00   0.0000000E+00
                     -0.4626204E+04        -90.7556    -0.2530161E-02         -0.7556        -0.4438323E+03  -0.4438323E+03

          TERRA       0.0000000E+00   0.0000000E+00    -0.1918442E+00   0.1918608E+00         0.0000000E+00
                      0.0000000E+00          0.0000     0.2530161E-02        179.2444         0.0000000E+00

TRAN1L               -0.6101329E+02   0.4626606E+04    -0.6101329E+03   0.4626606E+05         0.1070274E+09   0.5351371E+08
                     -0.4626204E+04        -90.7556    -0.4626204E+05        -90.7556         0.0000000E+00   0.0000000E+00

          BKR   1    -0.3050664E+02   0.2313303E+04     0.6101329E+03   0.4626606E+05        -0.5351371E+08
                     -0.2313102E+04        -90.7556     0.4626204E+05         89.2444         0.0000000E+00

BKR   2              -0.3050664E+02   0.2313303E+04    -0.6101329E+03   0.4626606E+05         0.5351371E+08   0.5351371E+08
                     -0.2313102E+04        -90.7556    -0.4626204E+05        -90.7556         0.0000000E+00   0.0000000E+00

          TERRA       0.0000000E+00   0.0000000E+00     0.6101329E+03   0.4626606E+05         0.0000000E+00
                      0.0000000E+00          0.0000     0.4626204E+05         89.2444         0.0000000E+00

      TOTAL NETWORK LOSS "PLOSS" BY SUMMING BRANCH FLOWS =    0.1070274262E+09
OUTPUT FOR STEADY STATE SWITCH CURRENT
    NODE-K    NODE-M          I-REAL               I-IMAG               I-MAGN           DEGREES
   BKR  1    BKR  2     -0.6101328719E+03   -0.4626203911E+05    0.4626606234E+05      -90.7556

SOLUTION AT NODES WITH KNOWN VOLTAGE.      NODES SHORTED TOGETHER BY SWITCHES ARE SHOWN AS A GROUP OF NAMES, WITH
THE PRINTED RESULT APPLYING TO THE COMPOSITE GROUP.   THE ENTRY 'MVA' IS  SQRT(P**2 + Q**2)  IN UNITS OF POWER,
WHILE  'P.F.'  IS THE ASSOCIATED POWER FACTOR.
              NODE            SOURCE NODE VOLTAGE            INJECTED SOURCE CURRENT             INJECTED SOURCE POWER
              NAME         RECTANGULAR        POLAR        RECTANGULAR           POLAR            P AND Q     MVA AND P.F.

             TRAN1H     0.1021137E+05  0.1126700E+05    -0.6099410E+03  0.4626606E+05     0.1070274E+09  0.2606399E+09
                       -0.4761640E+04       -25.0000    -0.4626204E+05       -90.7554     0.2376516E+09  0.4106334E+00
COMMENT CARD.                                    1C NODE VOLTAGE OUTPUT
COMMENT CARD.                                    1C 345678901234567890123456789012345678901234567890123456789012345678901234567890
COMMENT CARD.                                    1C    3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
COMMENT CARD.                                    1C    BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.       1  TRAN1HBKR  1BKR  2
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT. 1BLANK CARD TERMINATING NODE VOLTAGE OUTPUT

COLUMN HEADINGS FOR THE    5  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
```

TABLE 1.3 (Cont'd)

Printed Output For Single-Frequency Case

```
  FIRST    3  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)\
   NEXT    1  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)\
   NEXT    1  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)\
   NEXT    0  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY\
  FINAL    0  OUTPUT VARIABLES BELONG TO 'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING\
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

 STEP      TIME        TRAN1H        BKR   1      BKR   2       BKR   1      BKR   1
                                                              BKR   2      BKR   2
***          PHASOR I(0) = -0.6101329E+03                                     SWITCH "BKR   1" TO "BKR- 2" CLOSED AFTER 0.00000E+00 SEC
    0 0.000000 0.102114E+05-0.305066E+02-0.305066E+02 0.000000E+00-0.610133E+03
    5 0.000010 0.102292E+05-0.217863E+02-0.217863E+02 0.000000E+00-0.435725E+03
   10 0.000020 0.102470E+05-0.130656E+02-0.130656E+02 0.000000E+00-0.261311E+03
   15 0.000030 C:102646E+05-0.434468E+01-0.434468E+01 0.00000CE+00-0.868937E+02
***                                                                        SWITCH  "BKR   1"  TO  "BKR  2"   OPEN  AFTER  0.360000E-04 SEC.
   20 0.000040 0.102820E+05 0.170626E+04 0 102318E-12 0.170626E+04 0.000000E+00
   25 0.000050 0.102993E+05 0.132211E+05-0.102318E-12 0.132211E+05 0.000000E+00
   30 0.000060 0.103165E+05 0.208123E+05 0.102318E-12 0.208123E+05 0.000000E+00
   35 0.000070 0.103335E+05 0.143087E+05-0.102318E-12 0.143087E+05 0.000000E+00
   40 0.000080 0.103503E+05 0.246679E+04 0.102318E-12 0.246679E+04 0.000000E+00
   45 0.000090 0.103670E+05 0.121155E+04-0.102318E-12 0.121155E+04 0.000000E+00
   50 0.000100 0.103836E+05 0.122511E+05 0.102318E-12 0.122511E+05 0.000000E+00
   55 0.000110 0.104000E+05 0.207827E+05-0.102318E-12 0.207827E+05 0.000000E+00
   60 0.000120 0.104163E+05 0.153715E+05 0.102318E-12 0.153715E+05 0.000000E+00
   65 0.000130 0.104324E+05 0.330591E+04-0.102318E-12 0.330591E+04 0.000000E+00
   70 0.000140 0.104483E+05 0.810347E+03 0.102318E-12 0.810347E+03 0.000000E+00
   75 0.000150 0.104642E+05 0.112575E+05-0.102318E-12 0.112575E+05 0.000000E+00
   80 0.000160 0.104798E+05 0.206393E+05 0.102318E-12 0.206393E+05 0.000000E+00
   85 0.000170 0.104954E+05 0.163780E+05-0.102318E-12 0.163780E+05 0.000000E+00
   90 0.000180 0.105107E+05 0.421695E+04 0.102318E-12 0.421696E+04 0.000000E+00
   95 0.000190 0.105260E+05 0.507731E+03-0.102318E-12 0.507731E+03 0.000000E+00
  100 0.000200 0.105410E+05 0.102519E+05 0.102318E-12 0.102519E+05 0.000000E+00
  105 0.000210 0.105560E+05 0.203843E+05-0.102318E-12 0.203843E+05 0.000000E+00
  110 0.000220 0.105707E+05 0.173184E+05 0.102318E-12 0.173184E+05 0.000000E+00
  115 0.000230 0.105854E+05 0.519109E+04-0.102318E-12 0.519109E+04 0.000000E+00
  120 0.000240 0.105998E+05 0.307715E+03 0.102318E-12 0.307715E+03 0.000000E+00
  125 0.000250 0.106142E+05 0.924550E+04-0.102318E-12 0.924550E+04 0.000000E+00
  130 0.000260 0.106283E+05 0.200212E+05 0.102318E-12 0.200212E+05 0.000000E+00
  135 0.000270 0.106424E+05 0.181833E+05-0.102318E-12 0.181833E+05 0.000000E+00
  140 0.000280 0.106562E+05 0.621871E+04 0.102318E-12 0.621871E+04 0.000000E+00
  145 0.000290 0.106699E+05 0.213178E+03-0.102318E-12 0.213178E+03 0.000000E+00
  150 0.000300 0.106835E+05 0.824991E+04 0.102318E-12 0.824991E+04 0.000000E+00

COMMENT CARD.                         1C PLOTTING OF THE RESULTS
COMMENT CARD.                         1C CALCOMP PLOT                2
COMMENT CARD.                         1C (CASE TITLE UP TO 78 CHARACTERS)
COMMENT CARD.                         1C  EXAMPLE 1 - SINGLE FREQUENCY LUMPED CIRCUIT
COMMENT CARD.                         1C COLUMN 2.    "1"
COMMENT CARD.                         1C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
COMMENT CARD.                         1C COLUMN 4. UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
COMMENT CARD.                         1C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
COMMENT CARD.                         1C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
COMMENT CARD.                         1C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
COMMENT CARD.                         1C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
COMMENT CARD.                         1C 345678901234567890123456789012345678901234567890123456789012345678901234567890
COMMENT CARD.                         1C                    UP TO  4 NODE NAMES FOR            49-64          65-80
COMMENT CARD.                         1C                            NODE VOLTAGE PLOTS
COMMENT CARD.                         1C                    UP TO  2  PAIRS OF  NODE            GRAPH   VERTICAL AXIS
COMMENT CARD.                         1C                    NAMES  FOR   BRANCH   OR          HEADING         HEADING
COMMENT CARD.                         1C                                 SWITCH PLOTS           LABEL           LABEL
COMMENT CARD.                         1C                    1ST  ELEMENT 2ND ELEMENT
COMMENT CARD.                         1C                     25-30 31-36 37-42 43-48
COMMENT CARD.                         1C                      BUS1  BUS2  BUS3  BUS4
COMMENT CARD.                         1C 4525.     300.     TRAN1H
COMMENT CARD.                         1C 4525.     300.     BKR  1
```

TABLE 1.3 (Cont'd)

Printed Output For Single-Frequency Case

```
COMMENT CARD.                                                1C 4525.    300.        BKR  2
COMMENT CARD.                                                1C 8525.    300.        BKR  1BKR  2
COMMENT CARD.                                                1C 9525.    300.        BKR  2BKR  1
BLANK CARD TERMINATING PLOT SPEC. CARDS.                     1BLANK CARD TERMINATING PLOTTING

CORE STORAGE FIGURES FOR PRECEDING DATA CASE NOW COMPLETED.  ------------------------------------  PRESENT    PROGRAM
A VALUE OF  -9999 INDICATES DEFAULT, WITH NO FIGURE AVAILABLE.                                       FIGURE     LIMIT (NAME)
   SIZE LIST 1.   NUMBER OF NETWORK NODES.                                                                 5       602 (LBUS)
   SIZE LIST 2.   NUMBER OF NETWORK BRANCHES.                                                              4       600 (LBRNCH)
   SIZE LIST 3.   NUMBER OF DATA VALUES IN R, L, C TABLES.                                                 4       600 (LDATA)
   SIZE LIST 4.   NUMBER OF ENTRIES IN SOURCE TABLE.                                                       1       150 (LEXCT)
   SIZE LIST 5.   STORAGE FOR (Y) AND TRIANGULARIZED (Y).        NO. TIMES =      2                       11      4000 (LYMAT)
   SIZE LIST 6.   NUMBER OF ENTRIES IN SWITCH TABLE.                NO. FLOPS =      2                     1       104 (LSWTCH)
   SIZE LIST 8.   NUMBER OF PAST HISTORY POINTS FOR DISTRIBUTED LINES.                                     0     15000 (LPAST)
   SIZE LIST 9.   NUMBER OF NONLINEAR ELEMENTS.                                                            0       100 (LNONL)
   SIZE LIST 10.  NUMBER OF POINTS DEFINING NONLINEAR CHARACTERISTICS.                                     0       150 (LCHAR)
   SIZE LIST 11.  NUMBER OF BRANCH OR SELECTIVE-NODE-VOLTAGE OUTPUTS.                                      3       150 (NOUT)
   SIZE LIST 12.  NUMBER OF OUTPUT QUANTITIES (LIMITED ONLY WHEN PRINTING MAX ABSOLUTE VALUES).            5       150 (LPEAK)
   SIZE LIST 13.  NUMBER OF 'WEIGHTING' FREQUENCY-DEPENDENT LINE MODES.                                    0         8 (LFDEP)
   SIZE LIST 14.  NUMBER OF CELLS USED TO STORE FREQ.-DEPENDENCE WEIGHTING FUNCTIONS.                      0         8 (LWT)
   SIZE LIST 15.  NUMBER OF CELLS USED FOR EXPONENTIAL-TAIL LINE-HISTORY STORAGE.                          0        50 (LTAILS)
   SIZE LIST 17.  NUMBER OF DYNAMIC SYNCHRONOUS MACHINES.                                                  0         4 (LSYN)
   SIZE LIST 18.  NUMBER OF BRANCH POWER-AND-ENERGY OUTPUTS.                                               0        24 (MAXPE)
   SIZE LIST 19.  FLOATING-POINT WORKING SPACE FOR ALL TACS ARRAYS.                                      137      8000 (LTACST)
   SIZE LIST 20.  RECURSIVE CONVOLUTION PARAMETER STORAGE FOR NON-COPIED BRANCH COMPONENTS.                0      1000 (LFSEM)
   SIZE LIST 21.  TOTAL STORAGE CELLS FOR MODAL-PHASE TRANSFORMATION MATRICES.                             0       100 (LFD)
   SIZE LIST 22.  NUMBER OF CELLS FOR CONVOLUTION HISTORY.                                                 0       100 (LHIST)
   SIZE LIST 23.  GIANT ARRAYS FOR RENUMBERING AND STEADY-STATE SOLUTION CALCULATIONS.                     7     17952 (LSIZ23)
   SIZE LIST 24.  NUMBER OF PHASES OF COMPENSATION, BASED ON MAXIMUM NODES.                                0         9 (NCOMP)
   SIZE LIST 25.  FLOATING-POINT WORKING SPACE FOR  U.M.  ARRAYS.                                      -9999      1500 (LSPCUM)
   SIZE LIST 26.  SQUARE OF MAXIMUM NUMBER OF COUPLED PHASES.                                          -9999        50 (LSIZ26)
TIMING FIGURES (DECIMAL) CHARACTERIZING CASE SOLUTION SPEED.  ------------------------------------   CP SEC   I/O SEC   SUM SEC
   DATA INPUT, SORTING, AND RENUMBERING (PRE STEADY STATE STUFF) .....                                 0.116    0.000     0.116
   STEADY-STATE (S.S.) SOLUTION CALCULATIONS .....                                                     0.024    0.000     0.024
   POST-S.S. TO PRE-INTEGRATION-SETUP CALCULATIONS .....                                               0.005    0.000     0.005
   INTEGRATION CALCULATION (TIME IN TIME-STEP LOOP) .....                                              0.030    0.000     0.030
   COMPUTER TIME IN PLOTTING OR STATISTICS TERMINATION OVERLAY .....                                   0.015    0.000     0.015
   'DELTAT'-CHANGE RESTART TIME  .......                                                               0.000    0.000     0.000
                                                                                                     ------------------------------
                                                                                           TOTALS      0.190    0.000     0.190

ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CRAY TRANSLATION, PRODUCED BY THE WESTINGHOUSE ELECTRIC CORPORATION, AST DIVISION.
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =   04/04/85  07:29:44    ANY PLOTS BEAR THE SAME FIGURES.
FOR INFORMATION, CONSULT THE 840-PAGE EMTP RULE BOOK DATED   MARCH,  1983.   PROGRAM VERSION = "M35."
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS  96419  INTEGER WORDS.    602   500   600   150  4000
   104  5400 15000   100   150   150   150     8     8    50     9     4    24  8000  1000   100   100  4000     9  1500    50
-----------------------------------------------------+------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA 1 INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                   0         1         2         3         4         5         6         7         8
                                                   0         0         0         0         0         0         0         0         0
-----------------------------------------------------+------------------------------------------------------------------------
BLANK TERMINATION-OF-RUN CARD.                     1BLANK CARD TERMINATING THE CASE
```

A fault on the 4.16-kV terminal of Transformer 2 has to be cleared by Circuit Breaker B (see Figure 1.1). As in the previous example, the equivalent circuit of Transformer 2 can be approximated by an inductor and a capacitor. The following data will be assumed for Transformer 2:

13.8/4.16 kV; 10 MVA; 6% Impedance; Wye/Wye

X_{T2} = .60 p.u. (on 100 MVA) or L_2 = 3.03 mH at 13.8 kV

C_2 = .004 μF (transformer capacitance only)

$$f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}} = \frac{1}{2\pi\sqrt{(3.03 \times 10^{-3})(.004 \times 10^{-6})}} = 45{,}716 \text{ Hz} \qquad (1\text{-}2)$$

The equivalent circuit of the system which was modelled is shown in Figure 1.7. It can be expected that the TRV will have a double frequency shape. The frequency of the oscillations at each terminal is determined by the natural frequency of the transformers connected. Transformers 1 and 2 are connected to breaker terminals 1 and 2. The natural frequencies of Transformers 1 and 2 were calculated previously as 19,772 Hz and 45,716 Hz, respectively.

In order to keep the model simple, it was assumed that the transformer circuits have no damping. If the resistance of the transformer windings were included, damping would be observed.

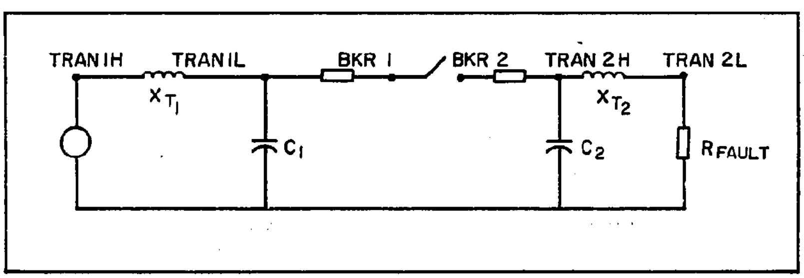


FIGURE 1.7. Circuit Modeled For the Double-Frequency Case

The complete input data is shown in Table 1.4.

Figures 1.8 and 1.9 show the results. The fault current zero occurred at 37.05 μs at which time the voltage to ground at the circuit breaker terminals started to build up. Figure 1.8 shows the voltages to ground at the breaker terminals and the source voltage. Prior to opening the breaker, the voltage at "BKR 1" (solid line in Figure 1.8) equaled the source voltage minus the voltage drop across Transformer 1. This voltage drop can be calculated as 1,825 V which corresponds to the drop observed in Figure 1.8. The voltage on breaker terminal "BKR 2" (dashed line in Figure 1.8) oscillates around zero with a frequency of 45,716 Hz (the period is 21.9 μs), and the voltage on breaker terminal "BKR 1" oscillates around the source voltage (solid line with tic marks in Figure 1.8) with a frequency of 19,772 Hz (the period is 50.6 μs). Figure 1.9 shows that the TRV (branch voltage "BKR 1" to "BKR 2") has a double frequency characteristic.

These EMTP simulations ran in approximately .5 seconds on a Cray 1S computer.

Suggested investigation:

> Vary C_2 in the double frequency case to change the tuned frequency of the C_2 - X_{T_2} loop. Show the effect of using very large time steps, such as 10 or 20 microseconds.

TABLE 1.4

Input Data For The Double-Frequency Case

```
C FILE NAME: "DOUBLE.OSC.1": FAULT ON THE 4.16KV BUS, DOUBLE OSCILLATION TRV
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8    9-16   17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C                  F(HZ)   F(HZ)
   .5E-6 240.E-6       0       0
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8    9-16   17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  NENERG   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
       5       1       1       1       0       0       0       1
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.               (OUTPUT IN COLUMN 80)
C                   BRANCH          MH    UF                              I=   1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                              V=   2
C                                                                         I,V  3
C                                                                         P.E  4
C 345678901234567890123456789012345678901234567890
C
  TRAN1HTRAN1L                  .58900
  TRAN2HTRAN2L                  3.0300
  TRAN1L                              .11000
  TRAN2H                              .00400
  TRAN1LBKR   1            .00010
  TRAN2HBKR   2            .00010
  TRAN2L                   .10000
BLANK CARD TERMINATING BRANCH CARDS
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14     15-24     25-34     35-44     45-54     55-64     65-74
C                                                   (OUTPUT OPTION IN COLUMN 80)
C   NODE NAMES                            IE FLASHOVER   SPECIAL   REFERENCE
C                 TIME TO   TIME TO       OR   VOLTAGE   REQUEST SWITCH-NAME
C   BUS1  BUS2      CLOSE      OPEN    NSTEP                WORD  BUS5  BUS6
  BKR   1BKR   2       -1.    1.0E-6                                             3
BLANK CARD TERMINATING SWITCHES
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C    3-8       11-20     21-30     31-40     41-50     51-60     61-70     71-80
C   NODE   AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1   TIME-T1   T-START    T-STOP
C   NAME                 IN HZ      DEGR             SECONDS   SECONDS   SECONDS
14TRAN1H      11267.      60.0      -5.0                          -1.0
BLANK CARD TERMINATING SOURCE CARD
C NODE VOLTAGE OUTPUT
C IN COLUMN 2:: "1" ALL NODES WILL BE OUTPUT, NO BLANK CARD USED TO
C                                             TERMINATE NODE VOLTAGE OUTPUT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C   BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  BKR   1BKR   2TRAN1H
BLANK CARD TERMINATING NODF VOLTAGE OUTPUT
```

TABLE 1.4 (Cont'd)

Input Data For The Double-Frequency Case

```
C PLOTTING OF THE RESULTS
C CALCOMP PLOT                2
C (CASE TITLE UP TO 78 CHARACTERS)
C  DOUBLE FREQUENCY LUMPED ELEMENTS
C COLUMN 2,    "1"
C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
C COLUMN 4, UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C                       UP TO  4 NODE NAMES FOR             49-64           65-80
C                             NODE VOLTAGE PLOTS
C                       UP TO  2  PAIRS OF  NODE            GRAPH   VERTICAL AXIS
C                       NAMES  FOR  BRANCH   OR           HEADING         HEADING
C                                   SWITCH PLOTS            LABEL           LABEL
C                       1ST  ELEMENT 2ND ELEMENT
C                        25-30 31-36 37-42 43-48
C                         BUS1  BUS2  BUS3  BUS4
 14520.    240.         BKR   1BKR   2TRAN1H
 18520.    240.         BKR   1BKR   2
 19520.    240.         BKR   2BKR   1
BLANK CARD TERMINATING PLOTTING
BLANK CARD TERMINATING THE CASE
```

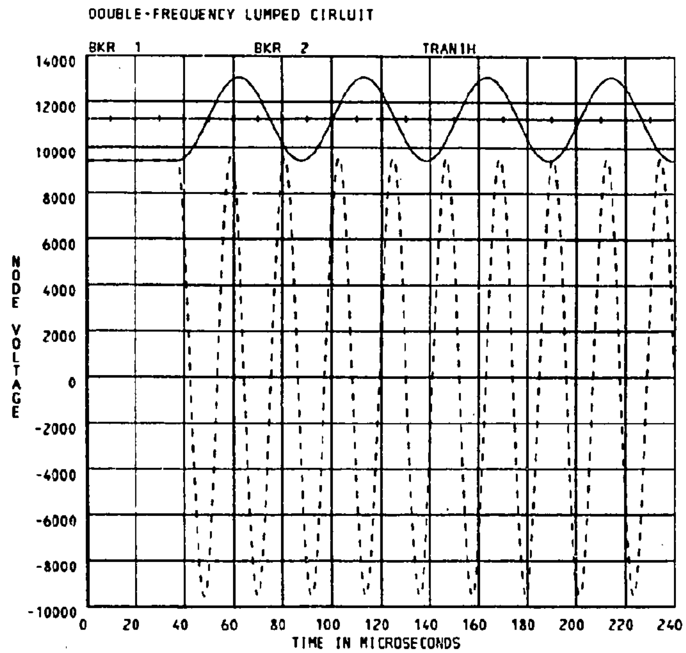


FIGURE 1.8. Double-Frequency Case Node Voltages

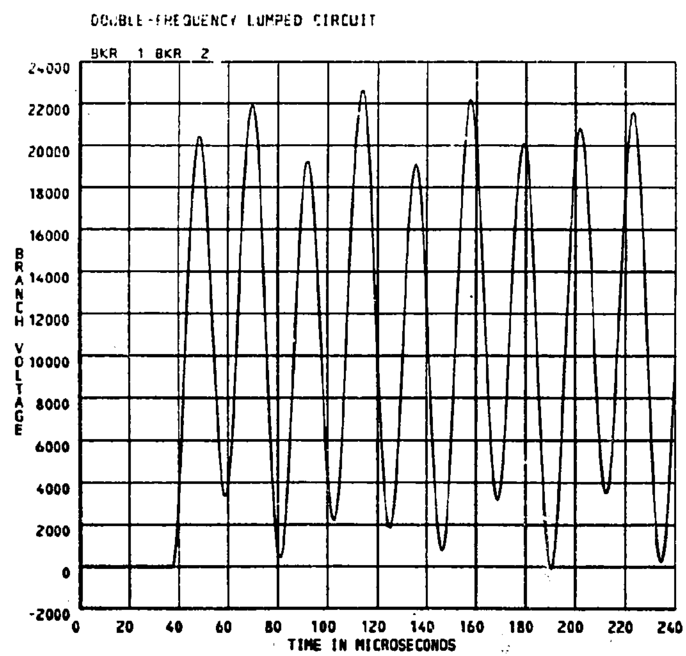


FIGURE 1.9. Circuit Breaker Recovery Voltage

Section 2

CASE 2: TRANSIENT RECOVERY VOLTAGE

In this case, circuit breaker TRV's will be calculated in a transmission system. Besides lumped inductive and capacitive elements, constant parameter transmission line models are introduced to simulate the traveling wave characteristics of surges.

The TRV will be calculated by the current injection method. After arc interruption at a current zero, the recovery voltage is proportional to the product of the current as a function of time and the impedance connected to the circuit breaker. If the peak of the TRV occurs within the first 500 microseconds, the interrupted current can be represented by a ramp. Reference (4) gives more details about current injection and circuit representations.

The fault considered in this case is a three-phase ungrounded fault on ' line side terminal of a breaker (this is practically a "bus fault"). These aults generally result in the most severe TRV's. The one-line diagram for the substation and the system is shown in Figure 2.1. This is a "typical" substation layout with transformers and transmission lines connected to the bus. One of the lines is open at the remote end in order to illustrate an initial positive reflection. The transmission line to Station 6 is disconnected.

System data was based on typical values for 230-kV systems. The base impedance for 230 kV and 100 MVA can be calculated as $(230)^2/100$ or 529 ohms. Tables 2.1 through 2.3 show the relevant system parameters. Figure 2.2 shows the assumed fault current contributions of each branch in per-unit on 100 MVA. The total fault current equals the sum of the individual contributions, or 50.66 per-unit. At rated voltage, the base current equals 251 A. Therefore, the total fault current equals 12.7 kA rms or 18 kA crest (since the program input has to be in peak values).

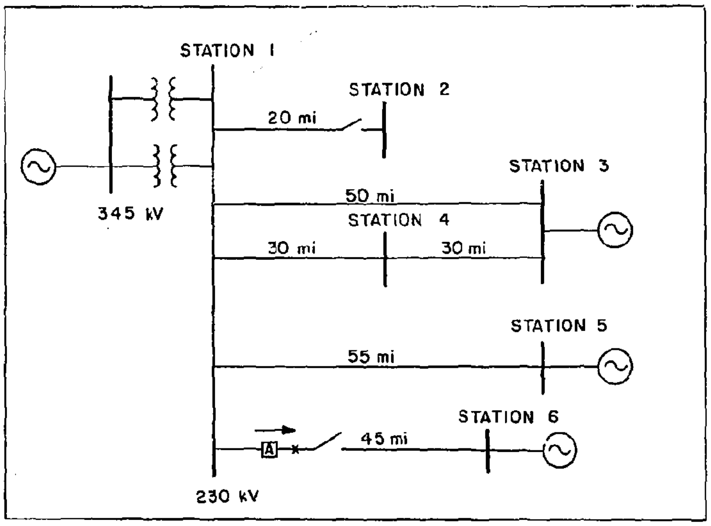


FIGURE 2.1. System One-Line Diagram

TABLE 2.1

Station 1 Representation

Two Tie-Transformers: each 345/230 kV, 250 MVA, 8% Impedance

Parallel Reactance: 0.016 p.u. (on 100 MVA) = 8.46 Ω or 22.5 mH

345-kV Equivalent Source Reactance = .03 p.u. = 42.1 mH

230-kV Bus Capacitance = .005 μF

TABLE 2.2

Station 3 and 5 Representations

Station 3: L = 35.0 mH, (.025 p.u.); R = .377 Ω

Station 5: L = 35.0 mH, (.025 p.u.); R = .694 Ω

TABLE 2.3

Transmission Line Representation

230-kV Rating

R = .243 Ω/mi.

Z = 450 ohms

V = 1.78×10^5 mi/sec

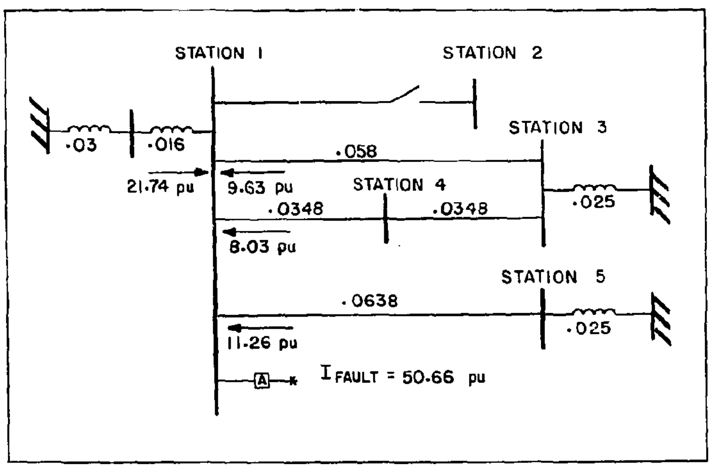


Figure 2.2. System Reactances and Fault Current Contributions With Reactances in Per Unit on 100 MVA and Base Currents in Per-Unit Amperes

A traveling wave model is used for the single-phase transmission lines. Each line has a surge impedance ($Z = \sqrt{L/C}$) and wave velocity ($V = 1/\sqrt{LC}$) associated with it. A resistance to simulate losses in the line can also be specified. The line model can be considered a "black box" with terminals at each end. In this case, single-phase transmission lines are simulated. Case 3 describes multiphase traveling wave models.

The data can be input in four different ways:

1. Code "0" in Column 52: R (Ω); L (mH); C (μF) (for X - OPT = 0, C - OPT = 0)
2. R (Ω); L (Ω); C (μ mho) (X - OPT = 60, C - OPT = 60)
3. Code "1" in Column 52: R (Ω); Z (Ω); v (per unit length/sec.)
4. Code "2" in Column 52: R (Ω); Z (Ω); τ (sec.)

For this case, three lines will be input using code "0", and two lines will be input using code "1".

The line inductance L and the capacitance C can be calculated from the parameters in Table 2.3.

$$L = \frac{Z}{V} = \frac{450}{1.78 \times 10^5} = 2.528 \text{ mH/mile} \qquad (2\text{-}1)$$

$$C = \frac{1}{ZV} = \frac{1}{450 \times 1.78 \times 10^5} = .01248 \ \mu\text{F/mile} \qquad (2\text{-}2)$$

Each transmission line has a finite travel time given by

$$\tau = \ell/V \qquad (2\text{-}3)$$

where ℓ is the line length, and V is the wave velocity. A surge entering a transmission line will reach the remote end in τ seconds, be reflected, and return to the local end in 2τ seconds. The line's natural frequency has a period of 4τ seconds, corresponding to two complete reflection cycles.

When a surge reaches a line termination, part of the surge is reflected back onto the line, and part is transmitted into the termination. These new components are:

$$E_R = E_I \frac{Z_T - Z_L}{Z_T + Z_L} \qquad (2\text{-}4)$$

$$E_T = E_I \frac{2\,Z_T}{Z_T + Z_L} \qquad (2\text{-}5)$$

where E_I is the incident surge voltage.

Z_L is the incoming line surge impedance.

Z_T is the equivalent termination impedance.

E_R is the reflected component.

E_T is the transmitted component.

The voltage at the termination itself is given by:

$$E_T = E_R + E_I \tag{2-6}$$

The termination impedance might consist of other line surge impedances, in which case both Z_L and Z_T are resistive and equations 2-4 and 2-5 become constant scaling factors. Station 4 in Figure 2.1 has one incoming line and one outgoing line, so that $Z_T = Z_L$, $E_R = 0$, and $E_T = E_I$. In effect, the surge travels straight through Station 4, and there is no wave reflected back to Station 1.

If the termination is a short circuit, then $Z_T = 0$, $E_R = -E_I$, and $E_T = 0$. This reflected wave will return to the local end of the line and reduce the voltage there.

If the termination is an open circuit, then Z_T approaches infinity, $E_R = E_I$, and $E_T = 2\ E_I$. This reflection will return and tend to increase the voltage at the local bus. Therefore, the 20-mile line open-circuited at Station 2 in Figure 2.1 will have an adverse affect on the TRV.

If the termination is an inductance or capacitance, Z_T is equal to either sL or 1/sC, and the reflection can be analyzed by Laplace transforms as described in Reference (1). Inductances initially look like open circuits and then become short circuits as s approaches zero (d.c. conditions), while capacitances initially look like short circuits and then become open circuits. It will be seen that the inductance terminations at Stations 3 and 5 increase the peak TRV at Station 1, even though they decrease the TRV after the peak has been reached.

Usually, sources in the EMTP program are connected between a node and ground. In order to properly model the injected fault current, which is connected between two nodes, two current sources were connected to ground as seen in Figure 2.3. This simulates current interruption between two terminals of a circuit breaker pole.

The value of current injected is equal in magnitude and opposite in polarity to the fault current. By superposition in a linear circuit, the resulting current in the circuit breaker is zero, which simulates current interruption. Voltages appearing in the network as a result of the injected current define the TRV occurring as a result of current interruption.

In order to estimate the TRV for the first phase of the circuit breaker to clear a three-phase ungrounded fault, a simplified circuit can be developed , as shown in Figure 2.4. Since the fault is ungrounded, the second and third phases are connected in parallel to ground. Since the 230-kV bus capacitance is only .005 μF, it can be ignored for the simplified calculation.

This simplified circuit shows why a three-phase ungrounded fault is so severe. The system neutral shifts and increases the TRV. The parallel combination of L_T and Z/n on Phases B and C increases the TRV by 1.5 times over what it would be for a three-phase grounded fault. This factor can be accounted for in a single-phase analysis by multiplying the fault current by 1.5. Therefore, the total current injection magnitude is:

$$I = 1.5\ (\sqrt{2})(12.7\ \text{kA}) = 27\ \text{kA peak} \qquad (2\text{-}7)$$

Figure 2.5 shows the system diagram, the node names, and the system data as it was used in the EMTP. The corresponding input data is shown in Table 2.4.

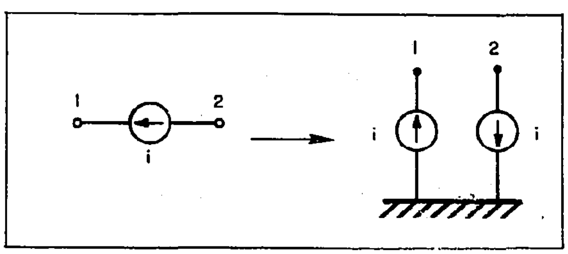


FIGURE 2.3. Connection of the Current Injection Sources

TABLE 2.4

Input Data for the TRV Case

```
C FILE NAME: "TRV" THREE PHASE UNGROUNDED FAULT ON THE 230-KV BUS
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C    1-8     9-16    17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECONDS SECONDS   O=MH    O=UF
C                  F(HZ)   F(HZ)
  1.OE-61000.E-6       O       O
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8     9-16    17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  ENERG.   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
    3000       1       1       O       1
C
C BRANCHES ,
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C    3-8   9-14  15-20 21-26 27-32 33-38 39-44
C    NODE NAMES   REFERENCE  RES.   IND.  CAP.                  (OUTPUT IN COLUMN 80)
C                   BRANCH           MH    UF                                   I=  1
C    BUS1   BUS2  BUS3  BUS4    OHM    OHM  UOHM                                 V=  2
C                                                                               I,V  3
C                                                                               P,E  4
C TIE TO 345 KV
C 345678901234567890123456789012345678901234567890123456789O
  STAT1A                                     64.600
C 230-KV BUS CAPACITANCE
  STAT1A                                            .00500
C BUS TO CIRCUIT BREAKER
  STAT1ABKR1 A                         .00010
C FAULT
  BKR2 A                               .00010
C TRANSMISSION LINES
C 345678901234567890123456789012345678901234567890123456789O
C                                        27-32 33-38 39-44 45-50  CODE IN COLUMN "52"
C                                            R     Z     V     L  (L=LENGTH)
-1STAT1ASTAT2A                         .24300450.001.78E520.000 1
-1STAT1ASTAT3A                         .24300450.001.78E550.000 1
-1STAT1ASTAT4A                         .24300450.001.78E530.000 1
-1STAT4ASTAT3A                         .243002.5280.0124830.000 O
-1STAT1ASTAT5A                         .243002.5280.0124855.000 O
C -EQUIVALENT SOURCE IMPEDANCES AT THE STATIONS
  STAT3A                                .377  35.
  STAT5A                                .763  35.
BLANK CARD TERMINATING BRANCH CARDS
C
C SWITCHES
C 345678901234567890123456789O
C    3-8  9-14      15-24      25-34
C   BUS1  BUS2      CLOSE       OPEN
  BKR1 ABKR2 A     1.OE-3        O.O                                                 2
BLANK CARD TERMINATING SWITCH CARDS
C
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890
C    3-8          11-20      21-30      31-40
C   BUS1   AMPLITUDE  FREQUENCY          TO
14BKR1 A-1    -27000.       60.0       90.0
14BKR2 A-1     27000.       60.0       90.0
BLANK CARD TERMINATING SOURCE CARDS
C
```

TABLE 2.4 (Cont'd)

Input Data for the TRV Case

```
C NODE VOLTAGE PRINT CARDS
C 34567890123456789O
C     3-8  9-14
C   BUS1  BUS2
  BKR1 ABKR2 A
BLANK CARD TERMINATING NODE VOLTAGE PRINT
C
C PLOTTING OF THE RESULTS
  CALCOMP PLOT
C (CASE TITLE UP TO 78 CHARACTERS)
2 BUS-FAULT TRANSIENT RECOVERY VOLTAGE
C THE FOLLOWING IS FORMAT OF THE PLOT REQUEST CARDS
C COLUMN 2,       "1"
C COLUMN 3,        4=NODE VOLTAGE
C                  8=BRANCH VOLTAGE
C                  9=BRANCH CURRENT
C COLUMN 4,        UNITS OF HORIZOTAL SCALE  1=DEGREES
C                                            2=CYCLES
C                                            3=SEC
C                                            4=MSEC
C                                            5=USEC
C COLUNNS 5-7      HORIZONTAL SCALE (UNITS PER INCH)
C COLUMNS 11-15    TIME WHERE PLOT ENDS
C COLUMNS 16-20    VALUE OF BOTTOM VERTICAL SCALE
C COLUMNS 21-24    VALUE OF TOP VERTICAL SCALE
C COLUMNS 25-48    UP TO FOUR NODE NAMES
C COLUMNS 49-64    GRAPH HEADING LABEL
C COLUMNS 65-80    VERTICAL AXIS LABEL
 185100     1000           BKR1 ABKR2 A
BLANK CARD TERMINATING PLOT REQUEST
BLANK CARD TRMINATING CASE
```

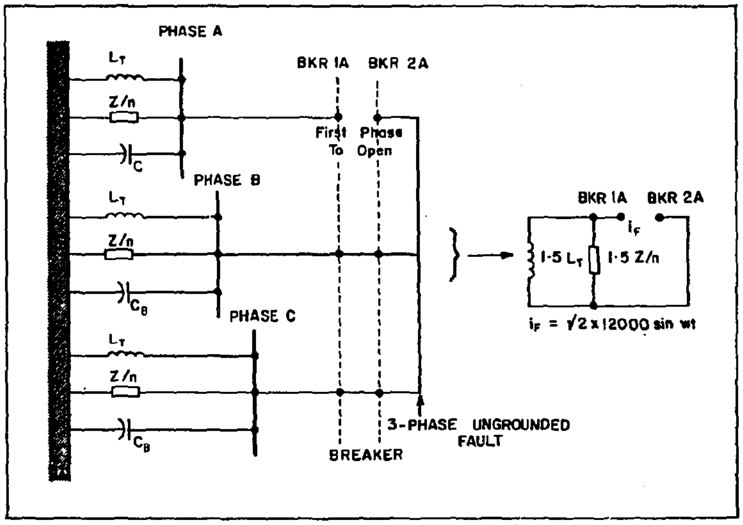


FIGURE 2.4. Simplified Circuit to Calculate the TRV

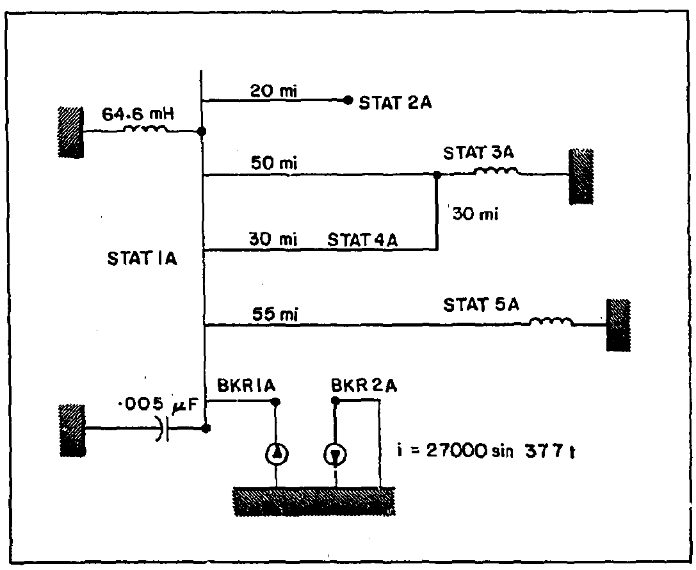


FIGURE 2.5. Circuit Diagram, Node Names, and Data For the System

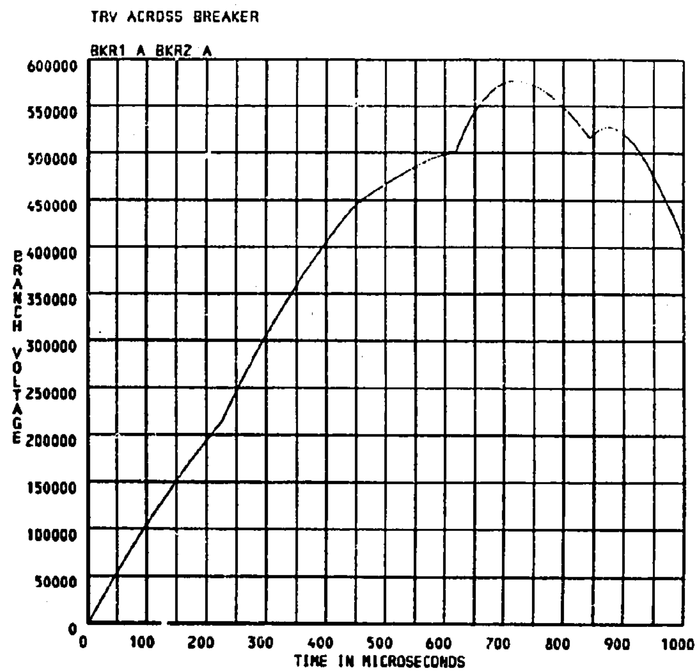


FIGURE 2.6. Voltage Across the Circuit Breaker Terminals "BKR1 A" and "BKR2 A" with Inductive Terminations at Stations 3 and 5

Figure 2.6 shows the TRV for the case with inductive terminations at Stations 3 and 5. It follows an exponential curve until the first reflections appear. This initial TRV is given by:

$$e(t) = 1.5\ (\sqrt{2}\ I_{rms})\ \omega\ L_T\ (1 - e^{-(Z/n\ L_T)t}) \tag{2-8}$$

where n is the number of lines at Station 1. In our case:

$$\begin{aligned} e(t) &= 27000 \times 377 \times .0646\ (1 - e^{-(450/4 \times .0646)t}) \\ &= 658\ (1 - e^{-1742t})\ \text{kV} \end{aligned} \tag{2-9}$$

At 200 microseconds, the TRV is 193 kV according to equation 2-9, which agrees with Figure 2.6.

The initial rate of rise of TRV is very important. By the ANSI Standards, this value must be no more than 1.8 kV/μsec for 242-kV class circuit breakers. This rate of rise, R, can be estimated by taking the derivative of equation 2-9 and then setting t = 0.

$$R = 658 \times 1742 \text{ kV/sec} = 1.14 \text{ kV/}\mu\text{sec} \qquad (2\text{-}10)$$

Therefore, R is within the circuit breaker's capability. This value is readily checked against Figure 2.6 by examining the range from 0 to 50 microseconds on the plot.

The specified speed of the surges was 1.78×10^5 mi./sec. or 5.62 µsec./mi. The open-ended line has a length of 20 miles. Therefore, the round-trip travel time is 20 x 2 x 5.62 or 224.7 µs. Figure 2.6 shows clearly the time when the first reflection from the open-ended line returns to Station 1 and increases the TRV. The second reflection from the open-ended line, which is a negative reflection, returns at 449.4 µs.

The initial reflections from Stations 3 and 5 reach Station 1 at 562 microseconds and 618 microseconds. The inductive terminations cause brief increases in the TRV in both instances, and then the TRV is reduced. The effect of Station 5 is more significant because it only has one incoming line, whereas Station 3 has two incoming lines. A reflection of the incoming surge from Station 5 appears at 843 microseconds. This reflection comes from the open line end at Station 2. The peak value of the TRV, E_2, is 576 kV in Figure 2.6, which exceeds the ANSI standard rating of 426 kV for 242-kV class circuit breakers.

The situation is improved by not interrupting full-rated fault current--the standards specify an increase in E_2 for lower currents given by the following multiplier:

$$K_e = \frac{15 - I\%}{567} + 1.15 \qquad (2\text{-}11)$$

With standard interrupting ratings of 31.5 kA, 40 kA, and 63 kA available in this voltage class, the actual limits on E_2 when interrupting 12.7 kA would be 471 kV, 477 kV, and 486 kV, respectively. Unfortunately, E_2 in Figure 2.6 still exceeds these ratings.

Faced with such a situation, four options are available:

1. Add more details to the TRV calculation to improve its accuracy and lessen its conservative assumptions.

2. Change the system configuration to reduce the TRV.

3. Use a circuit breaker with more TRV capabiity.

4. Consult the breaker manufacturer about the device's actual ratings and/or possible modifications which might help.

Option 3 would involve the use of a 362-kV class breaker on a 230-kV system, which is highly undesirable. Option 4 should always be explored, but is outside the scope of this Primer. Option 1 might involve reducing the interrupted fault current or reducing the total local source inductance. Reducing L_T would also increase the fault current, but the net effect on TRV would be beneficial according to equation 2-8.

As an example of Option 1, consider the inductive source impedances at Stations 3 and 5. It may be more realistic to consider each station as having three outgoing lines and a transformer. Each line has a 450-ohm surge impedance, which produces an equivalent 150-ohm resistance to ground at each station. The transformer source inductances are assumed to be .075 per-unit, which is three times the original station source inductance. The TRV case was repeated with new termination impedances as shown in Table 2.5, with results as shown in Figure 2.7.

TABLE 2.5

Transformer - Line Terminations at Stations 3 and 5

```
C -EQUIVALENT SOURCE IMPEDANCES AT THE STATIONS
  STAT3A                    .377 105.
  STAT5A                    .763 105.
  STAT3A                    150.
  STAT5A                    150.
BLANK CARD TERMINATING BRANCH CARDS
```

This change has no effect on the TRV until reflected surges from Stations 3 and 5 arrive at Station 1. The ultimate peak TRV is now 495 kV, which still exceeds the rating, but by a very small amount.

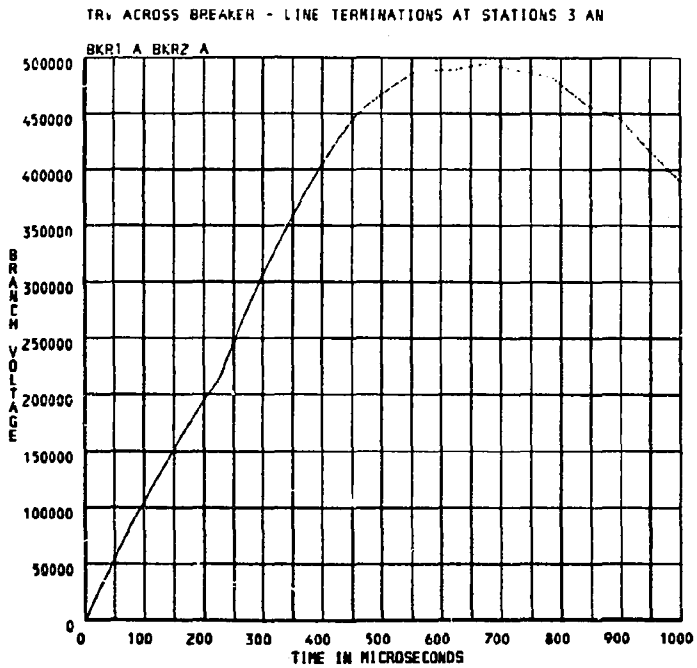


FIGURE 2.7. Voltage Across the Circuit Breaker Terminals "BKRI A" and "BKR2 A" with Transformer-Line Terminations at Stations 3 and 5

These EMTP simulations ran in approximately .5 second on a Cray 1S computer.

Suggested investigations:

- Vary the bus capacitance, line surge impedances, and total inductance L_T.
- Change the open-circuit termination at Station 2.

Section 3

CASE 3: LINE CONSTANTS CALCULATIONS

Transmission line models are very important parts of most EMTP simulations. Since it is usually necessary to model multiphase systems and high-frequency phenomena, the line models require different and more detailed data than is used in short circuit, load flow, and stability programs. The EMTP includes a LINE CONSTANTS subprogram which calculates model parameters from the conductor data and tower geometry.

The LINE CONSTANTS routine calculates the line's distributed resistance, inductance, and capacitance at a single frequency and prints the results in a format suitable for input to the EMTP. It forms the basis for setting up several types of line models.

1) Constant-parameter, transposed, travelling wave model. This represents positive and zero sequence parameters. It is most useful for low-frequency studies such as SSR (a positive-sequence phenomena). It is also acceptable for quick and simple studies conducted to obtain a feel for the phenomena. This model does not represent frequency-dependent losses, frequency-dependent earth return, or nontransposed lines.

2) Constant-parameter, nontransposed travelling wave model (K. C. Lee's model). This is similar to model number 1, but it represents unbalanced or nontransposed line impedances. It is most useful for low-frequency or steady-state studies where line unbalances are important.

3) Lumped pi sections. These are analogous to the TNA line models. They are computationally inefficient on the EMTP, do not represent frequency-dependent losses, and may cause spurious high-frequency oscillations. In most instances, model 2 should be used instead of pi sections. One example of their use in steady-state calculations has been included in this Primer.

4) Frequency-dependent models. There are two main varieties in current use. One (the Dommel-Meyer weighting functions) assumes a transposed line, and the other (Marti's model) does not. However, there are many other application considerations for these models which are outside the scope of this Primer. These models should be used for accurate line switching surge studies and other high-frequency studies.

Information on the CABLE CONSTANTS subprogram for underground lines may be found in the Operation Manual and Application Guide. The Application Guide also contains more information about frequency-dependent models and comparisons between various overhead line models. The LINE CONSTANTS program serves as the basic input for all overhead line models currently used by the EMTP. References (5) and (6) describe how lines are modeled in the EMTP and how line parameters are evaluated.

Three examples of LINE CONSTANTS program usage are presented. The first one considers a flat configuration 500-kV line. Parameters for model 1 above are used for switching surge studies in Cases 7 and 8. In the Application Guide, these studies are repeated with more detailed line models for comparison. The second example considers two 345-kV circuits sharing the same right-of-way. Six-phase pi sections will be used in Case 6 to represent the two three-phase circuits with intercircuit coupling during a steady-state condition. The third example considers a 230-kV line with the K. C. Lee model used to represent the shield wires and one-phase conductor in a "two-phase" representation. This model will be used for lightning studies in Case 4.

The 500-kV line tower geometry and conductor data are presented in Figure 3.1. This information is translated into the LINE CONSTANTS input shown in Table 3.1. The structure of a LINE CONSTANTS input file is:

```
BEGIN NEW DATA CASE
LINE CONSTANTS
     conductor data cards
BLANK CARD TERMINATING CONDUCTOR CARDS
     frequency and output option cards
BLANK CARD TERMINATING FREQUENCY CARDS
BLANK CARD TERMINATING LINE CONSTANTS INPUT
BLANK CARD TERMINATING EMTP INPUT
```

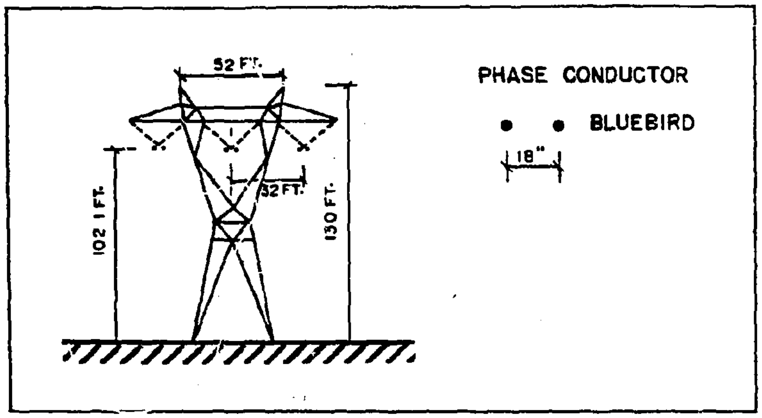


FIGURE 3.1. 500-kV Flat Line Configuration

More than one set of line constants can be calculated in the same case by adding sets of conductor and frequency cards before the BLANK CARD TERMINATING LINE CONSTANTS INPUT. Usually the data will be input in English units, namely feet and inches. However, there is an option for metric data input described in the Operation Manual.

There is one conductor card for each conductor. All conductors with the same phase number will be bundled into an equivalent conductor in the final line model. In Table 3.1, the first three conductor cards represent three separate phases and are numbered 1 through 3. The bundled subconductors are handled through an automatic bundling option described below. The fourth and fifth conductor cards represent the shield wires. Both have phase number 0, which means they will be reduced out of the final line model based on an assumption of constant zero

TABLE 3.1

500-kV LINE CONSTANTS Input

```
C FILE NAME: "L500"
C     THE LINE CONSTANTS FOR A TYPICAL 500-KV
C     FLAT LINE CONFIGURATION WILL BE CALCULATED
BEGIN NEW DATA CASE
LINE CONSTANTS
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C COLUMN 1-3: PHASE NUMBER
C COLUMN 17,18: USUALLY A "4"
C COLUMN 80:  NUMBER OF CONDUCTORS IN THE BUNDLE
C     4-8     9-16      19-26    27-34    35-42    43-50    51-58    59-66 59-72 73-78
C    SKIN    RESIS      REACT     DIAM    HORIZ   VTOWER     VMID    SEPAR ALPHA  NAME
C
C
  1   .5    .0426 4             1.762     -32.    102.1      32.      18.   0.         2
  2   .5    .0426 4             1.762      0.     102.1      32.      18.   0.         2
  3   .5    .0426 4             1.762     32.     102.1      32.      18.   0.         2
  0   .5    2.4   4              .385    -19.8     130.     83.5
  0   .5    2.4   4              .385     19.8     130.     83.5
BLANK CARD TERMINATING CONDUCTOR CARDS
C FREQUENCY CARD
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C COLUMN 44: ICAP
C     1-8        9-18      19-28  30-35  37-42
C   EARTH FREQUENCY       CARSON  PRINT  PRINT
C   RESIS          HZ   ACCURACY    (C)    (Z)
    100.        60.0           1 111111 111111 1
BLANK CARD TERMINATING FREQUENCY CARDS
BLANK CARD TERMINATING LINE CONSTANTS CASES
BLANK CARD TERMINATING THE CASE
```

potential along the shield wires. Besides the phase number, the following conductor card parameters will be of interest to the beginning user.

RESIS - d.c. resistance of the conductor in ohms per mile.

DIAM - conductor diameter in inches.

HORIZ - horizontal conductor displacement from a vertical reference line, in feet. The reference line might be the center line of the tower.

VTOWER - height of the conductor at the tower, in feet.

VMID - height of the conductor at midspan, in feet.

The program uses an average height defined by h = (VTOWER + 2 VMID)/3. The user may, optionally, input this average height as VTOWER and leave VMID blank.

The automatic bundling option for the three phases is triggered by the "2" in column 80 of the phase conductor cards. This signifies two subconductors per bundle. SEPAR is the subconductor separation in inches. ALPHA is one subconductor's angle with respect to the horizontal. Use the following ALPHA's:

ALPHA = 0 for 2-conductor horizontal bundle
ALPHA = 90 for 2-conductor vertical bundle
ALPHA = 45 for 4-conductor bundle
ALPHA = 30 for 3-conductor bundle, inverted triangle

There is usually just one frequency card for elementary LINE CONSTANTS calculations. Additional cards and output options are used for frequency-dependent line models. The parameters of interest to the beginning user are:

EARTH RESIS	=	earth resistivity in ohm-meters. Set equal to 100 in the absence of other information.
FREQUENCY	=	frequency at which inductances and resistances are evaluated. Usually, but not necessarily, set equal to power frequency.
CARSON ACCURACY	=	1 for most cases. This controls the correction for earth return effects by Carson's equations.
Column 44	=	1 for capacitance matrices in microfarads
	=	0 for shunt admittance matrices in micromhos.

The matrix printout parameters in columns 30-35 and 37-42 request the printout of impedance and admittance (or capacitance) matrices and their inverses. These are evaluated for the system of physical conductors (8 in our example), the equivalent system after bundling and reduction of shield wires (3 phases in our example), and the symmetrical components representation. These can all be set equal to 1 to obtain complete printouts. Refer to the Operation Manual to obtain selective printouts.

The output from this LINE CONSTANTS case is shown in Table 3.2. The first page contains the echo of the input data and a line conductor table. The program internally generates three extra conductor cards for subconductors defined by the automatic bundling option, and prepares a total of 8 entries for the conductor table. Note that each subconductor is placed ± 9 inches from the position defined in HORIZ on the conductor card. The conductor average heights are also calculated.

The following pages contain matrix printouts in the following order:

C^{-1} or P, physical conductors
C , physical conductors
C^{-1} or P, equivalent phase conductors
C^{-1} or P, symmetrical components
C , equivalent phase conductors
C , symmetrical components
Z , physical conductors
Z^{-1} , physical conductors
Z , equivalent phase conductors
Z , symmetrical components
Traveling Wave Parameters, symmetrical components
Z^{-1} , equivalent phase conductors
Z^{-1} , symmetrical components

The travelling wave parameters can be used directly in the EMTP's constant-parameter transposed line model. The parameters in Table 3.3 were picked out of this section of Table 3.2 for use in Cases 7 and 8. Parameters in this format are convenient for thinking in terms of traveling waves. The only additional input required by the EMTP is the total line length in miles.

TABLE 3.2

500-kV LINE CONSTANTS Output

```
ELECTROMAGNETIC TRANSIENTS PROGRAM (EMTP), CRAY TRANSLATION, PRODUCED BY THE WESTINGHOUSE ELECTRIC CORPORATION, AST DIVISION
DATE (MM/DD/YY) AND TIME OF DAY (HH.MM.SS) =  03/25/85  08:59:45   ANY PLOTS BEAR THE SAME FIGURES.
FOR INFORMATION, CONSULT THE 840-PAGE EMTP RULE BOOK DATED  MARCH,  1983.  PROGRAM VERSION = "M35."
INDEPENDENT LIST LIMITS FOLLOW.   TOTAL LENGTH OF   /LABEL/   EQUALS  96419  INTEGER WORDS.    602   600   600   150  4000
   104  5400 15000   100   150   150   150     8     8    50     9     4    24  8000  1000   100   100  4000     9  1500    50
--------------------------------------------------+--------------------------------------------------------------------------------
DESCRIPTIVE INTERPRETATION OF NEW-CASE INPUT DATA | INPUT DATA CARD IMAGES PRINTED BELOW, ALL 80 COLUMNS, CHARACTER BY CHARACTER.
                                                  0         1         2         3         4         5         6         7         8
                                                  0         0         0         0         0         0         0         0         0
--------------------------------------------------+--------------------------------------------------------------------------------
COMMENT CARD.                                     |C FILE NAME: "L500"
COMMENT CARD.                                     |C     THE LINE CONSTANTS FOR A TYPICAL 500-KV
COMMENT CARD.                                     |C     FLAT LINE CONFIGURATION WILL BE CALCULATED
MARKER CARD PRECEDING NEW DATA CASE.              |BEGIN NEW DATA CASE
REQUEST FOR LINE-CONSTANTS SUPPORTING PROG.    98 |LINE CONSTANTS
COMMENT CARD.                                     |C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     |C COLUMN 1-3: PHASE NUMBER
COMMENT CARD.                                     |C COLUMN 17,18: USUALLY A "4"
COMMENT CARD.                                     |C COLUMN 80:  NUMBER OF CONDUCTORS IN THE BUNDLE
COMMENT CARD.                                     |C    4-8     9-16      19-26   27-34   35-42   43-50   51-58   59-66 59-72 73-78
COMMENT CARD.                                     |C    SKIN    RESIS     REACT    DIAM   HORIZ  VTOWER    VMID   SEPAR ALPHA  NAME
COMMENT CARD.                                     |C
COMMENT CARD.                                     |C
LINE-CONDUCTOR CARD.  0.500E+00  0.426E-01      4 |  1   .5   .0426 4          1.762    -32.   102.1     32.     18.    0.        2
LINE-CONDUCTOR CARD.  0.500E+00  0.426E-01      4 |  2   .5   .0426 4          1.762     0.    102.1     32.     18.    0.        2
LINE-CONDUCTOR CARD.  0.500E+00  0.426E-01      4 |  3   .5   .0426 4          1.762    32.    102.1     32.     18.    0.        2
LINE-CONDUCTOR CARD.  0.500E+00  0.240E+01      4 |  0   .5   2.4   4           .385   -19.8   130.     83.5
LINE-CONDUCTOR CARD.  0.500E+00  0.240E+01      4 |  0   .5   2.4   4           .385    19.8   130.     83.5
BLANK CARD TERMINATING CONDUCTOR CARDS.           |BLANK CARD TERMINATING CONDUCTOR CARDS
COMMENT CARD.                                     |C FREQUENCY CARD
COMMENT CARD.                                     |C 34567890123456789012345678901234567890123456789012345678901234567890123456789
COMMENT CARD.                                     |C COLUMN 44: ICAP
COMMENT CARD.                                     |C    1-8      9-18     19-28  30-35  37-42
COMMENT CARD.                                     |C   EARTH FREQUENCY    CARSON  PRINT  PRINT
COMMENT CARD.                                     |C   RESIS       HZ   ACCURACY   (C)    (Z)
FREQUENCY CARD.  0.100E+03  0.600E+02  0.000E+00  |   100.       60.0          1 111111 111111 1

LINE-CONDUCTOR TABLE AFTER SORTING AND INITIAL PROCESSING.
TABLE   PHASE   SKIN EFFECT   RESISTANCE   REACTANCE-DATA SPECIFICATION    DIAMETER   HORIZONTAL   AVG HEIGHT   CONDUCTOR
 ROW   NUMBER       R-TYPE    R (OHM/MI)   X-TYPE    X(OHM/MI) OR GMR     (INCHES)    X (FEET)     Y (FEET)       NAME
   1       1       0.50000      0.04260       4             0.000000       1.76200     -32.750       55.367
   2       2       0.50000      0.04260       4             0.000000       1.76200      -0.750       55.367
   3       3       0.50000      0.04260       4             0.000000       1.76200      31.250       55.367
   4       1       0.50000      0.04260       4             0.000000       1.76200     -31.250       55.367
   5       2       0.50000      0.04260       4             0.000000       1.76200       0.750       55.367
   6       3       0.50000      0.04260       4             0.000000       1.76200      32.750       55.367
   7       0       0.50000      2.40000       4             0.000000       0.38500     -19.800       99.000
   8       0       0.50000      2.40000       4             0.000000       0.38500      19.800       99.000

FOLLOWING MATRICES ARE FOR EARTH RESISTIVITY=  100.00 OHM-M AND FREQUENCY=      60.00 HZ. CORRECTION FACTOR=  0.000001

         INVERTED CAPACITANCE MATRIX (DARAF-MILE) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
                       ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

  1   0.81744E+08

  2   0.14313E+08   0.81744E+08

  3   0.77330E+07   0.14313E+08   0.81744E+08
```

TABLE 3.2 (Cont'd)

500-kV LINE CONSTANTS Output

4	0.48047E+08	0.14810E+08	0.79327E+07	0.81744E+08				
5	0.13843E+08	0.48047E+08	0.14810E+08	0.14313E+08	0.81744E+08			
6	0.75402E+07	0.13843E+08	0.48047E+08	0.77330E+07	0.14313E+08	0.81744E+08		
7	0.13680E+08	0.13222E+08	0.98758E+07	0.13771E+08	0.13092E+08	0.97194E+07	0.10522E+09	
8	0.97194E+07	0.13092E+08	0.13771E+08	0.98758E+07	0.13222E+08	0.13680E+08	0.18195E+08	0.10522E+09

CAPACITANCE MATRIX (FARAD/MILE) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.18968E-07							
2	-0.74808E-09	0.19151E-07						
3	-0.22931E-09	-0.73402E-09	0.19025E-07					
4	-0.10681E-07	-0.87072E-09	-0.25324E-09	0.19025E-07				
5	-0.63594E-09	-0.10529E-07	-0.87072E-09	-0.73402E-09	0.19151E-07			
6	-0.20858E-09	-0.63594E-09	-0.10681E-07	-0.22931E-09	-0.74808E-09	0.18968E-07		
7	-0.78800E-09	-0.65092E-09	-0.39945E-09	-0.78643E-09	-0.61755E-09	-0.38323E-09	0.10174E-07	
8	-0.38323E-09	-0.61755E-09	-0.78643E-09	-0.39945E-09	-0.65092E-09	-0.78800E-09	-0.13521E-08	0.10174E-07

INVERTED CAPACITANCE MATRIX (DARAF-MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.62561E+08		
2	0.11811E+08	0.62084E+08	
3	0.55851E+07	0.11811E+08	0.62561E+08

INVERTED CAPACITANCE MATRIX (DARAF-MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

0	0.81874E+08 0.00000E+00		
1	-0.95812E+06 0.16595E+07	0.21549E+07 0.37323E+07	
2	-0.95812E+06 -0.16595E+07	0.52667E+08 0.00000E+00	0.21549E+07 -0.37323E+07

CAPACITANCE MATRIX (FARAD/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.16631E-07		
2	-0.29888E-08	0.17244E-07	
3	-0.92044E-09	-0.29888E-08	0.16631E-07

TABLE 3.2 (Cont'd)

500-kV LINE CONSTANTS Output

CAPACITANCE MATRIX (FARAD/MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

0	0.12237E-07 0.00000E+00		
1	0.24245E-09 -0.41993E-09	-0.79171E-09 -0.13713E-08	
2	0.24245E-09 0.41993E-09	0.19135E-07 -0.44116E-23	-0.79171E-09 0.13713E-08

IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.14038E+00 0.13119E+01							
2	0.91409E-01 0.54634E+00	0.14038E+00 0.13119E+01						
3	0.91358E-01 0.46224E+00	0.91409E-01 0.54634E+00	0.14038E+00 0.13119E+01					
4	0.91427E-01 0.91767E+00	0.91411E-01 0.55216E+00	0.91361E-01 0.46512E+00	0.14038E+00 0.13119E+01				
5	0.91408E-01 0.54078E+00	0.91427E-01 0.91767E+00	0.91411E-01 0.55216E+00	0.91409E-01 0.54634E+00	0.14038E+00 0.13119E+01			
6	0.91355E-01 0.45943E+00	0.91408E-01 0.54078E+00	0.91427E-01 0.91767E+00	0.91358E-01 0.46224E+00	0.91409E-01 0.54634E+00	0.14038E+00 0.13119E+01		
7	0.90025E-01 0.50518E+00	0.90022E-01 0.49972E+00	0.89989E-01 0.45799E+00	0.90026E-01 0.50626E+00	0.90021E-01 0.49815E+00	0.89987E-01 0.45594E+00	0.24886E+01 0.15018E+01	
8	0.89987E-01 0.45594E+00	0.90021E-01 0.49815E+00	0.90026E-01 0.50626E+00	0.89989E-01 0.45799E+00	0.90022E-01 0.49972E+00	0.90025E-01 0.50518E+00	0.88664E-01 0.52366E+00	0.24888E+01 0.15018E+01

INVERTED IMPEDANCE MATRIX (MHO-MILE) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.17939E+00 -0.15607E+01					
2	0.56113E-02 0.11377E+00	0.18067E+00 -0.15929E+01				
3	0.98363E-02 0.66942E-01	0.58029E-02 0.11088E+00	0.18038E+00 -0.15693E+01			
4	-0.13041E+00 0.93339E+00	0.38546E-02 0.12260E+00	0.94563E-02 0.68148E-01	0.18038E+00 -0.15693E+01		
5	0.70992E-02 0.10384E+00	-0.12967E+00 0.90568E+00	0.38546E-02 0.12260E+00	0.58029E-02 0.11088E+00	0.18067E+00 -0.15929E+01	
6	0.10166E-01 0.65989E-01	0.70992E-02 0.10384E+00	-0.13041E+00 0.93339E+00	0.98363E-02 0.66942E-01	0.56113E-02 0.11377E+00	0.17939E+00 -0.15607E+01

TABLE 3.2 (Cont'd)

500-kV LINE CONSTANTS Output

```
7  -0.41989E-01  -0.35096E-01  -0.28170E-01  -0.41352E-01  -0.34025E-01  -0.28094E-01   0.33543E+00
    0.24463E-01   0.21514E-01   0.19342E-01   0.24167E-01   0.21210E-01   0.19438E-01  -0.16076E+00

8  -0.28094E-01  -0.34025E-01  -0.41352E-01  -0.28170E-01  -0.35096E-01  -0.41989E-01  -0.22234E-01   0.33543E+00
    0.19438E-01   0.21210E-01   0.24167E-01   0.19342E-01   0.21514E-01   0.24463E-01  -0.15547E-01  -0.16076E+00

              IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                    ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1   0.19093E+00
    0.98869E+00

2   0.16946E+00   0.19757E+00
    0.41658E+00   0.98082E+00

3   0.16552E+00   0.16946E+00   0.19093E+00
    0.33662E+00   0.41658E+00   0.98869E+00

              IMPEDANCE MATRIX (OHM/MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
              ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

0   0.52944E+00
    0.17659E+01

1  -0.22572E-01  -0.48231E-01
   -0.89583E-02   0.28322E-01

2   0.19044E-01   0.24992E-01   0.48643E-01
   -0.15069E-01   0.59614E+00   0.27608E-01
SEQUENCE      SURGE IMPEDANCE        ATTENUATION   VELOCITY    WAVELENGTH   RESISTANCE   REACTANCE    SUSCEPTANCE
         MAGNITUDE(OHM) ANGLE(DEGR.)  DB/MILE      MILES/S      MILES       OHM/MILE     OHM/MILE     MHO/MILE
  ZERO     0.63217E+03 -0.83446E+01  0.36761E-02  0.13066E+06  0.21776E+04  0.52944E+00  0.17659E+01  0.46131E-05
POSITIVE   0.28760E+03 -0.12003E+01  0.37747E-03  0.18176E+06  0.30293E+04  0.24992E-01  0.59614E+00  0.72136E-05

           INVERTED IMPEDANCE MATRIX (MHO-MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                    ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1   0.98952E-01
   -0.12632E+01

2   0.22368E-01   0.10199E+00
    0.45109E+00  -0.13745E+01

3   0.39295E-01   0.22368E-01   0.98952E-01
    0.26802E+00   0.45109E+00  -0.12632E+01

           INVERTED IMPEDANCE MATRIX (MHO-MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
                  ROWS PROCEED IN SEQUENCE 0,1,2, 0,1,2 ETC. AND COLUMNS PROCEED IN SEQUENCE 0,2,1, 0,2,1 ETC.

0   0.15598E+00
   -0.52018E+00

1  -0.18421E-01  -0.14395E+00
   -0.15982E-01   0.68910E-01

2   0.23052E-01   0.71954E-01   0.13165E+00
   -0.79624E-02  -0.16904E+01   0.90208E-01
BLANK CARD TERMINATING FREQUENCY CARDS.            1BLANK CARD TERMINATING FREQUENCY CARDS
BLANK CARD TERMINATING LINE-CONSTANTS CASES.       1BLANK CARD TERMINATING LINE CONSTANTS CASES
```

TABLE 3.3

500-kV Line Model Parameters

	Resistance [Ω/mile]	Surge Impedance [Ω]	Wave Velocity [miles/sec]
Zero Sequence.........	.52944	632.17	1.31×10^5
Positive Sequence.....	.02499	287.60	1.82×10^5

In reality, there are two identical line modes (positive sequence) with 287.6-ohm surge impedances and velocities near the speed of light. The ground mode has a higher surge impedance, is more lossy, and has a slower wave velocity.

The matrices in Table 3.2 present both real and imaginary parts. For Z matrices, these are valid and define $R + j\omega L$, or their inverse. Only the real parts of certain elements of C and P for the symmetrical components should be used. In particular, only C_{00}, $C_{11} = C_{22}$, P_{00}, and $P_{11} = P_{22}$ should be used. For nontransposed lines, symmetrical components are only an approximation, which leads to non-zero sequence coupling elements in Z, C, etc.

The use of matrix printouts to provide input to EMTP line models is illustrated with the next example. These outputs may also be useful for comparisons with other line parameter programs or for other types of studies which may not involve the EMTP.

Two 345-kV circuits sharing the same right-of-way are depicted in Figure 3.2. The conductor data is given in Table 3.4. The LINE CONSTANTS input data in Table 3.5 is very similar to the input for the previous example. There are a total of 10 conductor cards, 4 of which describe shield wires. The remaining six conductor cards represent the phase conductors. The phases numbered 1 through 3 represent one circuit, while the phases numbered 4 through 6 represent the second circuit. Conductor names in columns 73-78 are optional and have no effect on the results. Note that each circuit has the same tower geometry but different conductor and shield wire types. Horizontal conductor displacements refer to a centerline midway between the two circuits. In this case, the average conductor heights are supplied in the VTOWER field. The final line model will have six phases, three for each circuit.

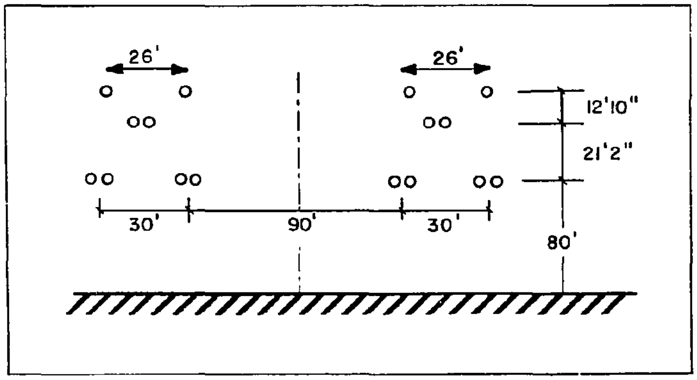


FIGURE 3.2. Two 345-kV Lines On the Same Right-of-Way

TABLE 3.4

345-kV Line Conductor Data

		Type, Name	Diameter (Inch)	Resistence (Ω/mi)	
Line 1:	Shield Wire	3/8" EHS	.36	6.59	
	Conductor	Cardinal	1.196	.1191	18-inch bundle (2)
Line 2:	Shield Wire	7 No. 8 Aluweld	.3854	1.901	
	Conductor	Rail	1.165	.1195	18-inch bundle (2)

The frequency card is identical to the one used for the previous example.

Selected output matrices from this LINE CONSTANTS case are shown in Table 3.6, namely C and Z for the equivalent phase conductors. These matrices are in units per mile, and must be multiplied by the number of miles per pi section. The resulting values can be directly used as EMTP input for multi-phase RLC coupled branches. The reference branch feature is convenient for cascading several pi sections to form a line model. If inductances are to be specified in millihenries rather than ohms, the Z-matrix data in Table 3.6 must be appropriately converted.

TABLE 3.5

345-kV LINE CONSTANTS Input

```
C FILE NAME: "LINECONST": THE LINECONSTANTS FOR THE DOUBLE CIRCUIT 345-KV
C                         TRANSMISSION SYSTEM WILL BE CALCULATED.
BEGIN NEW DATA CASE
LINE CONSTANTS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1-3: PHASE NUMBER
C COLUMN 17,18: USUALLY A "4"
C COLUMN 80:  NUMBER OF CONDUCTORS IN THE BUNDLE
C     4-8     9-16      19-26    27-34   35-42   43-50    51-58    59-66 67-72 73-78
C    SKIN    RESIS      REACT     DIAM   HORIZ  VTOWER     VMID    SEPAR ALPHA  NAME
C
C LEFT TOWER
  1    .5    .1195 4             1.165   -60.0   101.2               18.     0.  RAIL 2
  2    .5    .1195 4             1.165   -45.0    80.0               18.     0.  RAIL 2
  3    .5    .1195 4             1.165   -75.0    80.0               18.     0.  RAIL 2
  0    .5    1.901 4             .3854   -47.0   114.0
  0    .5    1.901 4             .3854   -73.0   114.0
C RIGHT TOWER
  4    .5    .1191 4             1.196    60.0   101.2               18.     0.CARDIN 2
  5    .5    .1191 4             1.196    45.0    80.0               18.     0.CARDIN 2
  6    .5    .1191 4             1.196    75.0    80.0               18.     0.CARDIN 2
  0    .5     6.59 4              .360    47.0   114.0
  0    .5     6.59 4              .360    73.0   114.0
BLANK CARD TERMINATING CONDUCTOR CARDS
C FREQUENCY CARD
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 44: ICAP
C     1-8        9-18      19-28  30-35  37-42
C   EARTH FREQUENCY     CARSON  PRINT  PRINT
C   RESIS          HZ  ACCURACY    (C)    (Z)
     100.        60.          1 111111 111111 1
BLANK CARD TERMINATING FREQUENCY CARDS
BLANK CARD TERMINATING LINE CONSTANTS CASES
BLANK CARD TERMINATING THE CASE
```

The pi sections will contain lumped series R and L elements, with C equally split and lumped at each end of the pi section. This is not a true traveling wave model, but it can yield good results if the time step and number of pi sections per line are carefully selected. Otherwise, the lumped L and C elements can give rise to spurious transients. In Case 6, the pi sections are used for steady-state calculations in which this consideration is not important.

Reference (7) describes another simple approach to modeling double circuit lines, or lines on the same right-of-way. It uses the K. C. Lee model for nontransposed lines, but assumes each individual circuit is transposed and identical. Only the dominant zero sequence intercircuit coupling is represented.

TABLE 3.6

345-kV LINE CONSTANTS Output

CAPACITANCE MATRIX (FARAD/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.17497E-07					
2	-0.29818E-08	0.16455E-07				
3	-0.30309E-08	-0.27299E-08	0.16351E-07			
4	-0.29142E-09	-0.39136E-09	-0.18109E-09	0.17533E-07		
5	-0.39073E-09	-0.70254E-09	-0.27028E-09	-0.30002E-08	0.16495E-07	
6	-0.18074E-09	-0.27016E-09	-0.12321E-09	-0.30497E-08	-0.27436E-08	0.16391E-07

IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.27986E+00 0.88895E+00					
2	0.19817E+00 0.34895E+00	0.24315E+00 0.94333E+00				
3	0.19673E+00 0.35068E+00	0.17999E+00 0.35872E+00	0.23995E+00 0.94666E+00			
4	0.17700E+00 0.19667E+00	0.16933E+00 0.23009E+00	0.16524E+00 0.20287E+00	0.24421E+00 0.98629E+00		
5	0.17503E+00 0.21167E+00	0.16608E+00 0.25277E+00	0.16269E+00 0.22001E+00	0.17282E+00 0.42212E+00	0.22566E+00 0.99247E+00	
6	0.16826E+00 0.19170E+00	0.16058E+00 0.22625E+00	0.15720E+00 0.20127E+00	0.16989E+00 0.42874E+00	0.16142E+00 0.41428E+00	0.21955E+00 0.10055E+01

Figure 3.3 illustrates the geometry of a 230-kV transmission line considered in Case 4 for lightning surge studies. If a lightning stroke terminates on a shield wire, both shield wires will be at the same potential after the surge reaches the first tower adjacent to the stroke point. In Case 4, the stroke point will be at or very near the tower. It is also important to model the tower itself with a surge impedance, travel time, and footing resistance. It is therefore necessary to retain the shield wires in a line model for lightning studies, but they can both be lumped into one equivalent conductor.

As the surge travels along the shield wires, coupled voltages of the same polarity will be induced on the phase conductors. At the tower, a backflash may occur if the difference between the coupled voltage and the shield wire or tower voltage is too high. For a flat line configuration, the outside phase conductors have the lowest coupled voltage and thus the highest insulation stress. In Case 4, only one outside phase conductor will be represented. This necessitates a two-phase or two-equivalent-conductor line model. The apparent simplicity in the model is commensurate with uncertainty in other parameters used in lightning studies, which are described in more detail in Case 4.

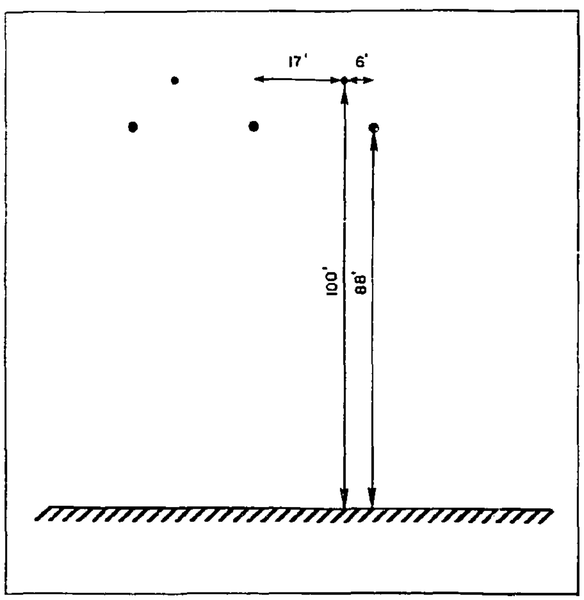


FIGURE 3.3. 230-kV Flat Line Configuration

Reference (8) describes some lossless high-frequency approximations which are useful for lightning studies. Specifically, these are:

a) zero penetration depth on the conductors
b) zero earth return depth
c) zero conductor and earth return losses

The LINE CONSTANTS input for the model is given in Table 3.7.

Phase 1 is an outside phase conductor. The two phase 2 cards are the shield wires which will be lumped into one equivalent conductor. Assumption a) above is equivalent to setting GMR/r = 1 for the conductors. This is implemented on the conductor cards by placing a 3 in column 18 and setting REACT = 1.0. Assumption b) is implemented by placing a 0 in column 28 of the frequency card, thereby bypassing Carson's equations. This also results in zero earth return losses and makes the input value of earth resistivity irrelevant.

Assumption c) could be implemented by setting all conductor resistances equal to zero, but this causes an eigenvector calculation within the LINE CONSTANTS program to break down. Instead, the resistance of each equivalent phase conductor will be set equal to the same small value, namely .001 ohms/mile. Since the shield wires are paralleled, the individual shield wire resistances should be approximately .002 ohms/mile. The resulting modal resistances will be set equal to zero for use in the EMTP line model.

The K. C. Lee nontransposed line parameters are requested by placing a 1 in column 70 of the frequency card, as shown in Table 3.7. The parameters are calculated at 500 kHz to be more representative of lightning surges. Power frequency voltages are not explicitly included in Case 4.

Output for the K. C. Lee parameter calculation is similar to the preceding two examples. In addition, the nontransposed line parameters are inserted immediately after Z for the equivalent phase conductors. This portion of the output is shown in Table 3.8. Three important parts of this output are the traveling wave parameters, the modal transformation matrix, and the surge impedances in phase domain.

TABLE 3.7

230-kV LINE CONSTANTS Input

```
C FILE NAME: "LINE.LIGHTNING"
C    LINE CONSTANTS FOR A 230-KV LINE ARE CALCULATED USING
C    THE LOSSLESS HIGH-FREQUENCY APPROXIMATIONS.
C    ONE EQUIVALENT SHIELD WIRE AND ONE OUTSIDE PHASE CONDUCTOR
C    ARE RETAINED IN THE NON-TRANSPOSED LINE MODEL.
BEGIN NEW DATA CASE
LINE CONSTANTS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1-3: PHASE NUMBER
C COLUMN 17,18: USUALLY A "4"
C COLUMN 80:  NUMBER OF CONDUCTORS IN THE BUNDLE
C     4-8     9-16       19-26    27-34    35-42   43-50     51-58    59-66 59-72 73-78
C    SKIN    RESIS       REACT     DIAM    HORIZ  VTOWER      VMID    SEPAR ALPHA  NAME
C
  1  0.0   .001  3     1.0      .994      0.     88.        50.
  2  0.0   .002  3     1.0      .525      6.0    100.       75.
  2  0.0   .002  3     1.0      .525      40.    100.       75.
BLANK CARD TERMINATING CONDUCTOR CARDS
C FREQUENCY CARD
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 44: ICAP
C     1-8      9-18      19-28  30-35  37-42
C   EARTH FREQUENCY      CARSON  PRINT  PRINT                          K.C. LEE FLAG
C   RESIS         HZ  ACCURACY.   (C)    (Z)
       1.  500000.0          0 111111 111111 1                                  1
BLANK CARD TERMINATING FREQUENCY CARDS
BLANK CARD TERMINATING LINE CONSTANTS CASES
BLANK CARD TERMINATING THE CASE
```

The format of the traveling wave parameters is similar to the sequence parameters. There is one mode for each equivalent conductor, two in our case. Note that each modal resistance is approximately equal to .001 ohms. Both modal wave velocities are near the speed of light as a result of assumption b) above. The modal surge impedances are 521.39 ohms and 273.37 ohms.

The modal transformation matrix is produced from the eigenvectors of the matrix product ZY or YZ for the equivalent conductors. This eigenvector calculation is what required non-zero resistance values on the input conductor cards. This modal transformation matrix decouples the line equations the same way that a symmetrical component transformation would for a three-phase transposed line. A decoupling modal transformation can be found for any line configuration, but it will be different for each line depending on the geometry and, to a lesser extent, the frequency. The printed out matrix, T_i, is the transformation from modal currents to phase currents. Other transformations are easily related to this matrix.

$$I_\phi = T_i \, I_m \tag{3-1}$$

$$I_m = T_i^{-1} \, I_\phi \tag{3-2}$$

$$V_\phi = T_v \, V_m = T_i^{-T} \, V_m \tag{3-3}$$

$$V_m = T_v^{-1} \, V_\phi = T_i^T \, V_\phi \tag{3-4}$$

$$Z_m = T_v^{-1} \, Z_\phi \, T_i = T_i^T \, Z_\phi \, T_i \tag{3-5}$$

$$C_m = T_i^{-1} \, C_\phi \, T_v = T_i^{-1} \, C_\phi \, T_i^{-T} \tag{3-6}$$

In this case, $T_i^{-1} = T_i^T$, so that

$$I_\phi = T_i \, I_m \qquad V_\phi = T_i \, V_m \tag{3-7}$$

$$I_m = T_i^T \, I_\phi \qquad V_m = T_i^T \, V_\phi \tag{3-8}$$

$$Z_m = T_i^T \, Z_\phi \, T_i \tag{3-9}$$

$$Z_\phi = T_i \, Z_m \, T_i^T \tag{3-10}$$

$$C_m = T_i^T \, C_\phi \, T_i \tag{3-11}$$

$$C_\phi = T_i \, C_m \, T_i^T \tag{3-12}$$

The EMTP input utilizes both the real and imaginary parts of T_i, but approximations are made to arrive at a real matrix for the time-step calculations. In this case, T_i should be real so the imaginary parts will be set to zero in Case 4.

TABLE 3.8

230-kV LINE CONSTANTS Output

```
                 IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                     ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

  1   0.10092E-02
      0.80706E+04

  2   0.43368E-18    0.10000E-02
      0.15815E+04    0.53332E+04

MODAL PARAMETERS AT FREQ =    0.50000E+06 HZ

MODE    RESISTANCE  REACTANCE  SUSCEPTANCE              SURGE IMPEDANCE(OHM)             VELOCITY  ATTENUATION
          OHM/MILE    OHM/MILE    S/MILE          REAL          IMAG        LOSSLESS     MILE/SEC   NEPER/MILE
   1     0.10075E-02 0.87930E+04 0.32346E-01 0.52139E+03-0.29871E-04 0.52139E+03 0.18628E+06 0.96621E-06
   2     0.10016E-02 0.46104E+04 0.61691E-01 0.27337E+03-0.29695E-04 0.27337E+03 0.18628E+06 0.18319E-05


EIGENVECTOR MATRIX TI FOR CURRENT TRANSFORMATION I(PHASE)=TI*I(MODE)

     REAL COMPONENTS, ROW BY ROW
  0.90643E+00-0.41920E+00
  0.42237E+00 0.90790E+00

    IMAGINARY COMPONENTS, ROW BY ROW
 -0.42209E-07-0.16684E-08
 -0.12836E-06 0.99997E-07

ZSURGE IN PHASE DOMAIN ( R & IMAG. PART OF TI IGNORED)
  0.47854E+03
  0.93773E+02 0.31623E+03


                 IMPEDANCE MATRIX (OHM/MILE) FOR THE SYMMETRICAL COMPONENTS OF THE EQUIVALENT PHASE CONDUCTORS
                          THIS IS A TWO-PHASE LINE. ROWS AND COLUMNS PROCEED IN SEQUENCE 0,1

  0   0.10046E-02
      0.82834E+04

  1   0.45992E-05    0.10046E-02
      0.13687E+04    0.51204E+04

SEQUENCE        SURGE IMPEDANCE          ATTENUATION   VELOCITY    WAVELENGTH   RESISTANCE    REACTANCE    SUSCEPTANCE
         MAGNITUDE(OHM) ANGLE(DEGR.)     DB/MILE      MILES/S       MILES       OHM/MILE      OHM/MILE      MHO/MILE
  ZERO    0.48020E+03 -0.34744E-05   0.90856E-05  0.18212E+06  0.36424E+00  0.10046E-02  0.82834E+04  0.35922E-01
POSITIVE  0.29683E+03 -0.56206E-05   0.14698E-04  0.18212E+06  0.36424E+00  0.10046E-02  0.51204E+04  0.58113E-01
```

The surge impedances in phase domain can be calculated from the equations above. This output is useful because it provides the values for a surge impedance termination. A matrix of these resistance values placed at an open line end will produce no reflections from that line end. This represents the line continuing on past the point where the system model has been truncated.

The modal parameters were calculated by hand using information presented in Reference (8) and using the equations presented above. This calculation is more precise because it does not involve the adjustment of conductor resistances to complete the eigenvector calculation. The results are compared in Table 3.9.

TABLE 3.9

Modal Parameter Comparison

		LINE CONSTANTS	Hand Calculation
Mode 1	R	.001 Ω/mile	0.0
	Z	521.39 Ω	523.18 Ω
	V	1.86×10^5 miles/sec.	1.86×10^5 miles/sec.
Mode 2	R	.001 Ω/mile	0.0
	Z	273.37 Ω	274.07 Ω
	V	1.86×10^5 miles/sec.	1.86×10^5 miles/sec.
T_i =		$\begin{bmatrix} .90643 & -.41920 \\ .42237 & .90790 \end{bmatrix}$	$\begin{bmatrix} .91097 & -.41247 \\ .41247 & .91097 \end{bmatrix}$

Both methods yield nearly identical results. The hand-calculated parameters were actually used in Case 4.

All of these LINE CONSTANTS cases ran in approximately .1 seconds on a Cray 1S computer.

Suggested investigation:

Run the first example 500-kV line with a K. C. Lee model output request. Compare the modal traveling wave parameters to the symmetrical component traveling wave parameters. Compare T_i to the following T_i, which is used by the EMTP for transposed lines.

$$T_i = \begin{bmatrix} 1/\sqrt{3} & 1/\sqrt{2} & 1/\sqrt{6} \\ 1/\sqrt{3} & -1/\sqrt{2} & 1/\sqrt{6} \\ 1/\sqrt{3} & 0 & -2/\sqrt{6} \end{bmatrix}$$

This is actually an $\alpha\beta 0$ or Clarke transformation, but it uses the same positive and zero sequence modal parameters as the symmetrical components transformation for transposed lines.

It may also be interesting to calculate the 500-kV line constants at a higher frequency which is representative of switching surges; for example, 1000 Hz.

Section 4

CASE 4: LIGHTNING SURGE STUDIES

Modern high-voltage transmission lines are designed for perfect shielding from direct lightning strokes, so that most lightning outages occur due to backflash. The backflash occurs when a lightning stroke terminates on a tower or shield wire, and the resulting voltage on the tower is sufficient to cause a flashover from the tower to phase conductor. This case will illustrate the backflash using a 230-kV line as an example. The predominant parameters of surge front time and tower footing resistance will be illustrated, as well as the effect of adjacent towers. Using the EMTP results, lightning outage rates will be calculated.

The line considered has two shield wires. A stroke current surge terminating on the tower will divide between each outgoing shield wire and the tower according to the shield wire and tower surge impedances. The shield wire currents will also induce coupled voltages and currents on the phase conductors, as illustrated in Figure 4.1. The stress on the tower insulation corresponds to the difference between the coupled phase conductor voltage and the voltage on the tower adjacent to the phase conductor, also shown in Figure 4.1. Insulation strength for steep-fronted lightning surges has a very small standard deviation relative to the mean strength. Therefore, if the peak stress exceeds the critical flashover voltage (CFO) for any insulator string or air gap, a backflash is assumed to occur.

For a stroke to the tower, the initial rate of voltage rise is given by

$$S/\left(\frac{1}{\frac{2}{Z_g} + \frac{1}{Z_t}}\right), \qquad (4\text{-}1)$$

where, S is the current steepness,
Z_g is the shield wire surge impedance
Z_t is the tower surge impedance.

This rate of rise is altered by wave reflections from the tower footing resistance (TFR). A typical value of Z_t is 200 ohms, so usually TFR < Z_t and the reflections are negative, thereby reducing the ultimate peak voltage at the tower top.

If we make the approximation $Z_t = Z_g/2$, and also assume TFR << Z_t, then Figure 4.2 shows the voltage at the tower top when reflections from adjacent towers are not considered. The following approximate formulas apply:

$$E_T = Z_T \tau_T \frac{I}{T_f} \tag{4-2}$$

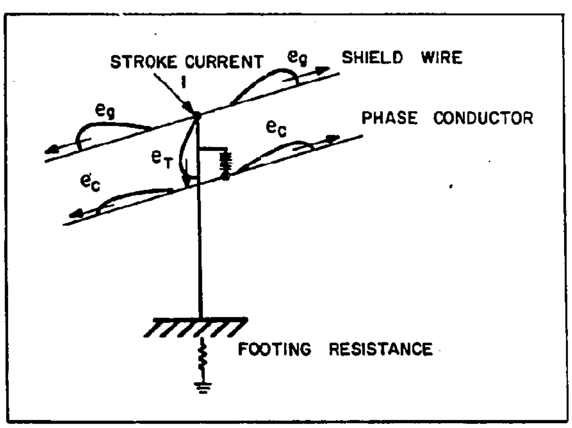
$$E_{TT} = TFR * I + E_T \tag{4-3}$$

$$E_F = TFR * I \tag{4-4}$$

where, τ_T is the tower travel time
T_f is the current surge front time
I is the peak current magnitude

An infinite surge tail time has been assumed. Note that E_T represents a tower "inductance" voltage drop which eventually disappears.

When reflections from adjacent towers are considered, the tail time is reduced, even when the input current surge has an infinite tail. This occurs because waves impinging the tops of adjacent towers see a surge impedance of Z_g in parallel with Z_T, compared with an incident surge impedance of Z_g. The negative reflections travel back to the stroke point and reduce the tower voltage there.



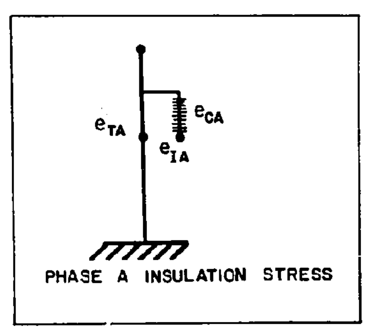


FIGURE 4.1. Backflash Phenomena For a Single-Phase Line With Shield Wire

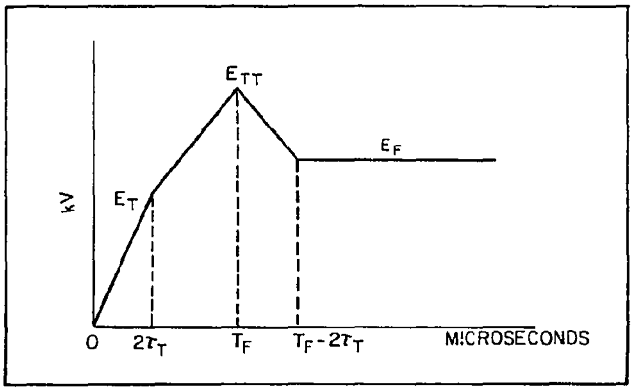


FIGURE 4.2. Tower Top Voltage Neglecting Adjacent Towers

Since the transmission line and towers are symmetrical about the struck tower, the line can be "folded" around the stroke point as shown in Figure 4.3 to simplify the analysis. The struck tower has its normal surge impedance and footing resistance, while the conductors and other towers and footing resistances are halved in value. Strokes to midspan can also be folded around the stroke point. In this case, all surge impedances and footing resistances are halved.

Only a limited number of adjacent towers need be considered. If the surge front time is T_f and the travel time between towers is T_s, then only $T_f/(2\ T_s)$ towers on each side can have an effect on the peak voltage. The line beyond the last tower considered can be represented with a surge impedance termination. For multi-conductor lines, the proper termination is a matrix of self and mutual resistances to achieve no reflections from the termination.

The tower geometry is shown in Figure 4.4. Only one of the outside phase conductors is simulated because the outside conductors will experience the highest insulation stress. This occurs because the induced voltage on the outside conductors is lower than on the middle conductor. Both shield wires have been lumped into one equivalent conductor as described in Case 3. A summary of the modal surge impedances and phase surge impedances is given in Table 4.1. Parallel lines in the "folded" system are represented by using halved modal impedances with the same transformation matrix and modal velocities.

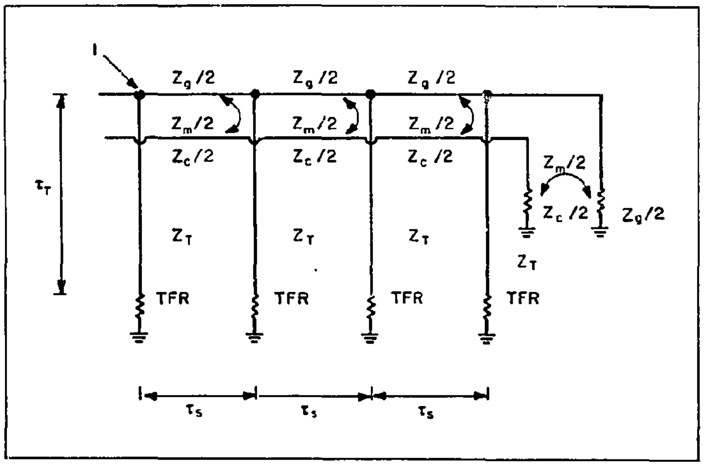


FIGURE 4.3. Simplified System For Stroke Terminating At a Tower

The towers are modeled with a single-conductor line to ground with a surge impedance of 200 ohms and wave velocity close to the speed of light. The total tower travel time is .102 microseconds. The distance along the tower from the top to a point adjacent to the phase conductors is not modelled separately, even though it takes a finite time for the tower surge to reach this point. The reason is that it also takes approximately the same finite amount of time for the coupled voltage to appear on the phase conductor, and the EMTP cannot model this effect.

The stroke current has a magnitude of -1000 amps crest and a tail time of 80 microseconds. The front time was a variable parameter in the study. Figure 4.5 shows the current waveform. Since the system model is linear, the EMTP results can be expressed in terms of kV per kA of stroke current.

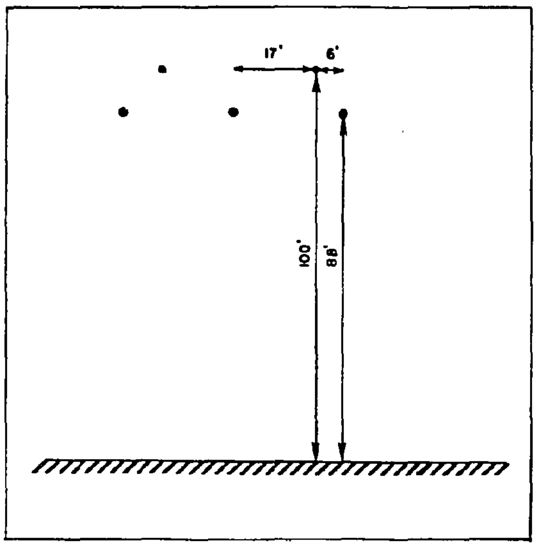


FIGURE 4.4. 230-kV Line Configuration

TABLE 4.1

230-kV Line Surge Impedances

Mode 1 - $Z = 523.18\ \Omega$
$V = 186{,}280$ miles/sec.

Mode 2 - $Z = 274.08\ \Omega$
$V = 186{,}280$ miles/sec.

Phase Domain - $Z_{gw} = 316.46\ \Omega$
$Z_{\emptyset} = 480.8\ \Omega$
$Z_m = 93.6\ \Omega$

Modal Transformation Matrix:

$$T_I = \begin{bmatrix} .91097 & -.41247 \\ .41247 & .91097 \end{bmatrix}$$

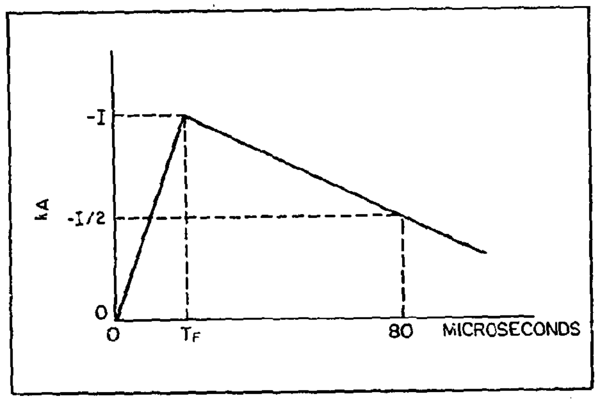


FIGURE 4.5. Input Lightning Current Surge

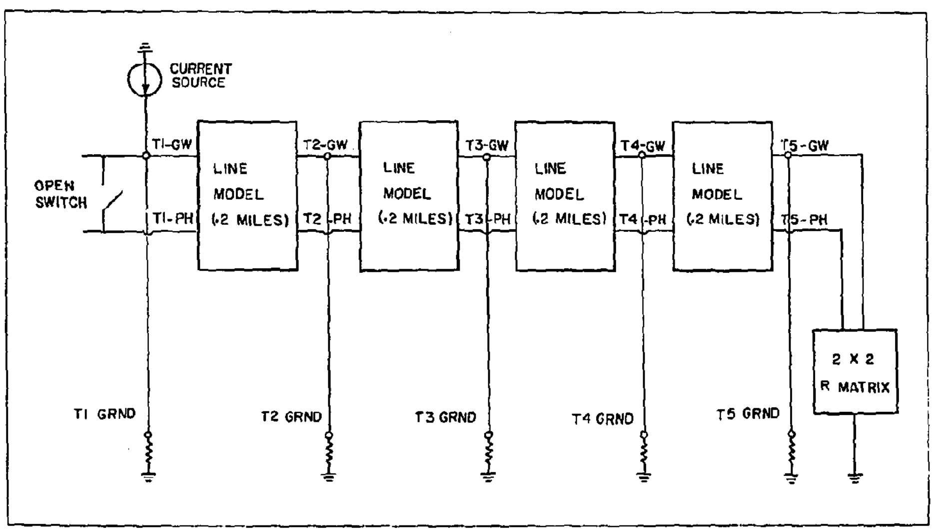


FIGURE 4.6. EMTP Model For a Stroke to Tower

TABLE 4.2

EMTP Input For a Stroke to Tower

```
C FILE NAME: "LIGHT", A LIGHTNING STROKE HITS A TOWER TOP ON A
C             230-KV TRANSMISSION LINE. THE VOLTAGE ACROSS
C             THE OUTSIDE PHASE INSULATORS WILL BE CALCULATED.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8     9-16    17-24    25-32
C T-STEP   T-MAX   X-OPT    C-OPT
C SECNDS SECONDS    0=MH     0=UF
C                  F(HZ)    F(HZ)
1.020E-8  6.0E-6     60.        0
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8     9-16    17-24    25-32    33-40    41-48    49-56    57-64    65-72    73-80
C  PRINT     PLOT NETWORK    PR.SS   PR.MAX    I PUN    PUNCH     DUMP    MULT. DIAGNOS
C 0=EACH   0=EACH    0= NO    0= NO    0= NO    0= NO    0= NO    INTO-  NENERG    PRINT
C K=K-TH   K=K-TH    1=YES    1=YES    1=YES    1=YES    1=YES    DISK  STUDIES     0=NO
   40000        1        1        1        1        0        0        1
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.                     (OUTPUT IN COLUMN 80)
C                  BRANCH            MH    UF                                      I=   1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                                       V=   2
C                                                                                  I,V  3
C                                                                                  P,E  4
C 34567890123456789012345678901234567890123456789O
C
C TERMINATING SURGE IMPEDANCE AT THE ENDS OF THE LINE.
 1T5-PH                    240.40
 2T5-GW                    46.800             158.23
C TOWER FOOTING RESISTANCES
  T1GRND                     50.0
  T2GRND                     25.0
  T3GRND                     25.0
  T4GRND                     25.0
  T5GRND                     25.0
C 34567890123456789012345678901234567890123456789O
C                          27-32 33-38 39-44 45-50  CODE IN COLUMN "52"
C                              R     Z     V    LE  (LE=LENGTH)
C                                                   (ZERO,POSITIVE SEQUENCE)
C TRANSMISSION LINE TOWERS
C TOWER 1
-1T1-GW T1GRND                0. 200.0 9.8E8 100.0 1
C TOWER 2
-1T2-GW T2GRND                0. 100.0 9.8E8 100.0 1
C TOWER 3
-1T3-GW T3GRND                0. 100.0 9.8E8 100.0 1
C TOWER 4
-1T4-GW T4GRND                0. 100.0 9.8E8 100.0 1
C TOWER 5
-1T5-GW T5GRND                0. 100.0 9.8E8 100.0 1
C
```

TABLE 4.2 (Cont'd)

EMTP Input For a Stroke to Tower

```
C UNTRANSPOSED LINE MODEL USING THE K.C. LEE UNTRANSPOSED LINE MODEL
C COL. "-" = UNTRANSPOSED LINE
C COL.2: PHASE NUMBER
C COL. 3 - 8: BUS 1
C COL. 9 -14: BUS 2
C COL.15 -20: BUS 3
C COL.21 -27: BUS 4  (BUSSES 3 AND 4 ARE REFERENCE BUSSES)
C COL.27 - 38: MODAL RESISTANCE IN OHMS/MILE
C COL.39 - 50: MODAL SURGE IMPEDANCE
C COL.51 - 62: MODAL SPEED OF PROPAGATION IN MILES/SECOND
C COL.63 - 74: LENGTH OF THE LINE IN MILES
C COL.76:  ILINE = 1
C COL.79:  NUMBER OF PHASES, INCLUDING THE GROUND WIRE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
$VINTAGE, 1
-1T1-PH T2-PH                 0.00000E+01 0.26159E+03 0.18628E+06-    .20E+00 1  2
-2T1-GW T2-GW                 0.00000E-01 0.13704E+03 0.18628E+06-    .20E+00 1  2
$VINTAGE, 0
C FIRST THE REAL PART OF ROW 1 OF MATRIX TI
C SECOND THE IMAG. PART OF ROW 1 OF MATRIX TI
C REAL PART OF ROW 2   ETC.
C 3456789012345678901234567890123456789012345678901234567890
  0.91097     -0.41247
  0.000000    0.000000
  0.41247     0.91097
  0.000000    0.000000
C
$VINTAGE, 1
C 3456789012345678901234567890
-1T2-PH T3-PH T1-PH T2-PH
-2T2-GW T3-GW T1-GW T2-GW
$VINTAGE, 1
-1T3-PH T4-PH T1-PH T2-PH
-2T3-GW T4-GW T1-GW T2-GW
$VINTAGE, 1
-1T4-PH T5-PH T1-PH T2-PH
-2T4-GW T5-GW T1-GW T2-GW
BLANK CARD TERMINATING BRANCHES
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24      25-34      35-44      45-54      55-64      65-74
C                                                            (OUTPUT OPTION IN COLUMN 80)
C   NODE NAMES                                  IE FLASHOVER   SPECIAL   REFERENCE
C                 TIME TO    TIME TO            OR   VOLTAGE   REQUEST SWITCH-NAME
C   BUS1  BUS2     CLOSE        OPEN      NSTEP                   WORD  BUS5  BUS6
  T1-GW T1-PH       1.0                                                            2
BLANK CARD TERMINATING SWITCHES
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17.(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C    3-8         11-20      21-30      31-40      41-50      51-60      61-70      71-80
C   NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1    TIME-T1    T-START     T-STOP
C   NAME                 IN HZ      DEGR               SECONDS    SECONDS    SECONDS
13T1-GW -1        -1.                   1.E-6      -.5      80.E-6          0.
BLANK CARD TERMINATING SOURCE CARDS
C NODE VOLTAGE OUTPUT
C IN COLUMN 2:: "1" ALL NODES WILL BE OUTPUT, NO BLANK CARD USED TO
C                                              , TERMINATE NODE VOLTAGE OUTPUT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C   BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  T1-GW T1-PH T2-GW T2-PH T3-GW T3-PH T4-GW T4-PH T5-GW T5-GW
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
```

TABLE 4.2 (Cont'd)

EMTP Input For a Stroke to Tower

```
C PLOTTING OF THE RESULTS
  CALCOMP PLOT
C (CASE TITLE UP TO 78 CHARACTERS)
 2 STROKE TO TOWER, TFR=50, TF=1
C COLUMN 2,    "1"
C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
C COLUMN 4, UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C                       UP TO  4 NODE NAMES FOR          49-64           65-80
C                             NODE VOLTAGE PLOTS
C                       UP TO  2  PAIRS OF  NODE          GRAPH   VERTICAL AXIS
C                       NAMES  FOR   BRANCH   OR        HEADING         HEADING
C                                   SWITCH PLOTS          LABEL           LABEL
C                       1ST  ELEMENT 2ND ELEMENT
C                        25-30 31-36 37-42 43-48
C                         BUS1  BUS2  BUS3  BUS4
 1450.5    6.00         T1-GW T1-PH
 1450.5    6.00         T2-GW T2-PH
 1450.5    6.00         T3-GW T3-PH
 1450.5    6.00         T4-GW T4-PH
 1450.5    6.00         T5-GW T5-PH
 1850.5    6.00         T1-GW T1-PH
BLANK CARD TERMINATING PLOTTING
BLANK CARD TERMINATING THE CASE
```

A model for simulating strokes to the tower is shown in Figure 4.6. Note that .2 mile, or 1,056 foot, span lengths were assumed. Input data for this model is given in Table 4.2. The span travel time is 1.074 microseconds for each mode. The particular time step chosen is one-tenth the travel time of the shortest conductor sections, which are the towers. In general, there should be an integer number of time steps in each mode's travel time, or else a large number of time steps.

Three cases were run with strokes to the tower, a front time of 2 microseconds for TFR's of 50 ohms and 20 ohms, and a front time of 1 microsecond with TFR of 50 ohms. The primary outputs were printed minimum values requested by a 1 in column 40 of the integer miscellaneous data card, and raw plot data requested by a 1 in column 64 of that data card.

Figure 4.7 shows the tower top voltage and coupled phase voltage for Case 1, which is a stroke to tower with TFR = 50 and $T_F = 1$. The tower top voltage (solid line) rises from time 0 to approximately .20 microseconds, when the first reflection from the tower footing reaches the tower top. At 1 microsecond, the input surge peak is reached, and further wave reflections on the struck tower eliminate the tower "inductance" voltage drop. From 1.2 to 2.15 microseconds the tower top voltage appears to have settled to a fairly constant value, but then the first adjacent tower reflection arrives, and subsequent reflections act to reduce the surge tail.

Estimating E_T, E_{TT}, and E_F using equations 4-2, 4-3, and 4-4:

$$E_T = 200 \frac{(.102)}{1} 1 = 20.4 \text{ kV} \quad \text{vs.} \quad 18 \text{ kV in Figure 4.7} \qquad (4\text{-}5)$$

$$E_{TT} = 50 + E_T = 70.4 \text{ KV} \quad \text{vs.} \quad 48 \text{ kV in Figure 4.7} \qquad (4\text{-}6)$$

$$E_F = 50 \text{ kV} \quad \text{vs.} \quad 38 \text{ kV in Figure 4.7} \qquad (4\text{-}7)$$

The approximate formulas are based on $Z_g/2 = Z_T$, but in the model we have $Z_g/2 = 158.23$ ohms and $Z_T = 200$ ohms. The approximations are still a useful check on the results.

Figures 4.8, 4.9, 4.10, and 4.11 show the tower top and phase conductor voltages at towers 2, 3, 4, and 5, respectively. The surge travels down the line and is attenuated by negative reflections at each tower top and each tower footing. Clearly only the struck tower is in danger of experiencing a back flash. At tower 5 (Figure 4.11), the tower surge impedance and footing resistance contribute to a non-perfect termination for the shield wire, so reflected voltages do appear there. Figure 4.12 shows the voltage across the insulation at tower 1.

It has been found that outage rates can be approximated by performing all calculations based on a front time of 2 microseconds, even though there is a probabilistic variation in actual stroke front times. Therefore, two more cases were run with TFR = 50 and TFR = 20, both with front times equal to 2 microseconds. Reference (9) provides more information on simplified lightning outage rate calculations.

Figures 4.13 and 4.14 show the tower top voltage, coupled phase voltage, and insulation stress for the case with TFR = 50. Figures 4.15 and 4.16 show these voltages for the case with TFR = 20. Comparing these cases it may be observed that lower footing resistance and longer front times have a significant effect on lowering the insulation stress.

For use in outage rate calculations, the voltage stresses are read from the printout as highlighted in Table 4.3 for the case with TFR=50 and T_F=2. The numbers of interest are the tower top voltage (K_{TT}) and phase insulation stress (K_{IA}) per ampere of stroke current. The results are presented in Table 4.4.

For purpose of illustration, it will be assumed that there are 12 insulators per string on the line. The total string length is 12 x 5.75 inch, or 5.75 feet. For a standard 1.2/50 negative polarity impulse wave, the insulation strength is 170 kV per foot. Therefore, the standard CFO is 977.5 kV for the 12-insulator string. This can be adjusted for nonstandard waves by the formula:

$$CFO_{NS} = \left(.58 + \frac{1.39}{\sqrt{T_F}}\right) CFO \qquad (4\text{-}8)$$

TABLE 4.3

Maximum/Minimum Printout for a Stroke to Tower

TFR = 50, T_F = 2

```
COLUMN HEADINGS FOR THE  11  EMTP OUTPUT VARIABLES FOLLOW.   THESE ARE ORDERED ACCORDING TO THE FIVE
POSSIBLE EMTP OUTPUT-VARIABLE CLASSES, AS FOLLOWS ....
  FIRST  10  OUTPUT VARIABLES ARE ELECTRIC-NETWORK NODE VOLTAGES (WITH RESPECT TO LOCAL GROUND)\
   NEXT   1  OUTPUT VARIABLES ARE BRANCH VOLTAGES (VOLTAGE OF UPPER NODE MINUS VOLTAGE OF LOWER NODE)\
   NEXT   0  OUTPUT VARIABLES ARE BRANCH CURRENTS (FLOWING FROM THE UPPER EMTP NODE TO THE LOWER)\
   NEXT   0  OUTPUT VARIABLES PERTAIN TO DYNAMIC SYNCHRONOUS MACHINES, WITH NAMES GENERATED INTERNALLY\
  FINAL   0  OUTPUT VARIABLES BELONG TO  'TACS'  (NOTE INTERNALLY-ADDED UPPER NAME OF PAIR).
BRANCH POWER  CONSUMPTION (POWER  FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH VOLTAGE FOR THIS GROUPING\
BRANCH ENERGY CONSUMPTION (ENERGY FLOW, IF A SWITCH) IS TREATED LIKE A BRANCH CURRENT FOR THIS GROUPING.

 STEP     TIME      T1-GW        T1-PH        T2-GW        T2-PH        T3-GW        T3-PH        T4-GW        T4-PH        T5-GW

                    T5-GW        T1-GW
                                 T1-PH
   0 0.000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00
               0.000000E+00 0.000000E+00
 588 0.600E-05-0.171672E+02-0.507751E+01-0.985040E+01-0.291344E+01-0.406844E+01-0.120332E+01-0.115420E+01-0.341375E+00-0.199331E+00
              -0.199331E+00-0.120896E+02

MAXIMA AND MINIMA WHICH OCCURRED DURING THE SIMULATION FOLLOW.   THE ORDER AND COLUMN POSITIONING ARE THE
SAME AS FOR THE REGULAR PRINTED OUTPUT VS. TIME.
VARIABLE MAXIMA %
               0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.609935E+00 0.180399E+00 0.531495E+00
               0.531495E+00 0.000000E+00
TIMES OF MAXIMA %
               0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.542640E-05 0.542640E-05 0.470220E-05
               0.470220E-05 0.000000E+00
VARIABLE MINIMA %
              -0.435026E+02-0.128667E+02-0.121393E+02-0.359043E+01-0.406844E+01-0.120332E+01-0.177440E+01-0.524813E+00-0.839185E+00
              -0.839185E+00-0.306359E+02
TIMES OF MINIMA %
               0.199920E-05 0.199920E-05 0.542640E-05 0.542640E-05 0.599760E-05 0.599760E-05 0.577320E-05 0.577320E-05 0.449820E-05
               0.449820E-05 0.199920E-05
```

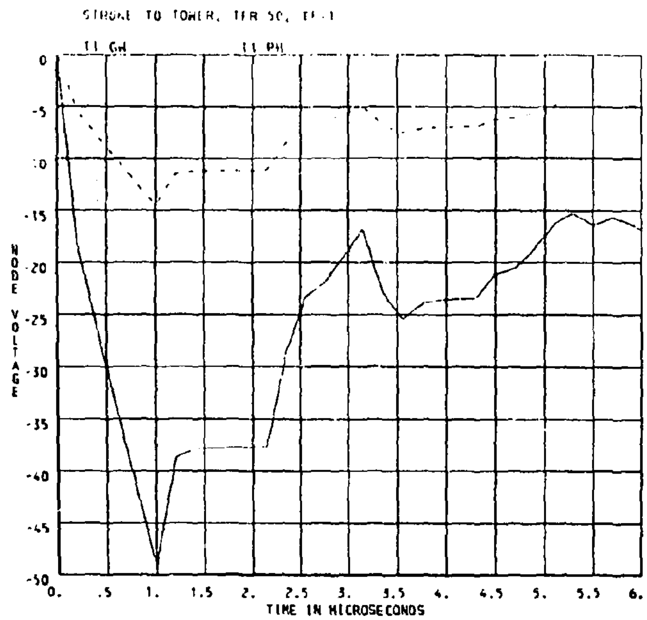


FIGURE 4.7. Tower 1 Shield Wire and Coupled Phase Voltages, $T_F = 1$, TFR = 50

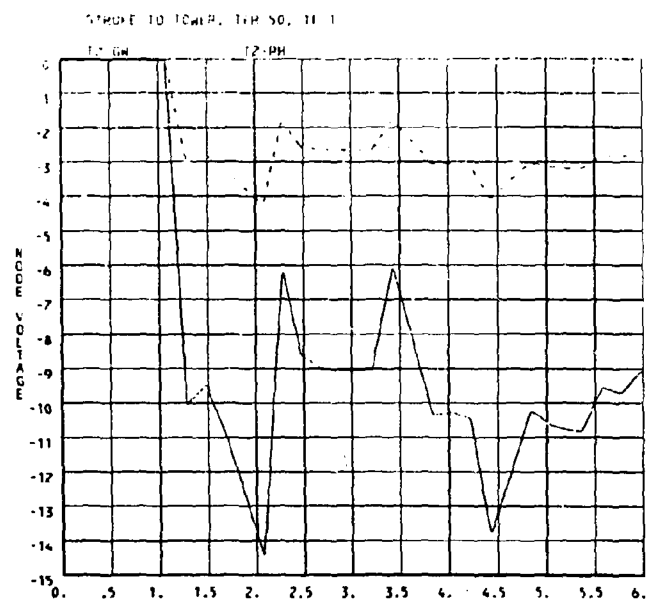


FIGURE 4.8. Tower 2 Shield Wire and Coupled Phase Voltages, $T_F = 1$, TFR = 50

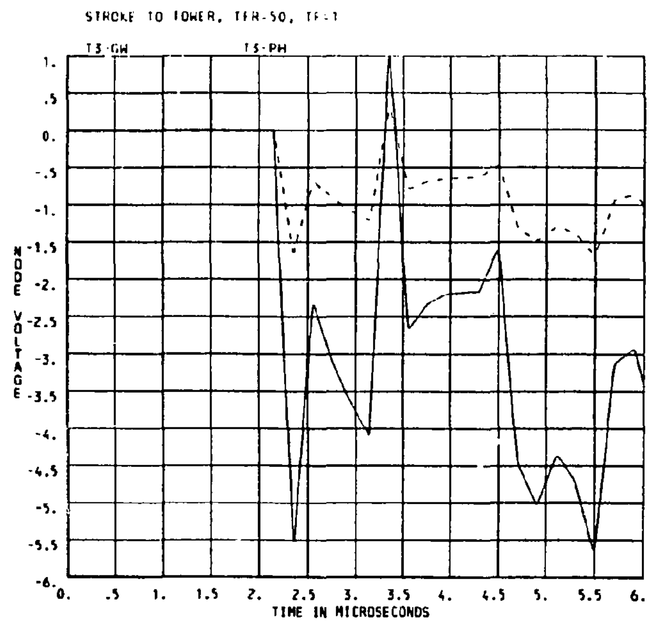


FIGURE 4.9. Tower 3 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50

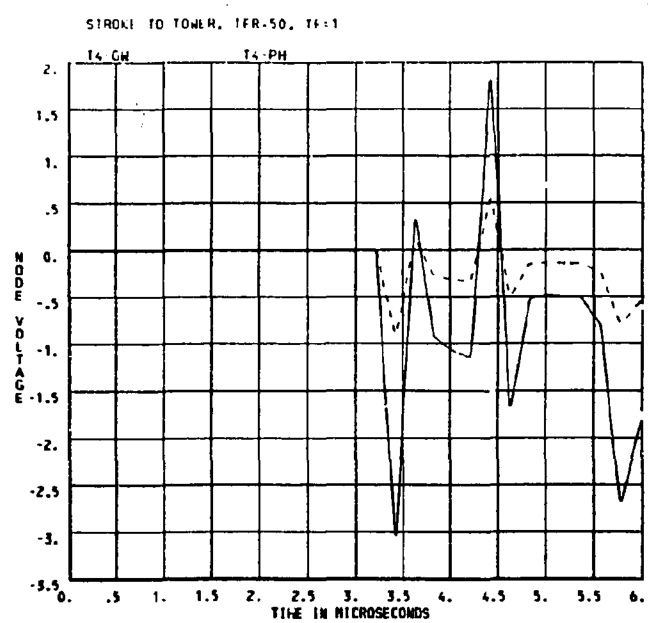


FIGURE 4.10. Tower 4 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50

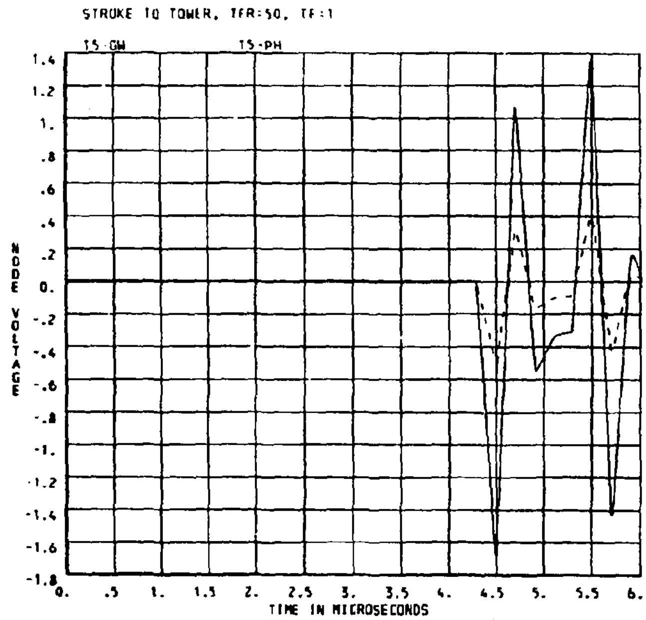


FIGURE 4.11. Tower 5 Shield Wire and Coupled Phase Voltages, T_F = 1, TFR = 50

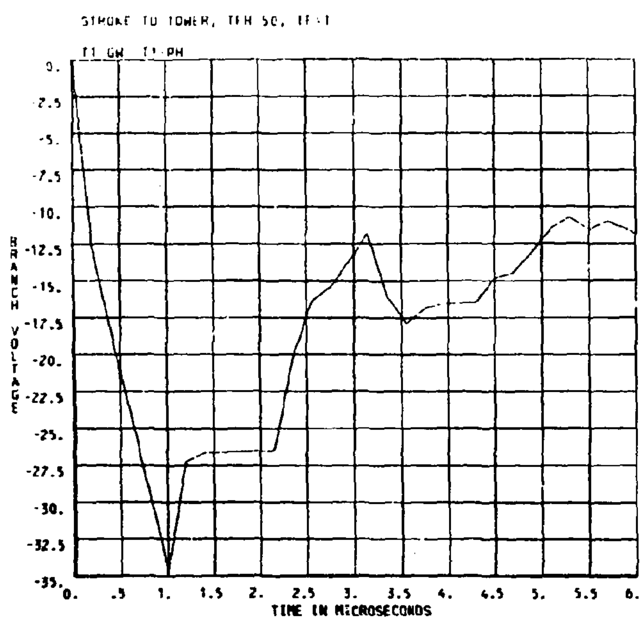


FIGURE 4.12. Insulation Stress, T_F = 1, TFR = 50

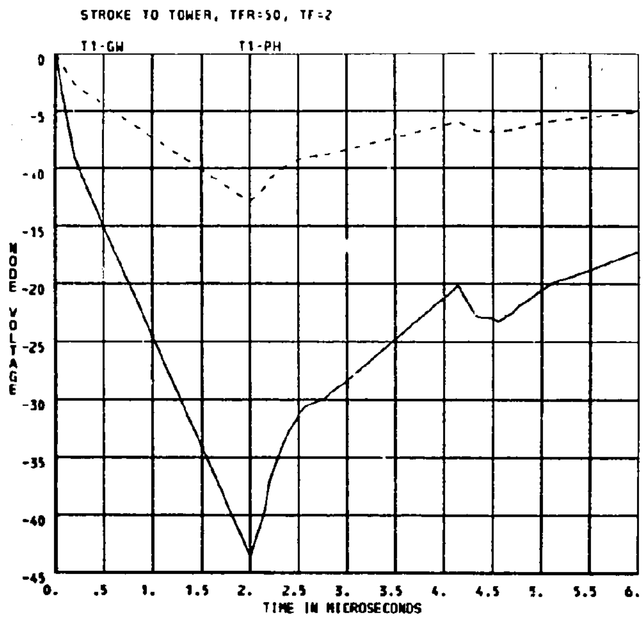


FIGURE 4.13. Tower 1 Shield Wire and Coupled Phase Voltages, T_F = 2, TFR = 50

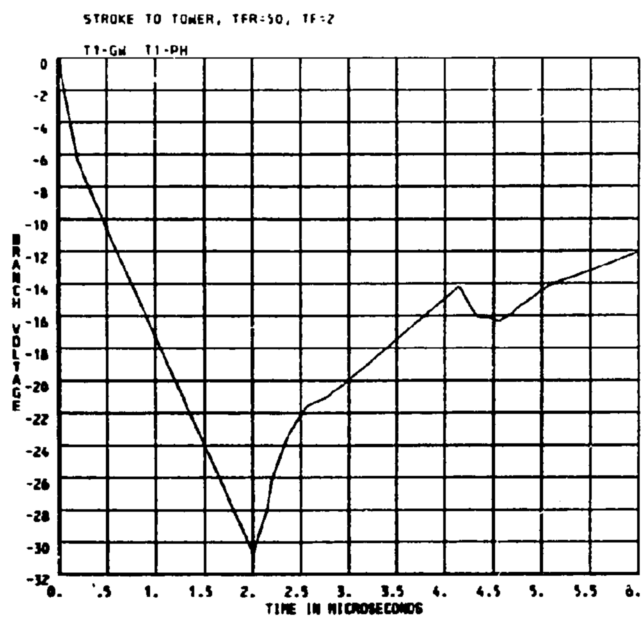


FIGURE 4.14. Insulation Stress, T_F = 2, TFR = 50

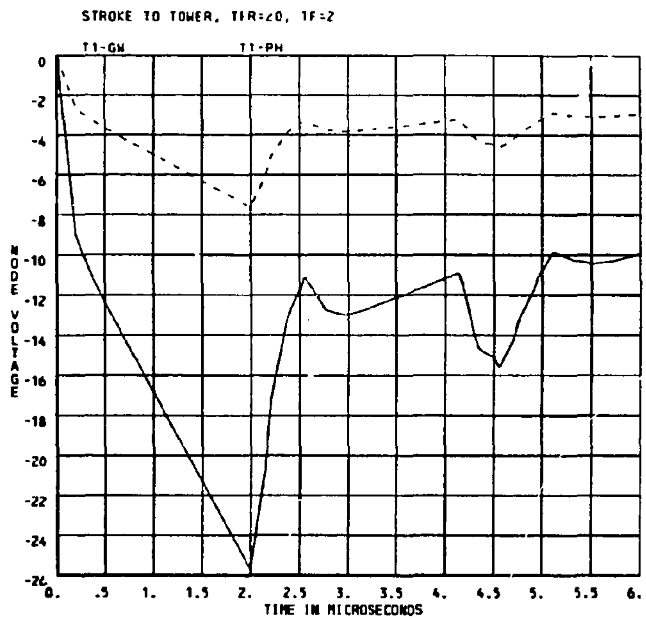


FIGURE 4.15. Tower 1 Shield Wire and Coupled Phase Voltages, T_F = 2, TFR = 20

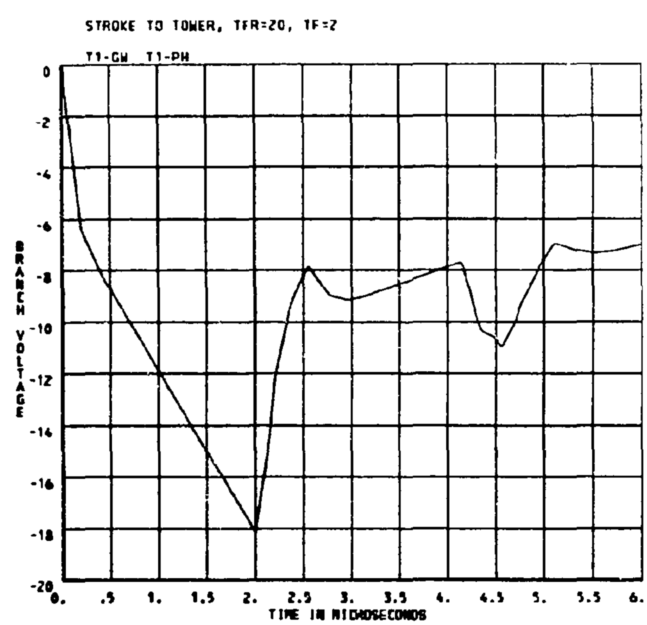


FIGURE 4.16. Insulation Stress, T_F = 2, TFR = 20

This formula makes approximations to the time to flashover for surges with short tails, as illustrated in Figures 4.14 and 4.16.

To calculate a critical current for lightning flashover, the insulation strength should be further adjusted for power frequency bias voltage. For this system, a reasonable peak voltage is

$$V_{pF} = \frac{230\sqrt{2}}{\sqrt{3}}(1.05) = 197.2 \text{ kV} \tag{4-9}$$

TABLE 4.4

Backflash Study Results

Case No.	Stroke Point	TFR Ohms	T_f μ-sec.	K_{TT} kilovolts/kiloamp	K_{IA} kilovolts/kiloamp	I_C kiloamps
1	Tower 1	50	1	48.0	34.0	51.8
2	Tower 1	50	2	43.0	30.5	44.8
3	Tower 1	20	2	25.5	18.0	75.8

TABLE 4.5

Insulation Strength as a Function of Wavefront

T_F μsec	CFO_{NS} kV	$CFO_{NS} - K\,V_{pF}$ kV
1	1926	1763
2	1528	1365

The critical current can be calculated as

$$I_C = \frac{CFO_{NS} - K\,V_{pF}}{K_{IA}} \tag{4-10}$$

where K = .551 for vertical lines, and K = .827 for horizontal lines (our case). For stroke currents of magnitude greater than I_C, a backflash is assumed to occur. The insulation strengths for various wavefronts are given in Table 4.5, while the corresponding critical currents have been included in Table 4.4.

The stroke current probability distribution is described by a log-normal distribution, LN (33.3, .605). This is similar to a Gaussian or normal distribution, except that the reduced variate is given by

$$Z = \frac{\ln (I/33.3)}{.605} \text{ for } I > 20 \text{ kA} \tag{4-11}$$

This value of Z can then be used with the probability tables found in basic text books. The probability of exceeding the critical current, which is the same as the probability of flashover given that a lightning stroke has terminated on the shield wire, is shown in Table 4.6.

The number of strokes terminating on the shield wire must be calculated. Assuming a keraunic level of 30 thunder days per year, the ground stroke density is

$$N_g = .063(30)^{1.25} = 4.4 \text{ strokes/km}^2 \tag{4-12}$$

TABLE 4.6

Flashover Probability

Stroke Location	TFR ohms	I_c kA	Z	$P[I > I_c]$ Per Unit
Tower 1	50	44.8	.490	.3121
Tower 1	20	75.8	1.360	.0869

The exposed area of the shield wire(s) is approximately

$$A = L\ (2\ R_A + S_g) \tag{4-13}$$

where L is the line length, S_g is the shield wire separation (34 ft. or 10.36 m in our case), and R_A is an attractive radius given by

$$R_A = 14.4\ h^{.44} \tag{4-14}$$

where h is the tower height in meters (100 ft. or 30.48 m in our case). Therefore

$$R_A = 14.4\ (30.48)^{.44} = 64.76\ \text{m} \tag{4-15}$$

The number of strokes terminating on the shield wire, per unit length of line, is then

$$\frac{N\ (G)}{L} = N_g\ (2\ R_A + S_g) = (4.4\ \text{strokes/km}^2/\text{yr}) \times [2(.0648\ \text{km}) + .0104\ \text{km}]$$

$$= .62\ \text{strokes/km/yr} = 1.00\ \text{strokes/mile/yr.} \tag{4-16}$$

It is usually assumed that, due to lower height of the shield wire at midspan, 60% of these strokes terminate on a tower and 40% on a shield wire at midspan. Furthermore, it is usually assumed that strokes to midspan cannot actually cause a backflash at the tower due to a predischarge voltage phenomena not included in the EMTP simulations. In this calculation, only strokes to the tower will be considered. The outage rate is given by

$$\text{LFOR} = \frac{N\ (G)}{L}\ (.6)(\text{P from Table 4.6}) \tag{4-17}$$

With TFR = 50, the LFOR is approximately 19/100 miles/yr, and with TFR = 20, the LFOR is approximately 5/100 miles/yr.

The LFOR with the lower footing resistance may be acceptable, since most of the faults are temporary and reclosing would usually be successful. If possible, calculations should be made for existing lines in the same geographic area and compared to actual performance for the purpose of "calibrating" the calculations. It should be clear that there are gaps in the present knowledge of lightning phenomena, and that precise calculations are not often justifiable.

Lightning insulation design is one part of a transmission line's electrical design. Shielding from direct strokes and insulation requirements for contamination and switching surges must also be considered. Switching surge insulation design is another area for EMTP application, and will be discussed in Cases 7 and 8 of this Primer.

These EMTP cases ran in 2 seconds on a Cray 1S computer.

Suggested investigations:

1. Try using 13 insulators instead of 12 insulators.

2. Try using TFR = 10. Footing resistances can be lowered by means of counterpoises, driven ground rods, etc. If other considerations have determined the number of insulators but the backflash rate is too high, lowering TFR is usually the most practical solution.

3. See what happens for a very short wavefront, such as .1 microseconds.

4. See what happens for a long wavefront, such as 4 microseconds.

Section 5

CASE 5: CAPACITOR SWITCHING

Switching three-phase shunt capacitor banks can lead to some interesting transient overvoltages. The effects on the banks themselves, their switching devices, nearby surge arresters, and nearby equipment insulation should be considered. References (10) and (11) provide more details on capacitor bank switching.

The analysis of capacitor switching is basically a lumped circuit problem. The frequencies involved are usually low compared to TRV, lightning, and line switching transients. This sample case will introduce three-phase system models. Capacitor switch recovery voltages and restrikes will be studied.

When a capacitor bank switch opens, the current is interrupted at a natural current zero, which occurs with peak voltage on the capacitor bank. This voltage is trapped on the capacitor and decays very slowly. After all poles of the switch are open, the recovery voltages are determined by the power frequency source voltages and the d.c. charges trapped on the capacitors. The grounding connection of the bank affects the trapped charges, and excessive switch pole spans can also affect the recovery voltages.

An EMTP model for simulating capacitor switch recovery voltages is shown in Figure 5.1. The actual parameter values are unimportant, although the source impedance was made into a small resistance to eliminate high frequency transients and to place the source voltage essentially at the capacitor bus. The bank grounding connection and the switch opening times (pole span) are the important parameters to be investigated. An input file for ungrounded banks is shown in Table 5.1. A small stray capacitance from the bank neutral to ground has been included.

Since the phenomena is a combination of d.c. and 60 Hz, a large time step can be used. One rule of thumb is to set the time step no greater than one degree of a power frequency cycle, or no greater than 46 microseconds. In this case, a value of 50 microseconds was chosen. One other limitation on the largest time step which should be selected concerns current interruption in the EMTP switch models. Because the EMTP performs calculations at discrete time steps, switches will interrupt current at the first time step after a zero crossing which occurs after the specified opening time. The small amount of current which is effectively

TABLE 5.1

Input Data for Capacitor Switch Recovery Voltages

```
C FILENAME: "CAP2": SIMULATES OPENING OF UNGROUNDED
C SHUNT CAPACITOR BANK WITH NORMAL SWITCH OPERATION
BEGIN NEW DATA CASE
C TIME     T-MAX    XL IN OHMS
C STEP
  50.E-6  50.E-3      60.
C PRINT   PLOT      NETWORK    SS     MAXIMA                   PLOT
C FREQUENCIES       OUTPUT     SCLN   PRINTOUT                 FILE DUMP
  20000        3         1        1         1        0        0      1
C SOURCE IMPEDANCE               R
  SRCE ABUS   A                 .01
  SRCE BBUS   BSRCE ABUS   A
  SRCE CBUS   CSRCE ABUS   A
C CAPACITOR BANK                         MICROFARADS                 VOLTAGE OUTPUT
  BANK ABANK N                             1000.0                                 2
  BANK BBANK NBANK ABANK N                                                        2
  BANK CBANK NBANK ABANK N                                                        2
C STRAY BANK NEUTRAL CAPACITANCE         MICROFARADS
  BANK N                                     .1
BLANK CARD ENDING BRANCHES
C CAPACITOR SWITCH
C             CLOSING TIME    OPENING TIME                           VOLTAGE OUTPUT
  BUS   ABANK A       -1.0        .001                                            2
  BUS   BBANK B       -1.0        .001                                            2
  BUS   CBANK C       -1.0        .001                                            2
BLANK CARD ENDING SWITCHES
C SINUSOIDAL SOURCES
C      1 PU VOLTS    60-HZ      PHASE ANGLE              ACTIVE IN SS
14SRCE A   1.0        60.        0.                         -1.
14SRCE B   1.0        60.        -120.                      -1.
14SRCE C   1.0        60.        -240.                      -1.
BLANK CARD ENDING SOURCES
C OUTPUT BUS AND CAPACITOR BANK VOLTAGES
  BANK ABANK BBANK CBANK NBUS  ABUS  BBUS  C
BLANK CARD ENDING NODE VOLTAGE OUTPUT REQUESTS
  CALCOMP PLOT
 2 OPENING UNGROUNDED BANKS
 1445.0      50.0           BUS    ABANK A
 1845.0      50.0           BUS    ABANK A
 1445.0      50.0           BUS    BBANK B
 1845.0      50.0           BUS    BBANK B
 1445.0      50.0           BUS    CBANK C
 1845.0      50.0           BUS    CBANK C
BLANK CARD ENDING PLOT CARDS
BLANK CARD TERMINATING THE CASE
```

"chopped" can lead to spurious high frequency transients if inductive elements are present in the model. Smaller time steps will limit the amount of current chopped when a switch opens. Also, the Application Guide provides information on circuit configurations which minimize the problem.

The source voltage magnitudes were set at 1, so that the output plots will be in per-unit.

If the bank is grounded, each phase of the capacitor banks is independent and behaves like a single-phase capacitor. Figure 5.2 shows Phase B opening with a trapped charge (dashed line) on the capacitor and the Phase B source voltage (solid line). The voltage across the switch contacts is the difference between these two voltages, shown in Figure 5.3. The peak recovery voltage for a grounded bank is 2 per-unit regardless of the pole span.

If the bank is ungrounded, the first phase to open is still connected to the other two phases through the bank neutral. This ungrounded bank neutral can acquire a trapped charge from the other two phases. When the remaining phases interrupt one-quarter cycle later, the bank neutral has .5 per-unit voltage trapped on it. Figure 5.4 shows the Phase C capacitor voltage to ground (dashed line) and source voltage (solid line). The capacitor voltage consists of 1 per-unit trapped on the capacitor plus .5 per-unit which is added to the bank neutral stray capacitance.

The buildup of voltages on the bank neutral ceases at 7.0 milliseconds, because Phases A and B interrupted. The Phase C recovery voltage is shown in Figure 5.5, reaching a peak of 2.5 per-unit. The A and B phase recovery voltages reach peaks of 1.87 per-unit.

If Phases A and B do not interrupt at 7.0 milliseconds, whether due to a mechanical or electrical problem, the bank neutral voltage will continue to build up. This is shown in Figure 5.6, where the bank neutral voltage follows a sinusoid of .5 per-unit half-peak magnitude until Phases A and B finally interrupt at 32 milliseconds. The Phase C recovery voltage in Figure 5.7 reaches a peak of 3 per-unit until the remaining phases interrupt.

If only one phase fails to interrupt, due to a mechanically hung pole, the entire ungrounded bank is connected to a single-phase source voltage. Figures 5.8, 5.9, and 5.10 show the capacitor bank and source voltages line-to-ground for this situation. Phases C and B open normally, but the Phase A interruption is delayed until 25 milliseconds. The peak recovery voltages are 2.0, -3.46, and 2.63 per-unit for Phases A, B, and C, respectively.

Capacitor switches must be designed to withstand these power frequency recovery voltages as a steady-state stress. Since ungrounded banks are very common, the switch should be designed for 2.5 per-unit recovery voltage plus a safety margin for 1.05 per-unit system operation, etc. If the switch malfunctions during opening, the recovery voltage could be even higher.

Shunt capacitor banks at 230-kV voltage levels and higher are usually grounded. If these banks are ungrounded, it may be necessary to use a switch from the next higher voltage class.

If the switch cannot support the recovery voltage stress, a restrike will occur. The voltage which was across the open pole becomes a surge input to the system.

The ensuing low frequency transient overvoltages may cause insulation to fail or surge arresters to operate. A surge arrester operation under these conditions may lead to arrester failure due to excessive energy dissipation from the shunt capacitors.

Figure 5.11 shows the schematic of an industrial plant capacitor installation. The capacitors are delta connected at 4160 volts with a total bank rating of 3600 kVAR in four steps of 900 kVAR each. Only the first two steps are shown in Figure 5.11. The capacitors are used to provide power factor correction and voltage support during motor starting. Delta connected capacitors are not common, but they can be used on low and medium voltage systems.

Field measurements of normal switching operations were conducted. Each step of capacitors is separately switched with a vacuum switch, and each step has current-limiting reactors. The normal mode of operation is to switch each step on or off in numerical sequence.

Figure 5.12 shows the measured bus voltages while energizing the first step. All three poles of step one's vacuum switch close at approximately the same time, near a peak in the Phase B bus voltage. Transient oscillations of approximately 875 Hz ensue, which reach a peak of 1.68 per-unit on Phase B. The damping rate can be estimated by computing the log decrement according to this definition:

$$\log \text{dec} = \frac{1}{n} \ln \left(\frac{A_0}{A_n}\right) \qquad (5\text{-}1)$$

where A_0 and A_n are the amplitudes of cycle 0 and cycle n of the transient.

On the Phase B voltage in Figure 5.12, the log dec is estimated by measuring the first two cycle amplitudes. A ruler may be used to measure the positive-going height of each cycle.

$$\log \text{dec} = \frac{1}{1} \ln \left(\frac{.94}{.42}\right) = .81 \qquad (5\text{-}2)$$

The Q of this oscillation can be derived and compared to the Q for an RLC circuit, or the damping characteristic may be visually compared to the curves on page 63 of Reference (1).

$$Q = \frac{\pi}{\log \text{dec}} = 3.9 \tag{5-3}$$

The parameter Q is equal to η for parallel RLC circuits or λ for series RLC circuits as described in Reference (1) and in Section IV of this Primer. Equation 5-3 holds for the usage of time constants defined in Reference (1). In many other instances, Q will be equal to $2\pi/\log$ dec.

The simplified single-phase circuit is an RLC, so an $\eta = R/Z_0$ of approximately 4 should give the proper damping characteristic. Only the parameter C is known at present.

$$\text{MVAR}_{\text{step}} = .900 = \frac{(\text{kV})^2}{X_c} \tag{5-4}$$

$$C = \frac{.900}{(4.16)^2(377)} = 138 \times 10^{-6} \text{ Farads} \tag{5-5}$$

This is a line-to-neutral capacitance, so the equivalent delta-connected capacitance would be 46 microfarads.

The system inductance, L, can be estimated from the natural frequency in Figure 5.12.

$$f_o = 875 \text{ Hz} = \frac{1}{2\pi\sqrt{LC}} \tag{5-6}$$

$$L = \frac{1}{4\pi^2(875)^2(138 \times 10^{-6})} = .00024 \text{ Henries} \tag{5-7}$$

This system inductance results in 26.6 kA of three-phase fault current at the capacitor bus. A parallel damping resistor of 5.3 ohms was chosen. Therefore,

$$Q = \frac{R}{Z_o} = \frac{5.3}{\sqrt{.24 \times 10^{-3}/138 \times 10^{-6}}} = 4.0 \tag{5-8}$$

TABLE 5.2

Back-to-Back Capacitor Switching EMTP Input

```
C FILE NAME: BACKTOBACK
C    SIMULATION OF TWO BACK-TO-BACK DELTA-CONNECTED CAPACITOR
C    BANKS WITH CURRENT-LIMITING REACTORS.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8    9-16   17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C                  F(HZ)   F(HZ)
 10.0E-6  40.E-3
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8    9-16   17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  ENERG.   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
   20000       3       1       1       1                       1
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.                 (OUTPUT IN COLUMN 80)
C                   BRANCH          MH    UF                                 I=   1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                                 V=   2
C                                                                            I,V  3
C                                                                            P,E  4
C SOURCE IMPEDANCE
  SRCE ABUS  A                  0.24
  SRCE BBUS  BSRCE ABUS  A
  SRCE CBUS  CSRCE ABUS  A
  BUS  ASRCE A            5.3
  BUS  BSRCE BBUS  ASRCE A
  BUS  CSRCE CBUS  ASRCE A
C CURRENT LIMITING REACTORS
  STP1 ACAP1 A                  .02500
  STP1 BCAP1 BSTP1 ACAP1 A
  STP1 CCAP1 CSTP1 ACAP1 A
  STP2 ACAP2 ASTP1 ACAP1 A
  STP2 BCAP2 BSTP1 ACAP1 A
  STP2 CCAP2 CSTP1 ACAP1 A
  CAP1 ASTP1 A            10.0
  CAP1 BSTP1 BCAP1 ASTP1 A
  CAP1 CSTP1 CCAP1 ASTP1 A
  CAP2 ASTP2 ACAP1 ASTP1 A
  CAP? BSTP2 BCAP1 ASTP1 A
  CAP2 CSTP2 CCAP1 ASTP1 A
C CAPACITOR BANKS
  CAP1 ACAP1 B                        46.000
  CAP1 BCAP1 CCAP1 ACAP1 B
  CAP1 CCAP1 ACAP1 ACAP1 B
  CAP2 ACAP2 BCAP1 ACAP1 B
  CAP2 BCAP2 CCAP1 ACAP1 B
  CAP2 CCAP2 ACAP1 ACAP1 B
  CAP1 A                                .001
  CAP1 B      CAP1 A
  CAP1 C      CAP1 A
  CAP2 A      CAP1 A
  CAP2 B      CAP1 A
  CAP2 C      CAP1 A
BLANK CARD ENDING BRANCHES
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24     25-34     35-44     45-54     55-64     65-74
C                                                       (OUTPUT OPTION IN COLUMN 80)
```

TABLE 5.2 (Cont'd)

Back-to-Back Capacitor Switching EMTP Input

```
C    NODE NAMES                                   IE FLASHOVER    SPECIAL    REFERENCE
C                  TIME TO     TIME TO            OR    VOLTAGE   REQUEST SWITCH-NAME
C    BUS1  BUS2      CLOSE        OPEN      NSTEP                    WORD   BUS5  BUS6
C CAPACITOR SWITCHES
  BUS   ASTP1 A    0.0005 1.00                                                            3
  BUS   BSTP1 B    0.0005 1.00                                                            3
  BUS   CSTP1 C    0.0005 1.00                                                            3
  BUS   ASTP2 A    0.0172 1.00                                                            3
  BUS   BSTP2 B    0.0172 1.00                                                            3
  BUS   CSTP2 C    0.0172 1.00                                                            3
BLANK CARD ENDING SWITCHES
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17.(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: 0=VOLTAGE SOURCE, -1=CURRENT SOURCE
C    3-8         11-20      21-30      31-40      41-50      51-60      61-70      71-80
C    NODE    AMPLITUDE FREQUENCY TO IN SEC    AMPL-A1    TIME-T1    T-START     T-STOP
C    NAME                  IN HZ       DEGR               SECONDS    SECONDS    SECONDS
C SOURCE VOLTAGES
14SRCE A        1.0     60.         120.00                                 -1.
14SRCE B        1.0     60.         000.00                                 -1.
14SRCE C        1.0     60.         240.00                                 -1.
BLANK CARD ENDING SOURCES
C NODE VOLTAGE OUTPUT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     3-8   9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C    BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  BUS   ABUS  BBUS  CCAP1 ACAP1 BCAP1 CCAP2 ACAP2 BCAP2 C
BLANK CARD ENDING NODE VOLTAGE OUTPUT REQUESTS
C PLOTTING OF THE RESULTS
  CALCOMP PLOT
C (CASE TITLE UP TO 78 CHARACTERS)
 2 BACK-TO-BACK CAPACITOR ENERGIZATION
C COLUMN 2,    "1"
C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
C COLUMN 4, UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C                        UP TO  4 NODE NAMES FOR                    49-64          65-80
C                               NODE VOLTAGE PLOTS
C                        UP TO  2  PAIRS OF  NODE                  GRAPH    VERTICAL AXIS
C                        NAMES  FOR  BRANCH  OR                  HEADING          HEADING
C                                      SWITCH PLOTS                  LABEL            LABEL
C                        1ST  ELEMENT 2ND ELEMENT
C                         25-30 31-36 37-42 43-48
C                          BUS1  BUS2  BUS3  BUS4
 1444.0     40.0         BUS  A
 1444.0     40.0         BUS  B
 1444.0     40.0         BUS  C
 1444.0     40.0         CAP1 A
 1444.0     40.0         CAP1 B
 1444.0     40.0         CAP1 C
 1444.0     40.0         CAP2 A
 1444.0     40.0         CAP2 B
 1444.0     40.0         CAP2 C
 1944.0     40.0         BUS  ASTP1 A
 1944.0     40.0         BUS  BSTP1 B
 1944.0     40.0         BUS  CSTP1 C
 1944.0     40.0         BUS  ASTP2 A
 1944.0     40.0         BUS  BSTP2 B
 1944.0     40.0         BUS  CSTP2 C
BLANK CARD ENDING PLOT CARDS
BLANK CARD TERMINATING THE CASE
```

The values of R and L are connected between the SRCE and BUS nodes in Figure 5.11. The delta value of C, which is 46 microfarads, is connected line-to-line at the CAP1 and CAP2 nodes in Figure 5.11. There are also small stray capacitances to ground at these nodes to ensure that the voltages remain mathematically defined in the EMTP whenever the capacitor switches are open. Table 5.2 shows the EMTP input data for this case.

The current limiting reactors in Figure 5.11 and Table 5.2 are also modeled with parallel RL circuits. These parameters are estimated from another field test where the second step of capacitors was energized. The capacitor terminal voltages on step 1 are presented in Figure 5.13. The voltage transients on Phase B reach a peak of 1.5 per-unit with a frequency of 2700 Hz and a log dec of .15 over the period from -4 to 0 milliseconds. There is also an 875 Hz oscillation superimposed on the more lightly damped 2700-Hz oscillations. These high frequency transients are the result of the two capacitor bank steps ringing through two current-limiting inductors in series. The current-limiting reactor's inductance may be calculated from the known capacitance value and the observed frequency of oscillation.

$$L_R = \frac{1}{4\pi^2(2700)^2(138 \times 10^{-6})} = .025 \text{ millihenries} \qquad (5\text{-}9)$$

One commercially available current-limiting inductor size is 25 microhenries, which matches the estimated value. This value is used in Table 5.2. An appropriate value of Q for the log dec of .15 is approximately 20. A parallel damping resistor of 10 ohms was chosen for the back-to-back loop. Therefore,

$$Q = \frac{10}{\sqrt{.025 \times 10^{-3}/138 \times 10^{-6}}} = 23.5 \qquad (5\text{-}10)$$

This completes the input parameters required for Figure 5.11 and Table 5.2. The source voltage magnitudes are 1.0 to directly obtain per-unit peak overvoltages in the output.

The first case considers energization of the first two capacitor steps. Step 1 is energized near a peak in the Phase B bus voltage. One cycle later, step 2 is energized near a peak in the Phase B bus voltage. In practice the bank steps are not energized that quickly, but the simulation results are valid because the transients from energizing step 1 have died out before step 2's switches close.

The switching times were chosen to facilitate comparison of EMTP plots with Figures 5.12 and 5.13. By energizing step 2, the hazards of back-to-back switching in terms of high magnitude and high frequency capacitor inrush currents will be illustrated.

Figure 5.14 shows the Phase B bus voltage during the back-to-back energization sequence. The peak while energizing step 1 is 1.58 per-unit, compared to 1.68 per-unit in Figure 5.12. The frequency and damping characteristics for both step energizations are approximately correct.

Figures 5.15 and 5.16 show the Phase B capacitor terminal voltages. When energizing step 2, both bank voltages exhibit a high frequency transient which does not appear on the capacitor bus because it does not participate in the capacitor bank-current limiting reactor loop. The peak on CAP1B is 1.65 per-unit, compared to 1.5 per-unit in Figure 5.13. The high frequency and damping characteristics are comparable to Figure 5.13.

Figures 5.17 and 5.18 show the Phase B capacitor line currents. Since the source voltage magnitudes are 1.0 and 4160-volt impedances are used, the base current is 3396 amps peak and rated current is .052 "per-unit" for each step. The peak current when energizing step 1 is .60 per-unit, or 11.5 times rating. When energizing step 2, both capacitor steps experience peak currents of approximately 1.25 per-unit, or 24 times rating. These transient inrush currents experienced while energizing additional steps of capacitors would be even higher without the current-limiting reactors.

A restrike on step 1 was simulated with step 2 already switched off. It was assumed that Phase A opened, but Phases B and C had not, and a restrike occurred on Phase A at 3 per-unit recovery voltage. A similar opening sequence was presented in Figures 5.6 and 5.7. To simulate the restrike, an additional switch was added between nodes SRCE A and BUS A in Figure 5.11. The first switch is initially closed and opens immediately to simulate the initial current interruption. The second switch is initially open, and closes at 11.1 milliseconds, or one-half cycle after the initial current interruption. The switch input cards for this case are presented in Table 5.3.

TABLE 5.3

Switches for Restrike Simulation

```
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24      25-34      35-44      45-54      55-64      65-74
C                                                          (OUTPUT OPTION IN COLUMN 80)
C   NODE NAMES                                 IE FLASHOVER   SPECIAL   REFERENCE
C                   TIME TO    TIME TO         OR   VOLTAGE   REQUEST SWITCH-NAME
C   BUS1  BUS2       CLOSE       OPEN    NSTEP                   WORD  BUS5  BUS6
C CAPACITOR SWITCHES
  BUS   ASTP1 A    -.0005 0.0005                                                  3
  STP1  ABUS  A    0.0111 1.00                                                    1
  BUS   BSTP1 B    -.0005 1.00                                                    3
  BUS   CSTP1 C    -.0005 1.00                                                    3
  BUS   ASTP2 A    0.9172 1.00                                                    3
  BUS   BSTP2 B    0.9172 1.00                                                    3
  BUS   CSTP2 C    0.9172 1.00                                                    3
BLANK CARD ENDING SWITCHES
```

Figures 5.19 and 5.20 show the capacitor bus and step 1 terminal voltages on Phase A. These transients exhibit the same frequency and damping characteristics observed when energizing step 1, but reach higher peak values of 2.3 per-unit and 2.45 per-unit on the bus and step 1 terminal, respectively. The maximum peak value without damping would be 3 per-unit. The peak inrush current on Phase A after the restrike was 24.4 times rating.

The capacitor switch opening cases ran in approximately .4 seconds on a Cray 1S computer. The back-to-back energization and restrike cases ran in approximately 2 seconds on the Cray 1S computer.

Suggested investigations:

1. Vary the sequence of pole openings in the case of an ungrounded bank with one hung pole. Recovery voltages of 4.1 per-unit are possible.

2. In the field test duplication case, simulate a restrike of step 2 with step 1 still on line.

3. Change the delta-connected capacitors to ungrounded-wye with 138 μF in each phase. Repeat the back-to-back energization and restrike cases with this configuration.

4. Add a permanently closed switch between the source impedance and capacitor bus in the field test duplication case. Then rerun the back-to-back energization case to obtain a plot of the total capacitor bank current through the new switch.

5. Simulate a restrike after all three poles of the capacitor switch have opened. It may be useful to choose a smaller time step and specify initial trapped charge on the capacitors to efficiently simulate the restrike. Plot the recovery voltage across the two healthy poles.

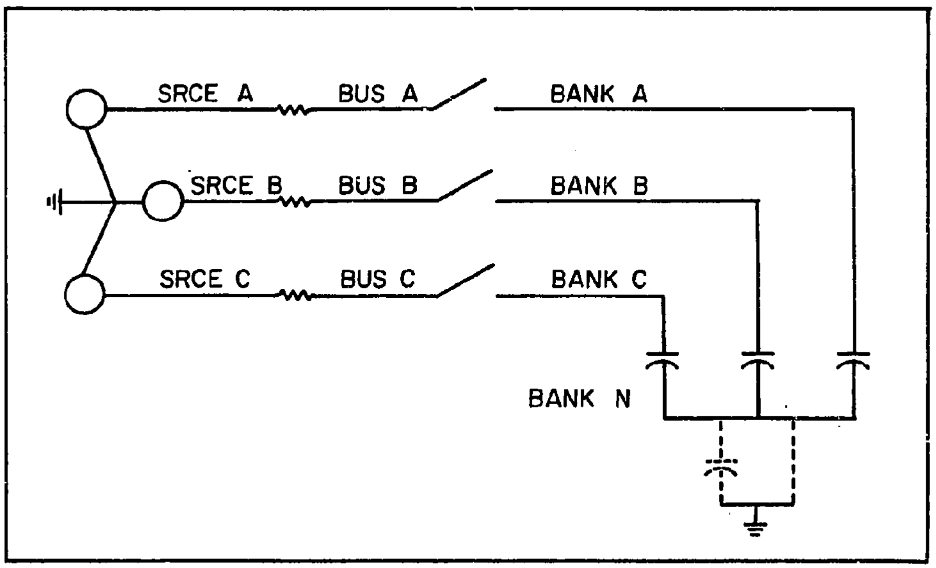


FIGURE 5.1. System Model for Capacitor Switch Recovery Voltages

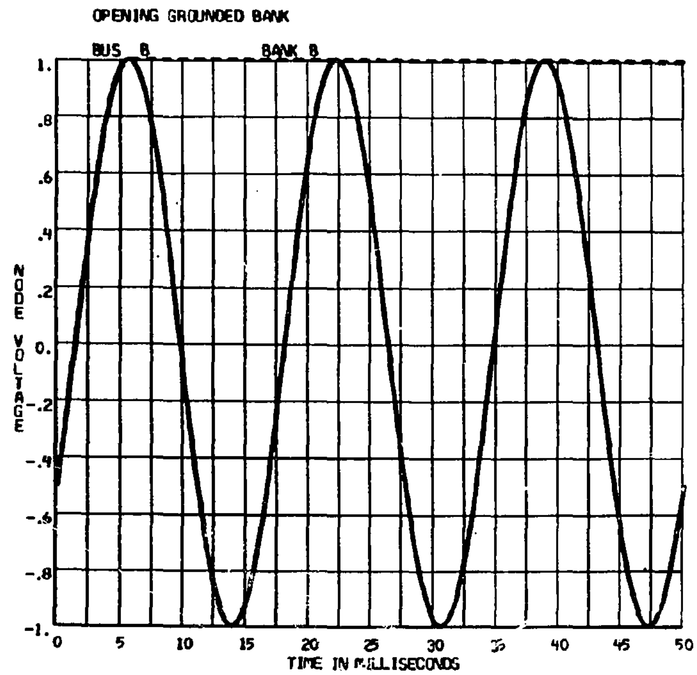


FIGURE 5.2. Phase B Voltages, Grounded Bank

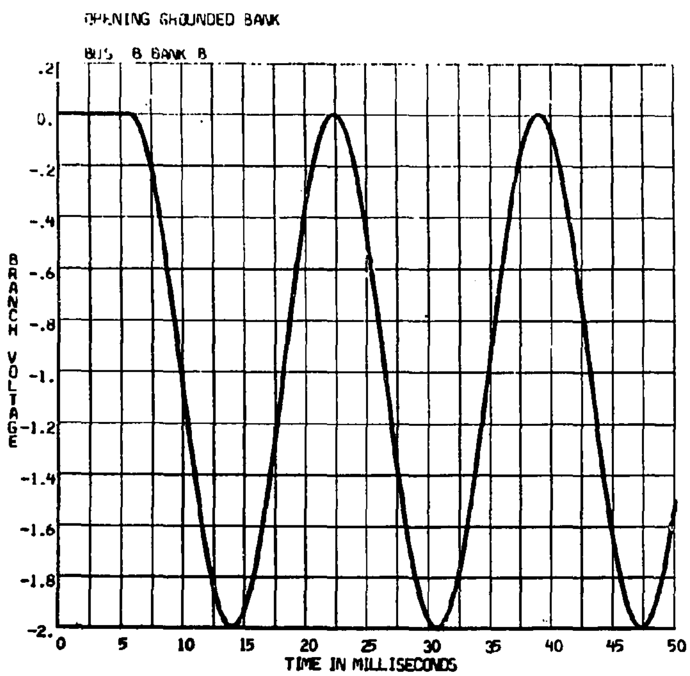


FIGURE 5.3. Phase B Recovery Voltage, Grounded Bank

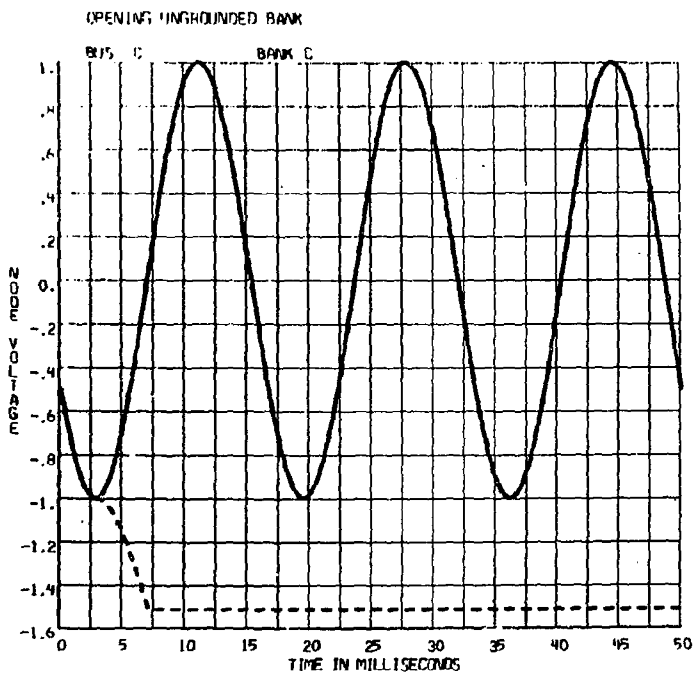


FIGURE 5.4. Phase C Voltages, Ungrounded Bank

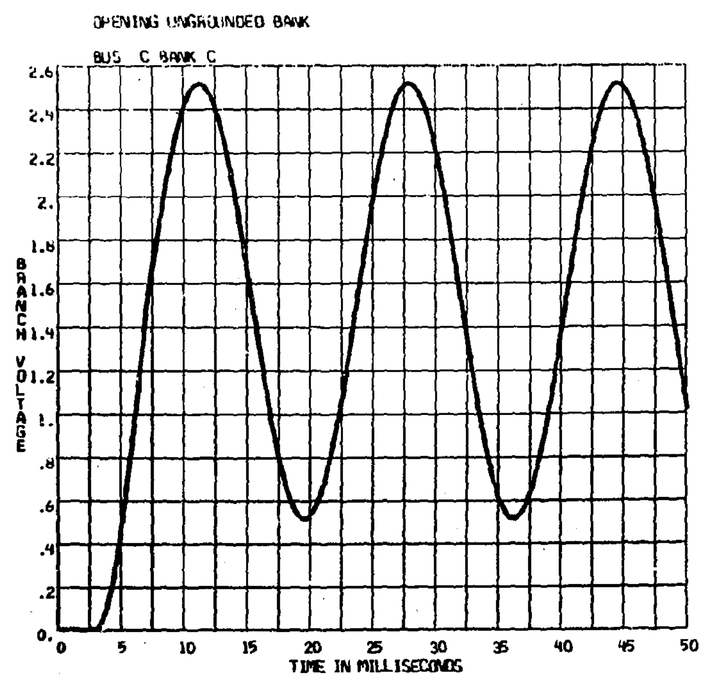


FIGURE 5.5. Phase C Recovery Voltage, Ungrounded Bank

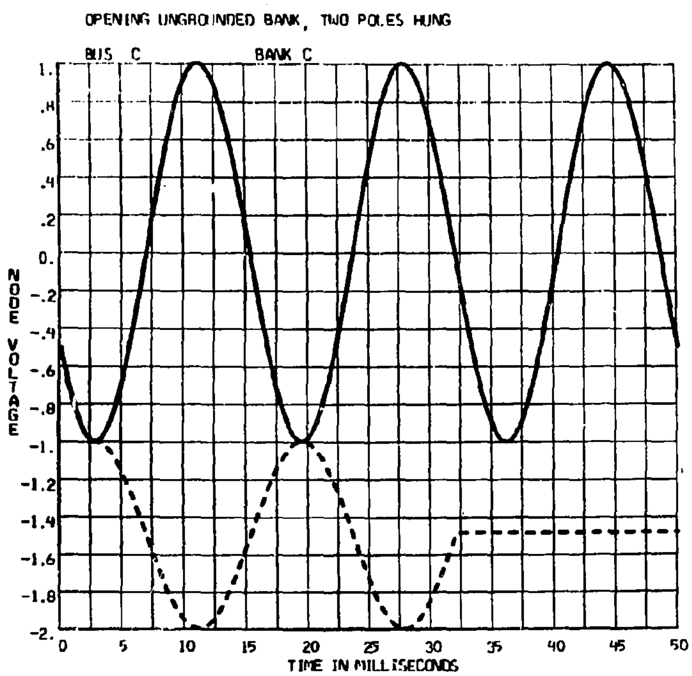


FIGURE 5.6. Phase C Voltages, Ungrounded Bank, Two Poles Hung

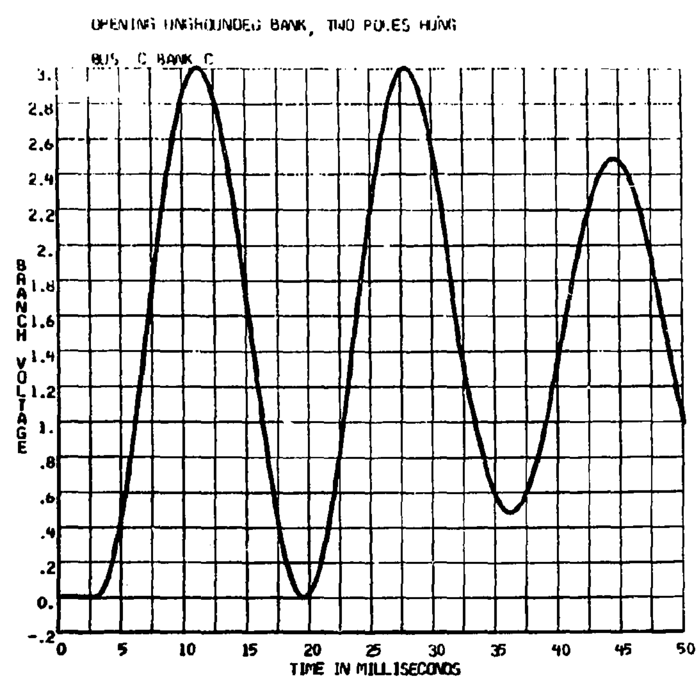


FIGURE 5.7. Phase C Recovery Voltage, Ungrounded Bank, Two Poles Hung

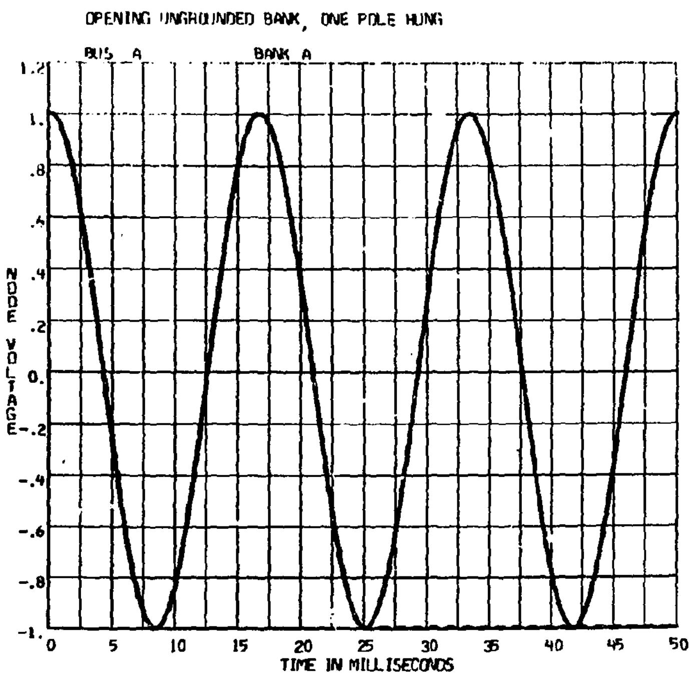


FIGURE 5.8. Phase A Voltages, Ungrounded Bank, One Pole Hung

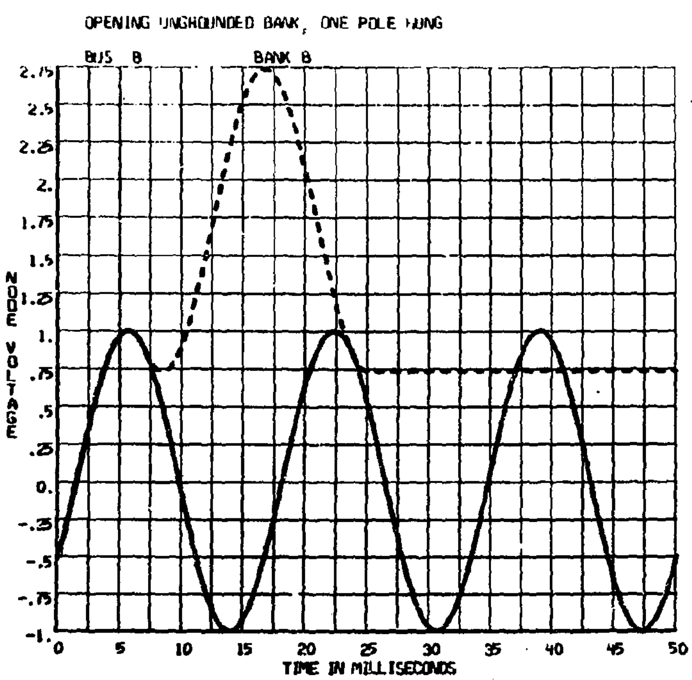


FIGURE 5.9. Phase B Voltages, Ungrounded Bank, One Pole Hung

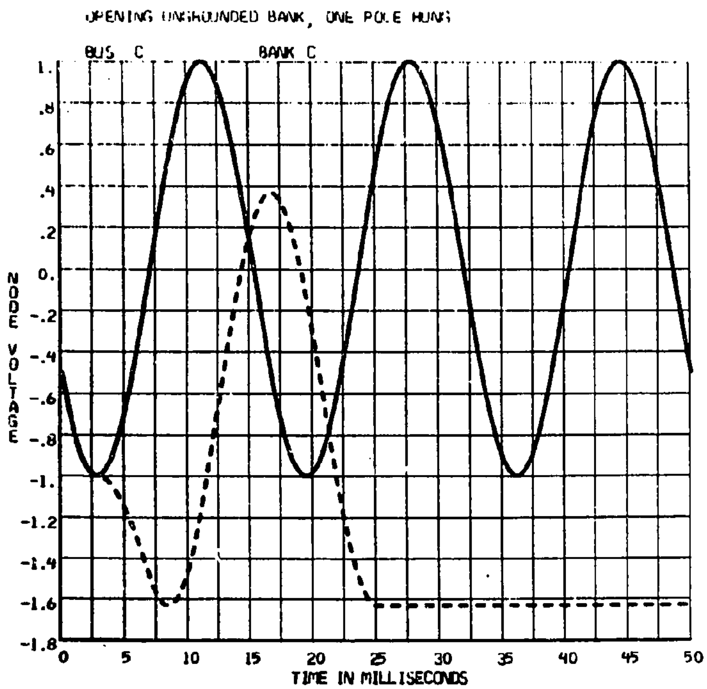


FIGURE 5.10. Phase C Voltages, Ungrounded Bank, One Pole Hung

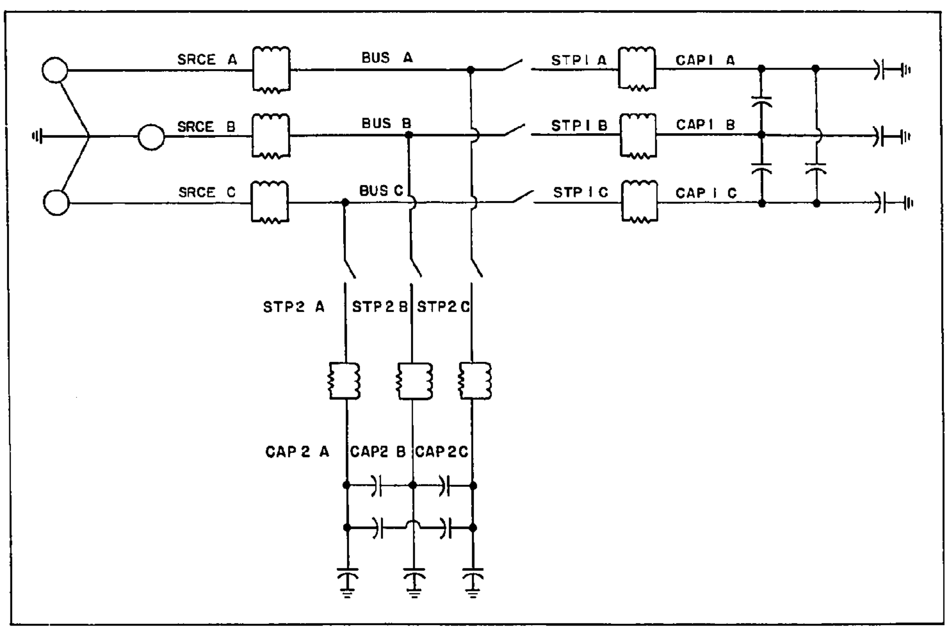


FIGURE 5.11. EMTP Model of Back-to-Back Capacitor Banks With Current-Limiting Reactors

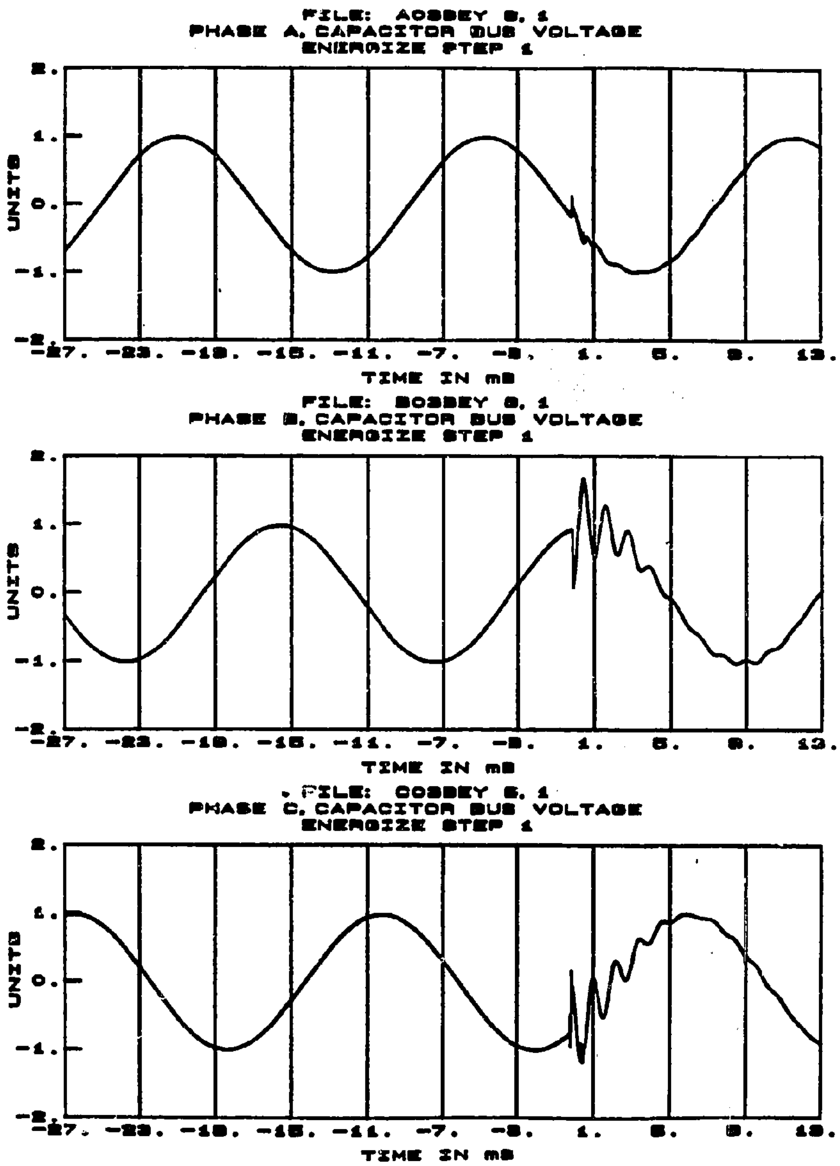


FIGURE 5.12. Capacitor Bus Voltages While Energizing Step 1

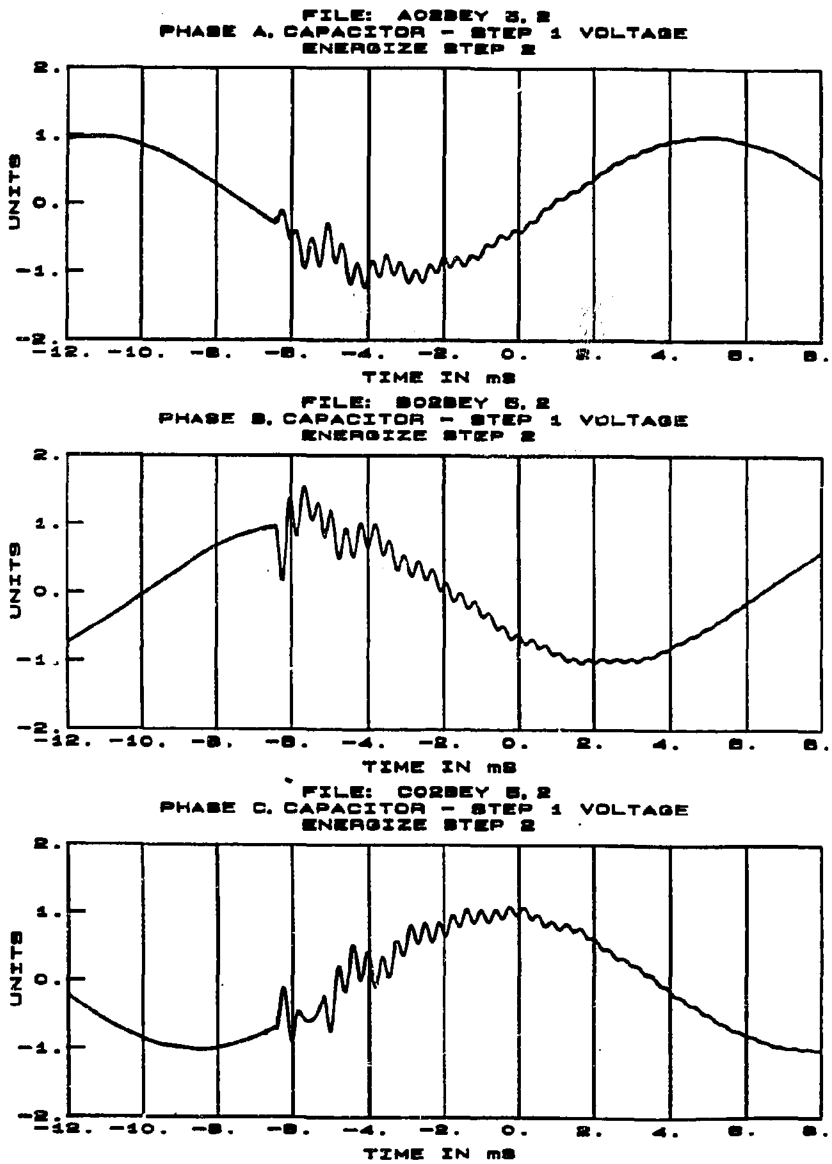


FIGURE 5.13. Capacitor Step 1 Voltages While Energizing Step 2

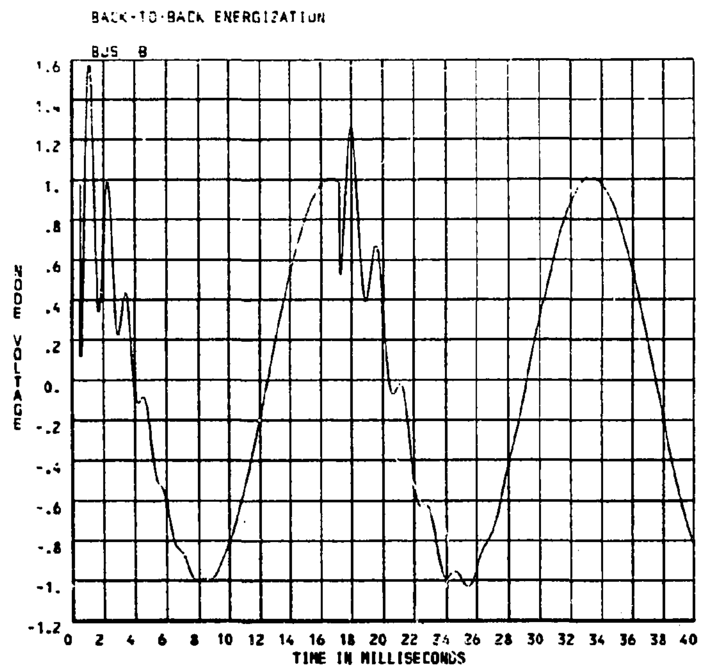


FIGURE 5.14. Phase B Bus Voltage During Back-to-Back Energization

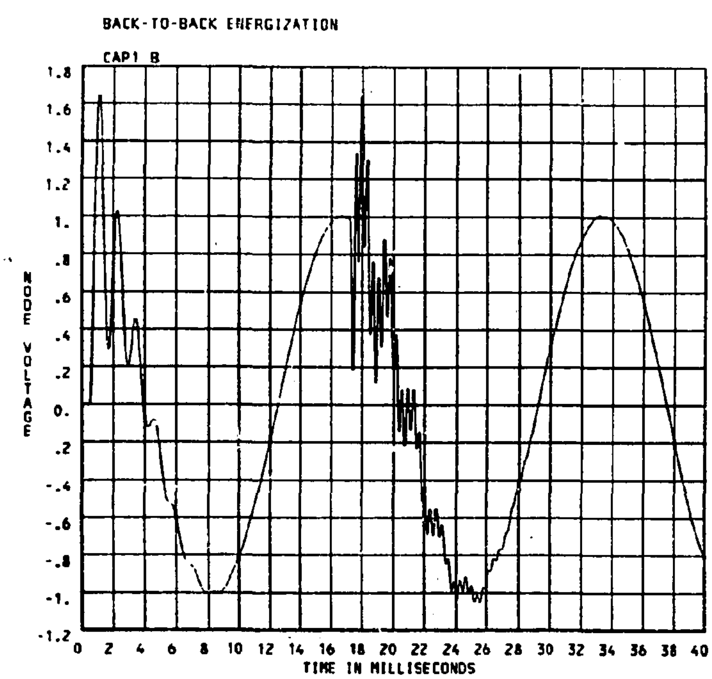


FIGURE 5.15. Phase B Step 1 Voltage During Back-to-Back Energization

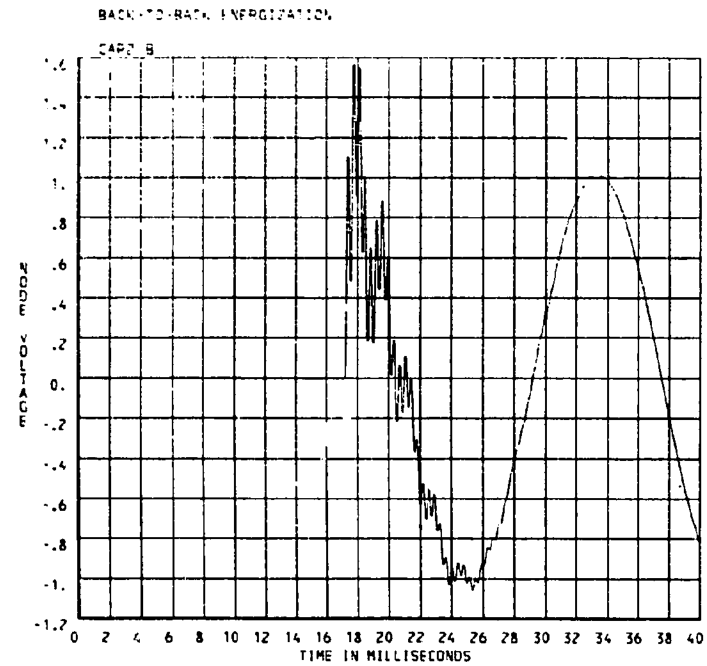


FIGURE 5.16. **Phase B Step 2 Voltage During Back-to-Back Energization**

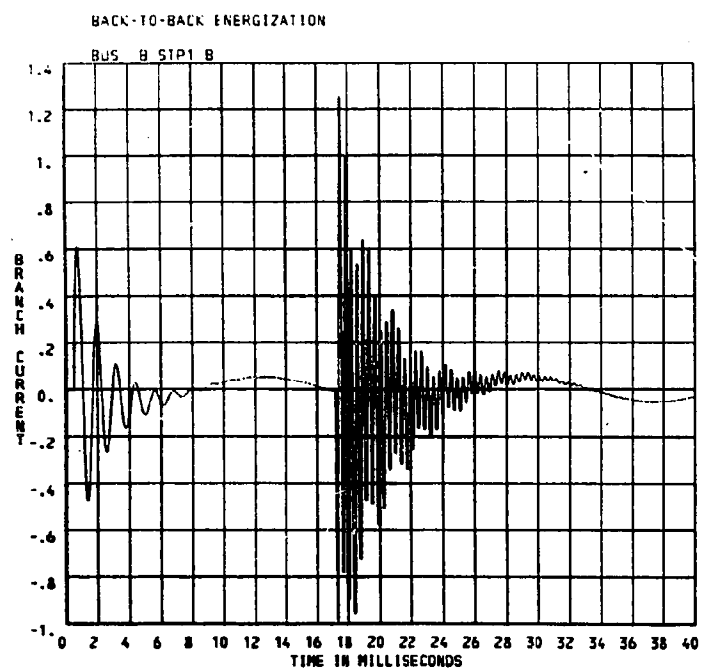


FIGURE 5.17. Phase B Step 1 Current During Back-to-Back Energization

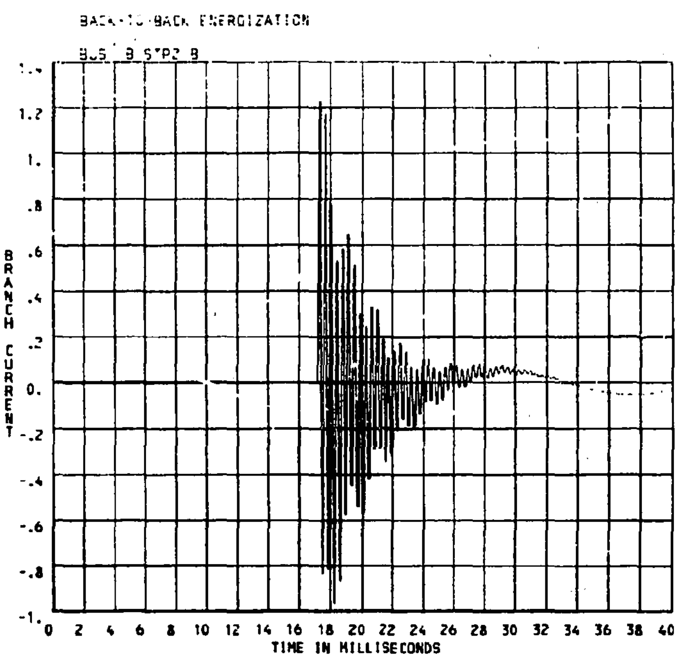


FIGURE 5.18. Phase B Step 2 Current During Back-to-Back Energization

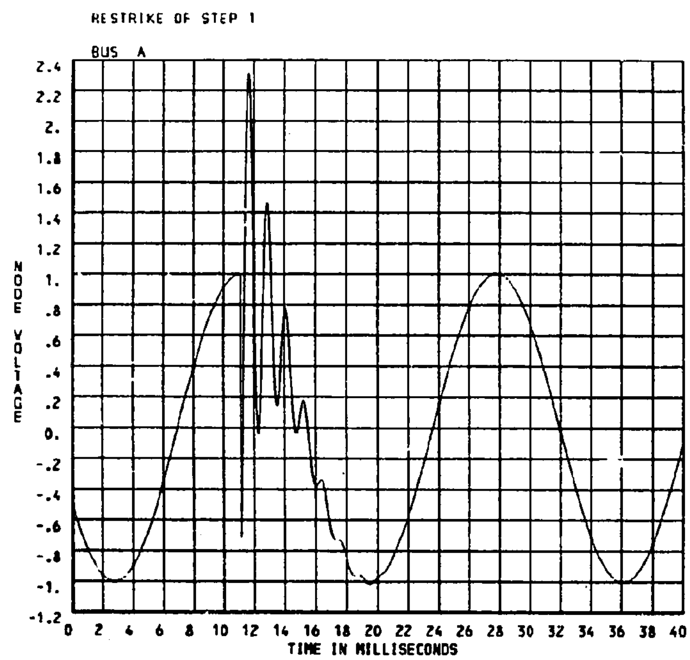


FIGURE 5.19. Phase A Bus Voltage During Restrike of Step 1

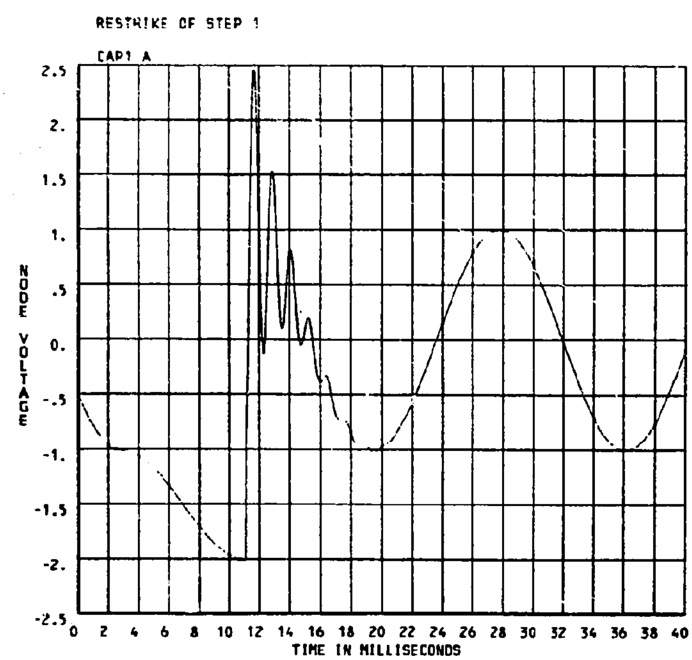


FIGURE 5.20. Phase A Step 1 Voltage During Restrike of Step 1

Section 6

CASE 6: PARALLEL EHV LINE RESONANCE

In this case, the steady-state analysis capabilities of the EMTP are demonstrated by calculating coupled voltages on parallel transmission lines. The lines are represented with cascaded pi-sections to facilitate direct comparisons with a TNA study of the same system.

High resonant voltages can occur under certain operating conditions on shunt reactor compensated parallel EHV transmission lines. One circuit is cleared due to a fault, and the shunt reactors remain connected. The resonant voltages occur on the deenergized line by coupling from the nearby energized line. The series resonant circuit consists of inter-line capacitance and shunt reactors on the deenergized line. Such a situation is described in detail in Reference (12). A simplified diagram of the system studied is shown in Figure 6.1. The results given in the reference indicate that for a shunt reactor size of approximately 47 MVAR, resonant voltages were observed on the deenergized line.

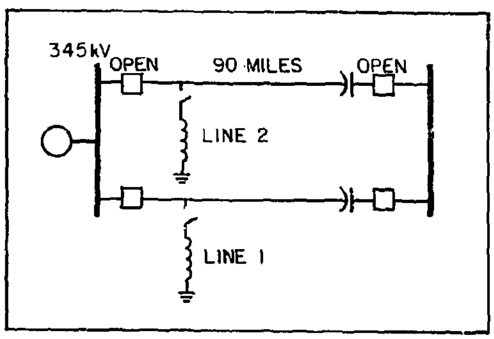


FIGURE 6.1. Simplified Diagram of the System Studied

Line constants for the parallel-line configuration were calculated in Case 3 of this manual. The resistance, inductive reactance, and capacitance matrices from the line constants printout are presented on a per-mile basis in Table 6.1. These 6 x 6 matrices define the self and mutual impedances and capacitances of both three-phase lines, as well as the electromagnetic and electrostatic coupling between the lines.

The transmission lines are modeled with several pi sections cascaded in series. This improves calculation accuracy for both steady-state and transients by more closely approximating the distributed-parameter nature of the line. From TNA studies, a rule of thumb that one pi section should be used for each ten miles of line has been developed. Since the lines in Figure 6.1 are each 90 miles long, 9 cascaded pi sections will be used. Whenever transmission line transients are to be simulated on the EMTP, different types of line models are usually more suitable than pi sections, as described in the Application Guide.

The per-mile values in Table 6.1 have to be multiplied by the number of miles per pi-section to get the proper input data for the pi-sections. Table 6.2 shows the input data format for the two coupled transmission lines. If a system has only one circuit, the required input matrix data would only have the first three rows.

It is assumed that the transmission lines have transposition points 30 miles from each end as shown in Figure 6.2.

In order to determine the variation of resonant overvoltage magnitude with shunt reactor size, several values of shunt reactance were selected. The reactance can be calculated by using the formula:

$$X_L = \frac{(kV_{LL})^2}{\text{Reactor MVA}} \tag{6-1}$$

From the LINE CONSTANTS program results, each line has a positive sequence capacitance of approximately .0197 μF per mile. The line charging is thus:

$$\frac{(k\ V_{LL})^2}{X_C} = 345^2 \times 377 \times .0197 \times 10^{-6} = .884 \text{ MVAC/mile} \tag{6-2}$$

For a 90-mile line, the total line charging is 79.6 MVAC.

TABLE 6.1

Matrix Data for the 345-kV Transmission System

IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.27986E+00					
	0.88895E+00					
2	0.19817E+00	0.24315E+00				
	0.34895E+00	0.94333E+00				
3	0.19673E+00	0.17999E+00	0.23995E+00			
	0.35068E+00	0.35872E+00	0.94666E+00			
4	0.17700E+00	0.16933E+00	0.16524E+00	0.24421E+00		
	0.19667E+00	0.23009E+00	0.20287E+00	0.98629E+00		
5	0.17503E+00	0.16608E+00	0.16269E+00	0.17282E+00	0.22566E+00	
	0.21167E+00	0.25277E+00	0.22001E+00	0.42212E+00	0.99247E+00	
6	0.16826E+00	0.16058E+00	0.15720E+00	0.16989E+00	0.16142E+00	0.21955E+00
	0.19170E+00	0.22625E+00	0.20127E+00	0.42874E+00	0.41428E+00	0.10055E+01

CAPACITANCE MATRIX (FARAD/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT

1	0.17497E-07					
2	-0.29818E-08	0.16455E-07				
3	-0.30309E-08	-0.27299E-08	0.16351E-07			
4	-0.29142E-09	-0.39136E-09	-0.18109E-09	0.17533E-07		
5	-0.39073E-09	-0.70254E-09	-0.27028E-09	-0.30002E-08	0.16495E-07	
6	-0.18074E-09	-0.27016E-09	-0.12321E-09	-0.30497E-08	-0.27436E-08	0.16391E-07

TABLE 6.2

Input Format for the Pi-Sections

Resistances in Ohm/Unit Length
Reactances in Ohm/Unit Length
Capacitances in Microfarad/Unit Length

R11 L11 C11) If only one
R21 L21 C21 R22 L22 C22) circuit is
R31 L31 C31 R32 L32 C32 R33 L33 C33) represented
R41 L41 C41 R42 L42 C42 R43 L43 C43
R44 L44 C44
R51 L51 C51 R52 L52 C52 R53 L53 C53
R54 L54 C54 R55 L55 C55
R61 L61 C61 R62 L62 C62 R63 L63 C63
R64 L64 C64 R65 L65 C65 R66 L66 C66

The shunt reactor ratings in Table 6.3 were simulated.

TABLE 6.3

Shunt Reactor Ratings

Shunt Reactor Rating In MVAR	Percent Shunt Compensation	Inductive Reactance In Ohms
30.0	37.7	3967.5
40.0	50.3	2975.6
43.5	54.5	2736.2
45.2	56.8	2633.3
46.4	58.3	2567.4
48.2	60.6	2469.4
53.0	66.6	2245.7
63.0	79.2	1889.3

Typical values of shunt compensation range from 40% to 80%.

It is assumed that the transmission lines are 60% series compensated. The LINE CONSTANTS program calculated the positive sequence reactance as 1.5213 mH/mile or .5735 Ω/mile. The total line reactance equals 90 x .5735 or 51.6 Ω. Assuming 60% series compensation, the series capacitance can be calculated:

$$C = \frac{1}{377 \times .6 \times 51.6} = 85.7\ \mu F \tag{6-3}$$

Figure 6.2 shows the system diagram represented and the node names. Table 6.4 shows the complete input data.

No transients are being investigated, and, therefore, on the first Miscellaneous Data card in Table 6.4 the time step (columns 1-8) and the maximum time (columns 9-16) are set to "0". The inductances for the transmission lines were calculated in ohms, and, therefore, all other inductances (e.g. the shunt reactor) will also be input in ohms. Since the power frequency is 60 Hz, a value of "60" is put in columns 17-24 of the first Miscellaneous Data card. Steady-state outputs are required, and, therefore, a "1" is placed in column 32 of the second Miscellaneous Data card.

TABLE 6.4

Input Data for the Line Resonance Case

```
C FILE NAME:"LINERES": FAULT ON LINE 1, 46.4 MVA SHUNT REACTOR CONNECTED.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8     9-16    17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C                  F(HZ)   F(HZ)
       0       0    60.0       0
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8     9-16    17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT     PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  ENERG.   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    C=NO
       5       1       1       1       0
C
C FIRST PI-SECTION
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C    BUS1  BUS2  BUS3  BUS4     R     L     C     R     L     C     R     L     C
 1JUAN1AP1.1 A                2.79868.8889.17497
 2JUAN1BP1.1 B                1.98173.4895-.02982.43159.4333.16455
 3JUAN1CP1.1 C                1.96733.5068-.03031.79993.3872-.02732.39959.4666.16351
 4JUAN2AP2.1 A                1.77001.9667-.00291.69332.3009-.00391.65242.0287-.0018
                              2.44219.8629.17533
 5JUAN2BP2.1 B                1.75032.1167-.00391.66082.5277-.00701.62692.2001-.0027
                              1.72824.2212-.03002.25669.9247.16495
 6JUAN2CP2.1 C                1.68261.9170-.00181.60582.2625-.00271.57202.0127-.0012
                              1.69894.2874-.03051.61424.1428-.02742.19551O.055.16391
C 2ND PI-SECTION
 1P1.1 AP1.2 AJUAN1AP1.1 A
 2P1.1 BP1.2 B
 3P1.1 CP1.2 C
 4P2.1 AP2.2 A
 5P2.1 BP2.2 B
 6P2.1 CP2.2 C
C 3RD PI-SECTION
 1P1.2 AP1.3 AJUAN1AP1.1 A
 2P1.2 BP1.3 B
 3P1.2 CP1.3 C
 4P2.2 AP2.3 A
 5P2.2 BP2.3 B
 6P2.2 CP2.3 C
C 3456789901234567890123456789012345678900
C 4TH PI-SECTION
 1P1.3 CP1.4 CJUAN1AP1.1 A
 2P1.3 AP1.4 A
 3P1.3 BP1.4 B
 4P2.3 CP2.4 C
 5P2.3 AP2.4 A
 6P2.3 BP2.4 B
C 5TH PI-SECTION
 1P1.4 CP1.5 CJUAN1AP1.1 A
 2P1.4 AP1.5 A
 3P1.4 BP1.5 B
 4P2.4 CP2.5 C
 5P2.4 AP2.5 A
 6P2.4 BP2.5 B
C 6TH PI-SECTION
 1P1.5 CP1.6 CJUAN1AP1.1 A
 2P1.5 AP1.6 A
 3P1.5 BP1.6 B
 4P2.5 CP2.6 C
 5P2.5 AP2.6 A
```

TABLE 6.4 (Cont'd)

Input Data for the Line Resonance Case

```
 6P2.5 BP2.6 B
C 7TH PI-SECTION
 1P1.6 BP1.7 BJUAN1AP1.1 A
 2P1.6 CP1.7 C
 3P1.6 AP1.7 A
 4P2.6 BP2.7 B
 5P2.6 CP2.7 C
 6P2.6 AP2.7 A
C 8TH PI-SECTION
 1P1.7 BP1.8 BJUAN1AP1.1 A
 2P1.7 CP1.8 C
 3P1.7 AP1.8 A
 4P2.7 BP2.8 B
 5P2.7 CP2.8 C
 6P2.7 AP2.8 A
C 9TH PI-SENCTION
 1P1.8 BP1.9 BJUAN1AP1.1 A
 2P1.8 CP1.9 C
 3P1.8 AP1.9 A
 4P2.8 BP2.9 B
 5P2.8 CP2.9 C
 6P2.8 AP2.9 A
C SERIES CAPACITORS
C 345678901234567890123456789012345678901234567890
  P1.9 AP1.10A                        85.700
  P1.9 BP1.10B                        85.700
  P1.9 CP1.10C                        85.700
  P2.9 AP2.10A                        85.700
  P2.9 BP2.10B                        85.700
  P2.9 CP2.10C                        85.700
C SHUNT REACTORS
C 345678901234567890123456789012345678901234567890
C                                33-38
  JUAN1A                        2567.4
  JUAN1B                        2567.4
  JUAN1C                        2567.4
  JUAN2A                        2567.4
  JUAN2B                        2567.4
  JUAN2C                        2567.4
C FAULT AT TRANSPOSITION POINT 2 ON LINE 1
C 3456789012345678901234567890123456789O
  P1.6 C                      .01
BLANK CARD TERMINATING BRANCHES
C SWITCH CARDS
C 3456789012345678901234567890123456789O
C                 CLOSE      OPEN
  JUAN AJUAN1A      -1.0        1.0
  JUAN BJUAN1B      -1.0        1.0
  JUAN CJUAN1C      -1.0        1.0
  JUAN AJUAN2A       1.0       -1.0
  JUAN BJUAN2B       1.0       -1.0
  JUAN CJUAN2C       1.0       -1.0
C BREAKERS AT MCKINLEY
  P1.10AMCKINA      -1.0        1.0
  P1.10BMCKINB      -1.0        1.0
  P1.10CMCKINC      -1.0        1.0
  P2.10AMCKINA       1.0       -1.0
  P2.10BMCKINB       1.0       -1.0
  P2.10CMCKINC       1.0       -1.0
BLANK CARD TERMINATING SWITCHES
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
14JUAN A      281700.     60.0         0.                        -1.0
14JUAN B      281700.     60.0      -120.                        -1.0
14JUAN C      281700.     60.0      -240.                        -1.0
BLANK CARD TERMINATING SOURCES
C NODE VOLTAGE OUTPUT
  JUAN2AJUAN2BJUAN2C
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
BLANK CARD TERMINATING PLOTTING
BLANK CARD TERMINATING THE CASE
```

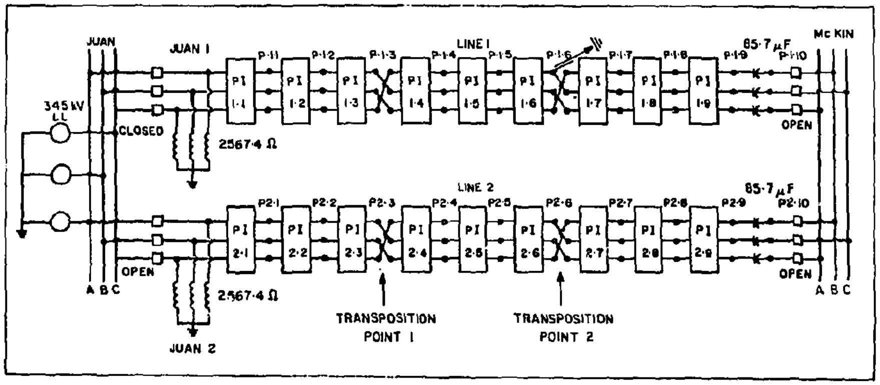


FIGURE 6.2. System Diagram With the Node Names

The simulated system condition occurred via the following sequence of events:

- Line 2 has been deenergized either due to a fault or for scheduled maintenance, and, therefore, the circuit breakers on both line ends have opened.
- A line-to-ground fault occurred on Line 1 60 miles from node "JUAN1C" (at a transposition point).
- The line relays tried to clear the fault by tripping the circuit breakers.
- The circuit breaker at the "MCKIN" end of Line 1 tripped properly, however, the circuit breaker at the "JUAN" end failed to trip (all three phases remain closed). The fault has yet to be cleared by a backup breaker.

This sequence of events leaves one line deenergized, and the other line energized from one end only. The steady-state voltages for this system condition were calculated for eight ratings of shunt reactors connected. The results show that the steady-state voltages on the deenergized Line 2 depend on the rating of the shunt reactors. The results given in Reference (12) indicate that a 47.0 MVAR shunt reactor causes a resonant condition. The results for the shunt reactor voltage (node "JUAN2A") as a function of shunt reactor size obtained from the input data as given in Table 6.4 are summarized in Table 6.5 and plotted in Figure 6.3. The plotted results indicate a resonant condition at approximately 46.4 MVAR which compares well with the results observed in Reference (12).

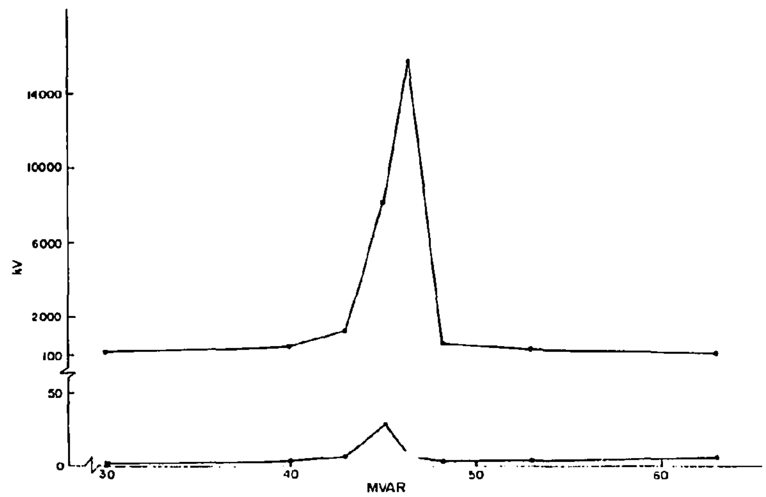


FIGURE 6.3. Voltage at Line 2 Reactor (Node "JUAN2A") Versus Shunt Reactor Size With and Without a Fault at Transposition Point 2 on Line 1

TABLE 6.5

Node Voltages in kV with a Line-to-Ground Fault 60 Miles from the Energized End

	30 MVA	40 MVA	43.5 MVA	45.2 MVA	46.4 MVA	48.2 MVA	53 MVA	63 MVA
JUAN2A	131.2	389.5	1254.2	8387.4	14960	624.5	246.7	108.2
JUAN2B	131.4	389.6	1254.3	8386.2	14956	624.2	246.5	108.0
JUAN2C	129.3	386.9	1250.6	8381.4	14973	626.8	249.8	113.2
P2.3 A	93.1	355.4	1234.3	8546.5	15600	674.9	291.1	150.4
P2.3 B	91.4	353.7	1232.3	8543.5	15607	676.0	292.3	151.4
P2.3 C	92.2	353.9	1231.9	8540.8	15605	676.2	293.2	154.4
P2.6 A	53.0	317.4	1204.4	8648.8	16151	722.3	335.2	[illegible]
P2.6 B	53.9	318.7	1205.9	8648.4	16138	720.9	333.6	191.4
P2.6 C	53.3	317.3	1203.9	8645.7	16148	722.5	335.9	195.8
P2.9 A	53.0	318.2	1208.2	8677.6	16207	724.9	336.4	194.1
P2.9 B	53.9	319.5	1209.7	8677.7	16194	723.5	334.9	192.2
P2.9 C	53.3	318.2	1207.7	8674.3	16203	725.0	337.2	196.6

TABLE 6.6

Node Voltages in kV without a Fault on the Line

	30 MVA	40 MVA	43.5 MVA	45.2 MVA	46.4 MVA	48.2 MVA	53 MVA	63 MVA
JUAN2A	2.3	3.4	6.4	27.7	5.8	3.3	3.5	5.8
JUAN2B	1.5	1.0	3.0	32.4	9.5	5.9	4.8	6.3
JUAN2C	2.5	3.9	7.7	31.9	5.7	2.7	3.2	5.6
P2.3 A	2.1	3.2	6.3	28.4	6.0	3.4	3.5	5.7
P2.3 B	1.7	1.2	2.8	33.1	9.9	6.2	5.1	6.6
P2.3 C	2.4	3.8	7.7	32.5	6.0	2.9	3.2	5.6
P2.6 A	2.2	3.3	6.4	28.6	6.1	3.5	3.6	5.8
P2.6 B	1.7	1.2	2.8	33.3	10.0	6.2	5.1	6.6
P2.6 C	2.3	3.8	7.7	32.8	6.0	2.8	3.1	5.5
P2.9 A	2.2	3.3	6.4	28.7	6.1	3.5	3.6	5.8
P2.9 B	1.7	1.2	2.8	33.5	10.0	6.2	5.1	6.6
P2.9 C	2.3	3.8	7.7	32.9	6.0	2.8	3.1	5.5

The runs were repeated without a fault on Line 1. This would represent an erroneous or manual trip of the Line 1 breakers. A summary of the voltages on Line 2 without a fault on Line 1 is given in Table 6.6 and is plotted in Figure 6.3. The observed shunt reactor voltages on Line 2 were significantly less than with a fault on Line 1. The observed results are in good agreement with the results observed in the Reference (12).

Table 6.7 gives a partial listing of the printout of the steady-state quantities for one of the runs. Quantities of interest are highlighted in the printout. The printout is for the case where a 43.5 MVA shunt reactor and a fault at transposition point 2 were simulated. The voltages of nodes "JUAN1A", JUAN1B", and "JUAN1C" are balanced since an infinite source is connected to nodes "JUAN1_". The voltages have the same magnitude of 281.7 kV L-G peak or 345 kV L-L rms, and the phase angles are 0, -120, and 120 degrees, respectively. The voltages at the line 2 shunt reactors are 1254, 1254, and 1251 kV for Phases A, B, and C, respectively.

In the faulted Phase C on line 1, fault current flows. As a manual check, the line impedance between the source and the fault can be calculated for the line-to-ground fault:

$$\frac{1}{3}(X_1 + X_2 + X_0) = \frac{1}{3}(.57353 + .57353 + 1.6319) = .9263\ \Omega/\text{mi} \qquad (6\text{-}4)$$

$$\text{total line impedance} = 60 \text{ miles} \times .9263\ \Omega/\text{mi} = 55.58\ \Omega \qquad (6\text{-}5)$$

TABLE 6.7

Partial Steady-State Printout

SINUSOIDAL STEADY STATE SOLUTION, BRANCH BY BRANCH. ALL FLOWS ARE AWAY FROM BUS, AND REAL PART, MAGNITUDE, OR P IS PRINTED ABOVE THE IMAGINARY PART, THE ANGLE, OR Q. FIRST SOLUTION FREQUENCY = 0.6000000000E+02 HERTZ.

BUS K	BUS M	NODE VOLTAGE RECTANGULAR	NODE VOLTAGE POLAR	BRANCH CURRENT RECTANGULAR	BRANCH CURRENT POLAR	POWER FLOW P AND Q	POWER LOSS P AND Q
JUAN1A		0.2817000E+06 0.0000000E+00	0.2817000E+06 0.0000	0.5622958E+02 0.1980850E+03	0.2059112E+03 74.1526	0.7919937E+07 -0.2790027E+08	0.1983633E+07 -0.2023921E+07
	P1.1 A	0.2893776E+06 -0.1793151E+05	0.2899326E+06 -3.5458	-0.5191081E+02 -0.1756247E+03	0.1831359E+03 -106.4665	-0.5936304E+07 0.2587635E+08	
JUAN1B		-0.1408500E+06 -0.2439594E+06	0.2817000E+06 -120.0000	0.2191146E+03 -0.8721463E+02	0.2358339E+03 -21.7041	-0.4792735E+07 -0.3286962E+08	-0.1818737E+07 -0.2179141E+07
	P1.1 B	-0.1347101E+06 -0.2611877E+06	0.2938806E+06 -117.2829	-0.1949059E+03 0.7775175E+02	0.2098419E+03 158.2520	0.2973998E+07 0.3069048E+08	
JUAN1C		-0.1408500E+06 0.2439594E+06	0.2817000E+06 120.0000	0.3559263E+04 0.3432718E+04	0.4944887E+04 43.9631	0.1680606E+09 0.6759069E+09	0.2328557E+08 0.1133292E+09
	P1.1 C	-0.1153064E+06 0.2038183E+06	0.2341740E+06 119.4982	-0.3573110E+04 -0.3442048E+04	0.4961332E+04 -136.0703	-0.1447751E+09 -0.5625778E+09	
JUAN2A		-0.1875536E+06 0.1240128E+07	0.1254231E+07 98.6001	-0.4532301E+03 -0.6854528E+02	0.4583841E+03 -171.3999	0.0000000E+00 -0.2874597E+09	0.3405840E+06 -0.3529883E+08
	P2.1 A	-0.1854356E+06 0.1234662E+07	0.1248510E+07 98.5415	0.3993777E+03 0.6053479E+02	0.4039393E+03 8.6189	0.3405840E+06 0.2521609E+09	
JUAN2B		-0.1939970E+06 0.1239159E+07	0.1254253E+07 98.8977	-0.4528759E+03 -0.7090014E+02	0.4583922E+03 -171.1023	0.1430511E-03 -0.2874698E+09	0.3885401E+06 -0.3341027E+08
	P2.1 B	-0.1913046E+06 0.1233071E+07	0.1247822E+07 98.8188	0.4022952E+03 0.6304425E+02	0.4072051E+03 8.9065	0.3885401E+06 0.2540595E+09	
JUAN2C		-0.1889782E+06 0.1236280E+07	0.1250640E+07 98.6910	-0.4518236E+03 -0.6906594E+02	0.4570718E+03 -171.3090	0.5602837E-04 -0.2858161E+09	0.3363710E+06 -0.3233345E+08
	P2.1 C	-0.1867769E+06 0.1231197E+07	0.1245283E+07 98.6262	0.4024221E+03 0.6159527E+02	0.4071088E+03 8.7022	0.3363710E+06 0.2534827E+09	

TABLE 6.7 (Cont'd)

Partial Steady-State Printout

JUAN1A		0.2817000E+06 0.0000000E+00	0.2817000E+06 0.0000	0.0000000E+00 -0.1029530E+03	0.1029530E+03 -90.0000	0.0000000E+00 0.1450093E+08	0.0000000E+00 0.1450093E+08
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	0.0000000E+00 0.1029530E+03	0.1029530E+03 90.0000	0.0000000E+00 0.0000000E+00	
JUAN1B		-0.1408500E+06 -0.2439594E+06	0.2817000E+06 -120.0000	-0.8915991E+02 0.5147650E+02	0.1029530E+03 150.0000	-0.2980232E-07 0.1450093E+08	-0.2980232E-07 0.1450093E+08
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	0.8915991E+02 -0.5147650E+02	0.1029530E+03 -30.0000	0.0000000E+00 0.0000000E+00	
JUAN1C		-0.1408500E+06 0.2439594E+06	0.2817000E+06 120.0000	0.8915991E+02 0.5147650E+02	0.1029530E+03 30.0000	0.0000000E+00 0.1450093E+08	0.0000000E+00 0.1450093E+08
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	-0.8915991E+02 -0.5147650E+02	0.1029530E+03 -150.0000	0.0000000E+00 0.0000000E+00	
JUAN2A		-0.1875536E+06 0.1240128E+07	0.1254231E+07 98.6001	0.4532301E+03 0.6854528E+02	0.4583841E+03 8.6001	0.0000000E+00 0.2874597E+09	0.0000000E+00 0.2874597E+09
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	-0.4532301E+03 -0.6854528E+02	0.4583841E+03 -171.3999	0.0000000E+00 0.0000000E+00	
JUAN2B		-0.1939970E+06 0.1239159E+07	0.1254253E+07 98.8977	0.4528759E+03 0.7090014E+02	0.4583922E+03 8.8977	0.0000000E+00 0.2874698E+09	0.0000000E+00 0.2874698E+09
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	-0.4528759E+03 -0.7090014E+02	0.4583922E+03 -171.1023	0.0000000E+00 0.0000000E+00	
JUAN2C		-0.1889782E+06 0.1236280E+07	0.1250640E+07 98.6910	0.4518236E+03 0.6906594E+02	0.4570718E+03 8.6910	0.0000000E+00 0.2858161E+09	0.0000000E+00 0.2858161E+09
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	-0.4518236E+03 -0.6906594E+02	0.4570718E+03 -171.3090	0.0000000E+00 0.0000000E+00	
P1.6 C		0.3605920E+02 0.3471281E+02	0.5005242E+02 43.9101	0.3605920E+04 0.3471281E+04	0.5005242E+04 43.9101	0.1252622E+06 0.0000000E+00	0.1252622E+06 0.0000000E+00
	TERRA	0.0000000E+00 0.0000000E+00	0.0000000E+00 0.0000	-0.3605920E+04 -0.3471281E+04	0.5005242E+04 -136.0899	0.0000000E+00 0.0000000E+00	

TABLE 6.7 (Cont'd)

Partial Steady-State Printout

```
      TOTAL NETWORK LOSS "PLOSS" BY SUMMING BRANCH FLOWS =    0.1711878488E+09
OUTPUT FOR STEADY STATE SWITCH CURRENT
     NODE-K    NODE-M          I-REAL               I-IMAG               I-MAGN             DEGREES
    JUAN A    JUAN1A      0.5622958377E+02     0.9513198218E+02     0.1105072854E+03      59.4140
    JUAN B    JUAN1B      0.1299547206E+03    -0.3573813316E+02     0.1347792402E+03     -15.3765
    JUAN C    JUAN1C      0.3648423385E+04     0.3484194012E+04     0.5044858879E+04      43.6810
    JUAN A    JUAN2A           OPEN                 OPEN                 OPEN               OPEN
    JUAN B    JUAN2B           OPEN                 OPEN                 OPEN               OPEN
    JUAN C    JUAN2C           OPEN                 OPEN                 OPEN               OPEN
    P1.10A    MCKINA      0.0000000000E+00     0.0000000000E+00     0.0000000000E+00      0.0000
    P1.10B    MCKINB      0.0000000000E+00     0.0000000000E+00     0.0000000000E+00      0.0000
    P1.10C    MCKINC      0.0000000000E+00     0.0000000000E+00     0.0000000000E+00      0.0000
    P2.10A    MCKINA           OPEN                 OPEN                 OPEN               OPEN
    P2.10B    MCKINB           OPEN                 OPEN                 OPEN               OPEN
    P2.10C    MCKINC           OPEN                 OPEN                 OPEN               OPEN

SOLUTION AT NODES WITH KNOWN VOLTAGE.     NODES SHORTED TOGETHER BY SWITCHES ARE SHOWN AS A GROUP OF NAMES, WITH
THE PRINTED RESULT APPLYING TO THE COMPOSITE GROUP.   THE ENTRY 'MVA' IS  SQRT(P**2 + Q**2)  IN UNITS OF POWER,
WHILE  'P.F.'  IS THE ASSOCIATED POWER FACTOR.
            NODE             SOURCE NODE VOLTAGE              INJECTED SOURCE CURRENT              INJECTED SOURCE POWER
            NAME        RECTANGULAR           POLAR         RECTANGULAR          POLAR               P AND Q    MVA AND P.F.

           JUAN A
           JUAN1A      0.2817000E+06  0.2817000E+06      0.5622958E+02  0.1105073E+03      0.7919937E+07  0.1556495E+08
                       0.0000000E+00         0.0000      0.9513198E+02        59.4140     -0.1339934E+08  0.5088315E+00

           JUAN B
           JUAN1B     -0.1408500E+06  0.2817000E+06      0.1299547E+03  0.1347792E+03     -0.4792735E+07  0.1898366E+08
                      -0.2439594E+06      -120.0000     -0.3573813E+02       -15.3765     -0.1836869E+08 -0.2524664E+00

           JUAN C
           JUAN1C     -0.1408500E+06  0.2817000E+06      0.3648423E+04  0.5044859E+04      0.1680606E+09  0.7105684E+09
                       0.2439594E+06       120.0000      0.3484194E+04        43.6810      0.6904079E+09  0.2365158E+00
COMMENT CARD.                                   1C NODE VOLTAGE OUTPUT
CARD OF BUS NAMES FOR NODE-VOLTAGE OUTPUT.      1   JUAN2AJUAN2BJUAN2C
BLANK CARD ENDING NODE NAMES FOR VOLTAGE OUTPUT. 1BLANK CARD TERMINATING NODE VOLTAGE OUTPUT

BEGIN STEADY-STATE PRINTOUT OF EMTP OUTPUT VARIABLES.   NODE VOLTAGE OUTPUT FOLLOWS.
    BUS              PHASOR          ANGLE IN              REAL             IMAGINARY
   NAME            MAGNITUDE          DEGREES              PART                  PART
  JUAN2A        0.12542306E+07      98.600083      -0.18755360E+06     0.12401283E+07
  JUAN2B        0.12542527E+07      98.897737      -0.19399697E+06     0.12391590E+07
  JUAN2C        0.12506399E+07      98.690981      -0.18897822E+06     0.12362796E+07
BLANK CARD TERMINATING PLOT SPEC. CARDS.           1BLANK CARD TERMINATING PLOTTING
```

The fault current in kA peak equals:

$$\frac{345 \times \sqrt{2}}{\sqrt{3}} \times \frac{1}{55.58} = 5.068 \text{ kA peak} \tag{6-6}$$

This fault current doesn't take into account the capacitive charging current of the line, and it compares well with the current value of 5.045 kA peak given in Table 6.7.

The currents at nodes "JUAN1C" and "P1.1 C" are shown in Figure 6.4. The voltage drop across the first pi-section is approximately 5000 A x 9.16 Ω, or 46.3 kV, which compares with the observed drop of 281.7 kV-234.2 kV, or 47.5 kV, shown in Figure 6.4. The shunt reactor current has a value of (43.5 x 1000)/($\sqrt{3}$ x 345) = 72.7 A rms or 102.95 A peak, which is identical to the current given in the EMTP printout.

Phases A and B have mostly capacitive line charging current. Using only positive sequence capacitance and a uniform voltage profile, a charging current can be estimated.

$$\frac{345{,}000 \times \sqrt{2}}{\sqrt{3}} \times 377 \times (.019682 \times 10^{-6} \text{ F/mi}) = 2.09 \text{ A/mile} \tag{6-7}$$

The total charging current equals 90 x 2.09 or 188 A crest. Table 6.7 shows charging currents of 206 A and 236 A for Phases A and B, respectively. The currents for nodes "JUAN1A" and "P1.1 A" are shown in Figure 6.5. All currents can be vectorially added.

Manual checks of current magnitudes, voltage drops, etc., can establish confidence in the EMTP results, and at the same time serve as checks that the correct input data was used. On this simple system, checks are easy to make, but even on complicated systems simple calculations can be made using system simplifications to make sure that the EMTP results are plausible. Furthermore, hand calculations may indicate reasonable simplifications in the system model which will permit the EMTP studies to be performed more efficiently.

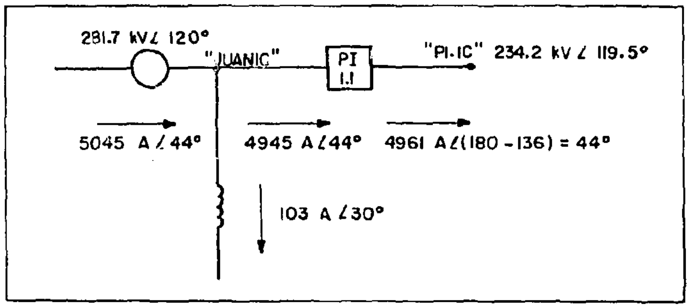


FIGURE 6.4. Node Currents In Crest Amperes At Nodes "JUAN1C" and "P1.1 C"

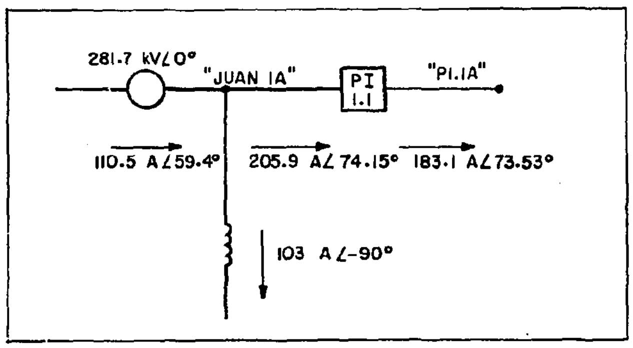


FIGURE 6.5. Node Currents In Crest Amperes At Nodes "JUAN1A" and "P1.1 A"

Several options are available to eliminate the problem of resonance between parallel shunt-compensated lines. These include:

1. Avoid reactor sizes which cause resonance.
2. Use circuit switchers to automatically disconnect shunt reactors from deenergized lines.
3. Install switched reactors in the substation rather than on the lines.

Of these, the second option is probably the simplest and most economical solution.

These EMTP simulations ran in approximately .3 seconds on a Cray 1S computer.

Suggested investigations:

- Determine a three-phse Thevenin equivalent circuit for nodes JUAN2A, JUAN2B, and JUAN2C for the fault case. With this equivalent and a shunt reactor model connected to the terminals of the equivalent, it should be possible to replicate Figure 6.3 with less CPU time.
- Experiment with different fault locations and with double line-to-ground faults.
- Determine the effect of a three-phase core form reactor with $X_0 \neq X_1$. These can be modeled in the EMTP with Type 51, 52, 53 branches. Refer to the Operation Manual or to Cases 7 through 10 of this Primer for illustrations.

Section 7

CASE 7: RECLOSING OF TRANSMISSION LINES

In this case, use of the EMTP for switching surge studies is illustrated. The new EMTP features to be introduced are the representation of transformers and statistical switches. A trapped charge on the transmission line is calculated and specified in the initial conditions. The study objective is to determine the probability distribution of switching overvoltage stresses (SOV) for comparison to the line's insulation strength. The insulation can be specified so as to achieve a design line outage rate criteria. The two operations which are usually considered are energizing and reclosing of a transmission line. When a line is energized, a surge equal to the voltage across the circuit breaker at the time of closure divides between the source impedance and the line surge impedance. The maximum input surge to the line with no trapped change can have a magnitude of up to 1 per-unit depending on the time of closure relative to the 60-Hz source voltage and the source impedance. This surge travels to the open line end and undergoes a positive reflection. On three-phase lines, multimodal wave propagation can result in overvoltages greater than 2 per-unit.

The following scenario is assumed for reclosing. A line-to-ground fault occurs on the transmission line. The breakers at both ends of the line open thereby clearing the fault. A charge of approximately 1 per-unit or higher will be trapped on the unfaulted phases. After 20 or more cycles of 60-Hz, a breaker on one end of the line closes. A surge approximately equal to the voltage across the breaker at time of closure travels down the line. The surge can have a magnitude of over 2 per-unit when the 60-Hz source voltage is totally out-of-phase with the trapped charge, resulting in a receiving end surge voltage of approximately 4 per-unit after the positive reflection from an open end. The total voltage in this case is 3 per-unit (4 per-unit surge minus 1 per-unit steady state).

This reclosing overvoltage can be reduced by preinsertion resistors. The schematic of a power circuit breaker with preinsertion resistors is shown in Figure 7.1. The auxiliary contact "A" closes first, inserting the preinsertion resistor. The preinsertion resistor is inserted in series with the surge impedance of the transmission line, and the input surge is reduced from a value of 2.0 per-unit (worst case without resistor) to 2.0 (Z/(R+Z)) as shown in Figure 7.2, where R is the value of the resistor and Z is the surge impedance of the line. If the preinsertion resistor and the surge impedance are equal, the outgoing surge is reduced to 2.0 x 1/2 or 1 per-unit. After a preinsertion time of approximately 8-10 ms, the main contact closes, and the resistor is shorted out which generates a surge. It can be shown that the shorting out surge is approximately

$$E' = \frac{R}{Z}\frac{\ell}{493}E \tag{7-1}$$

where ℓ is the length of line in miles and E is the instantaneous voltage to ground at the breaker. Reference (13) provides more information about line switching overvoltages.

The actual closings of the three poles of a circuit breaker do not occur at the same instant of time. The three poles aim for the same closing times (aiming point), but tests of circuit breakers have shown that actual circuit breaker closings can be represented by a Normal (Gaussian) distribution. The mean value of the distribution is the aiming point. The time between the first and last pole to close is called the pole span. Figure 7.3 shows the Normal distribution for the closing times of the main contacts. Truncating the distribution at +3 σ and -3 σ, the standard deviation is defined as the Pole Span in seconds divided by 6.

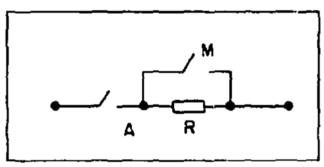


FIGURE 7.1. Schematic of One Pole of an EHV Circuit Breaker with a Preinsertion Resistor

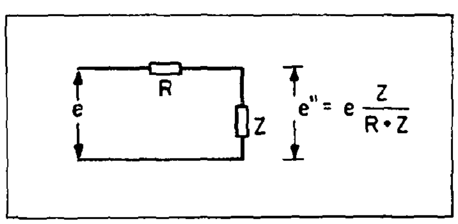


FIGURE 7.2. Traveling Voltage on the Transmission Line, e", as a Function of the Preinsertion Resistor R

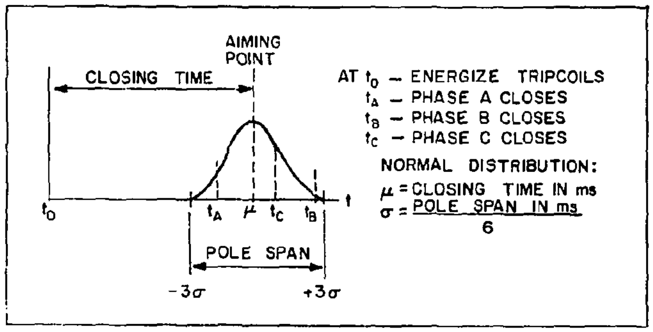


FIGURE 7.3. Closing Times of the Circuit Breaker Main Contacts

For a circuit breaker with preinsertion resistors, the closing of the auxiliary contact can be described by a Normal distribution given by the mean of the preinsertion time and a standard deviation of the auxiliary contacts, σ_A. Figure 7.4 shows the closing times of the Main and Auxiliary contacts in all three phases.

In closing a circuit breaker, two independent random events occur:

1. The random event of closing the breaker contacts around an aiming point was just discussed.

2. The second random event is that t_0 or the aiming point may occur at any point of the power frequency wave with equal likelihood, and can therefore be represented by a uniform distribution as shown in Figure 7.5.

A uniform random number is generated in the switching simulation which corresponds to a certain Aiming Point. After the Aiming Point is fixed, the closing times of all contacts are determined by random numbers applied to the Normal distributions for the Main and Auxiliary contacts.

For the 500-kV power circuit breaker, the following statistical data was specified:

- Mean Closing Time of the Main Contacts..... μ_M = 20 ms
- Mean Preinsertion Time..................... μ_R = 10 ms
- Pole Span of the Main Contacts............. $6\sigma_M$ = 8 ms
- Pole Span of the Auxiliary Contacts........ $6\sigma_A$ = 4 ms
- Preinsertion Resistor...................... R = 450 Ω

The window of aiming points was selected to be 360^{0} of a power frequency cycle. This data will be input in the "Statistic Switch" section of the input data after the Miscellaneous Data cards.

Usually, 200 closing operations are simulated. The SOV's obtained from these 200 circuit breaker closings can generally be represented by a Normal or Gaussian distribution. The Normal distribution probability tables can be found in basic textbooks.

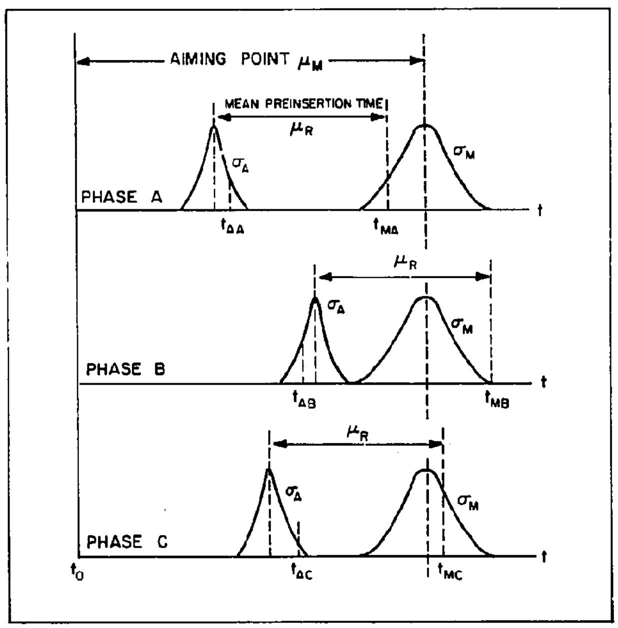


FIGURE 7.4. Closing Times of the Auxiliary and Main Contacts

The system studied consists of two 500-kV transmission lines connected to a substation, a local generator with stepup transformer, and a remote source on the unswitched line. This might represent a higher voltage system in the early stages of development.

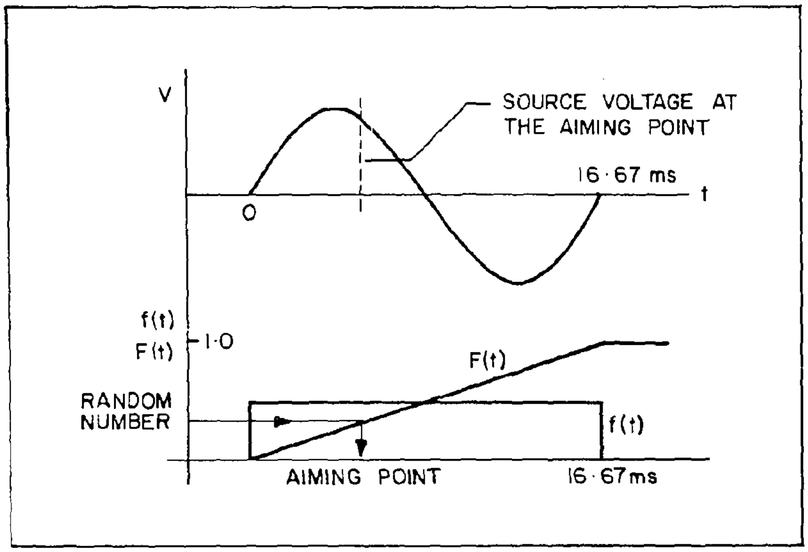


FIGURE 7.5. Uniform Distribution for Selecting the Aiming Point

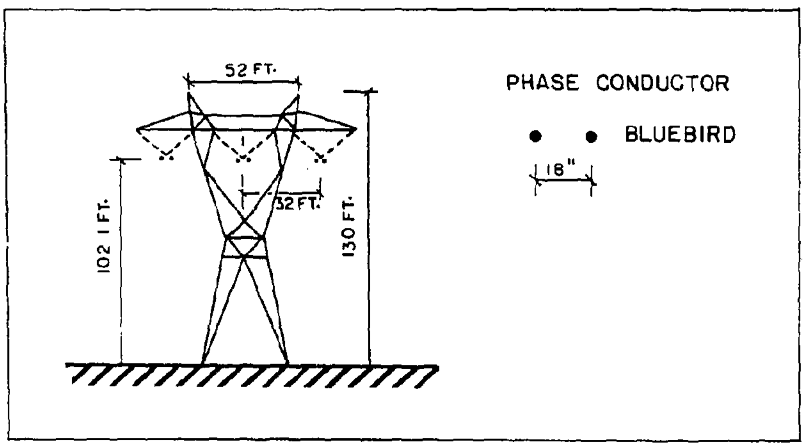


FIGURE 7.6. Typical 500-kV Transmission Tower

A typical 500-kV tower design as shown in Figure 7.6 was simulated for the 120-mile line which will be switched. The LINE CONSTANTS routine of the EMTP program was used to calculate the line data. The input data was shown in Table 3.1. The output data from the LINE CONSTANTS Program is summarized in Table 7.1.

TABLE 7.1

Data for the Switched, 120-Mile, 500-kV Line

		Zero Sequence	Positive Sequence
Surge Impedance	Ω	632.17	287.60
Velocity	mi/s	1.3066×10^5	1.8176×10^5
Resistance	Ω/mi	.529	.0245
Reactance	Ω/mi	1.766	.596
Capacitance	μF/mi	.01223	.01913

The data given in Table 7.2 was assumed for an adjacent 90-mile, 500-kV line. The line has a two-bundle conductor.

TABLE 7.2

Data for the 90-Mile, 500-kV Line

		Zero Sequence	Positive Sequence
Surge Impedance		591.3	281.7
Resistance	Ω/mi	.5580	.0310
Inductance	Ω/mi	1.6722	.5816
Capacitance	μF/mi	.01268	.0194

One of the easiest-to-use EMTP transformer models is the saturable TRANSFORMER component. It is a single-phase, multiwinding transformer with an optional excitation branch. The user supplies a turns ratio, winding resistance, and leakage inductance for each winding terminal in a star equivalent circuit. These parameters are calculated from the transformer voltage and MVA ratings, winding connections, and short-circuit tests. The excitation branch is defined by a resistance connected at the star point to account for core losses, and a nonlinear inductance connected at the star point which is input with current-flux linkage points.

The parameters for a generator stepup transformer model are calculated as follows for use in this case. The transformer model is not central to this case. For more information on EMTP transformer models, the user should refer to Case 9 of this Primer or to the Application Guide.

Given

- 26/525 kV, delta-wye connected, 500 MVA
- $Z_{HL} = 10\%$
- I_e at 100% Voltage = .3% rated current
- I_e at 110% Voltage = .7% rated current
- I_e at 120% Voltage = 3.0% rated current

$$X_{base} = \frac{kV^2}{MVA} = \frac{(525)^2}{500} = 551\ \Omega \tag{7-2}$$

$$\text{Assume that } Z_H = Z_L = 5\% \tag{7-3}$$

$$Z_H = 551 \times .05 = 27.55\ \Omega \tag{7-4}$$

$$\text{Turns Ratio} = \frac{525}{\sqrt{3} \times 26} = 11.66 \tag{7-5}$$

$$Z_L = \frac{27.55}{(11.66)^2} = .2026\ \Omega \tag{7-6}$$

$$\text{Rated Current} = \frac{500{,}000}{\sqrt{3} \times 525} = 550 \text{ A} \tag{7-7}$$

$$\text{Rated Exciting Current} = .003 \times 550 = 1.65 \text{ A rms or } 2.33 \text{ peak} \tag{7-8}$$

$$\text{Rated Flux} = \frac{525{,}000}{\sqrt{3}} \quad \frac{\sqrt{2}}{377} = 1137 \text{ Vs} \tag{7-9}$$

The estimated nonlinear magnetizing inductance characteristics are shown in Table 7.3.

TABLE 7.3

Magnetizing Characteristic of the Power Transformer

Voltage	Current (A peak)	Flux (Vs)
100%	2.33	1137
110%	5.44	1250
120%	23.33	1364
200%	1579.00	2274

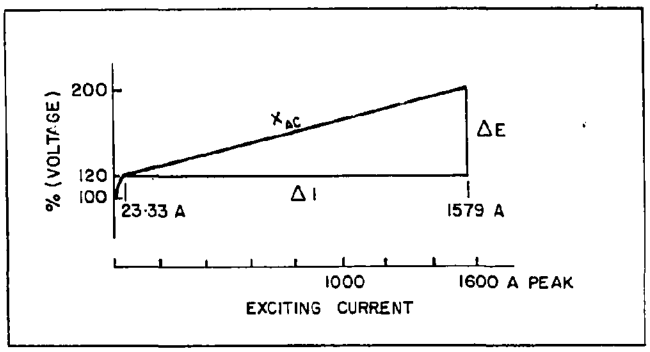


FIGURE 7.7. Transformer Magnetizing Current

The current at 200% voltage was estimated by using the air core inductance, as illustrated in Figure 7.7.

$$X_{AC} = 4 \times X_{HL} = 4 \times 55.1 = 220.4\ \Omega \tag{7-10}$$

This assumption for air core inductance is commonly used in TNA studies.

$$\Delta E = 80\% = .8 \times \frac{525}{\sqrt{3}} \sqrt{2} = 343\ \text{kV} \tag{7-11}$$

$$\Delta I = \frac{\Delta E}{X_{AC}} = \frac{343{,}000}{220.4} = 1556\ \text{A} \tag{7-12}$$

$$I_{200\%} = 23.33 + 1556 = 1579\ \text{A} \tag{7-13}$$

Local generators are commonly represented by their subtransient reactance for switching surge studies. A 500 MVA unit with $X_d'' = .15$ per-unit and 26-kV voltage rating was included in the model.

$$X_{base} = \frac{\text{kV}^2}{\text{MVA}} = \frac{(26)^2}{500} = 1.352\ \Omega \tag{7-14}$$

$$X_d'' = .15 \times 1.352 = .203\ \Omega \tag{7-15}$$

The parameters for the remote source are shown in Table 7.4.

TABLE 7.4

Remote Source Parameters

	Impedance	
	per-unit on 100 MVA* base	Ω
Positive Sequence:	.05	125
Zero Sequence:	.02	50

* $X_{base} = \frac{(500)^2}{100} = 2500\ \Omega$

Balanced source impedances are conveniently input to the EMTP as Type 51-53 branches as illustrated in Table 7.5. Three cards specify the terminal connections of the three-phase pi section impedance. The zero sequence R and L (or X) is input on the first card, and the positive sequence parameters are input on the second card. The ITYPE codes of 51 through 53 tell the EMTP to read these parameters and internally convert them to balanced self and mutual impedances as used by the program.

A steady-state pre-fault voltage of 525 kV (1.05 per-unit of nominal voltage) will be assumed. In order to get a voltage of 525 $kV_{rms\ L-L}$ at bus "B500", sources with peak voltages of 18.863 kV peak and 380.281 kV peak were connected at "EQUL" (equivalent source local) and "EQUR" (equivalent source remote), respectively. The steady-state voltage at the 500-kV bus "B500" prior to reclosing was 428.42 kV peak which converts to 525 $kV_{rms\ L-L}$. One or two iterations of source voltage selection might be necessary to get the desired 500-kV bus voltage.

Figure 7.8 shows the one-line diagram of the system represented, and Figure 7.9 shows the branches and node names which were represented. On the switched line, the voltage at the sending end "SEND" and receiving end "REC" will be recorded. A 33.3 microsecond time step was chosen because it divides evenly into the switched line's positive-sequence travel time of 660 microseconds.

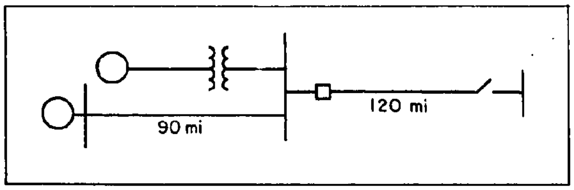


FIGURE 7.8. One-Line Diagram of the System Represented

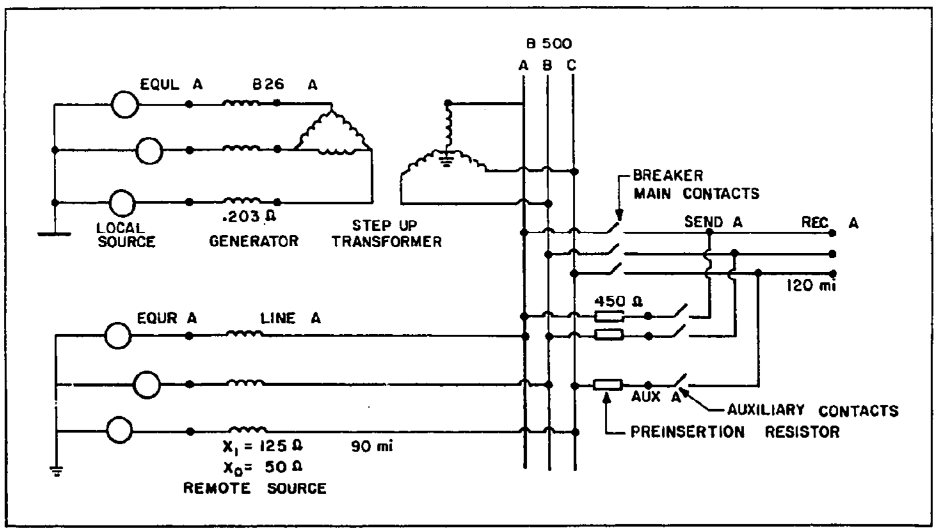


FIGURE 7.9. System as Represented with Node Names

Prior to simulating the 200 reclosing operations, the initial conditions (trapped charge) on the switched line have to be established. A line-to-ground fault is applied on Phase A at the receiving end node "REC A". It is assumed that the fault remains connected to "REC A" for several cycles, and therefore no trapped charge appears on the faulted Phase A. The auxiliary contacts were disconnected for this simulation. Phases B, A, and C opened at time 20.81 ms, 23.21 ms, and 26.44 ms, respectively. Input data for this case is presented in Table 7.5. Figures 7.10 and 7.11 show the sending end and receiving end voltages of the line. Phases A, B, and C are plotted on the same figure.

TABLE 7.5

Input Data for Calculating Trapped Charge

```
C FILE NAME: "L500FLT": A FAULT IS APPLIED AT "REC  A". THE MAIN
C BREAKER OPENS AFTER .02 SEC. THE AUXILIARY SWITCH IS TAKEN OUT. THIS
C RUN WILL SHOW THE TRAPPED CHARGE ON THE 120 MILE LINE AFTER THE BREAKER
C CLEARS THE FAULT.
C THE FAULT IS DISCONNECTED AFTER 96 MS.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     1-8     9-16    17-24    25-32
C T-STEP    T-MAX    X-OPT    C-OPT
C SECNDS SECONDS     O=MH      O=UF
C                   F(HZ)     F(HZ)
33.30E-6      .08     60.         0
C
C SECOND MISCELLANEOUS DATA CARD
C     1-8     9-16    17-24    25-32    33-40    41-48    49-56    57-64    65-72   73-80
C   PRINT     PLOT NETWORK    PR.SS   PR.MAX    I PUN    PUNCH     DUMP    MULT. DIAGNOS
C O=EACH   O=EACH     O= NO    O= NO    O= NO    O= NO    O= NO     INTO   NENERG   PRINT
C K=K-TH   K=K-TH    1=YES    1=YES    1=YES    1=YES    1=YES     DISK  STUDIES    O=NO
  20000        1        1        1        1        0        0        1        0
C LOCAL SOURCE (GENERATOR)
  B26   AEQUL A                         .203
  B26   BEQUL B                         .203
  B26   CEQUL C                         .203
C
C FAULT AT THE RECEIVING END, PHASE A
  FAULTA                             .01
C
C REMOTE SOURCE (MUTUALLY COUPLED)
C 34567890123456789012345678901234567890123456789012345
C                              SEQUENCE VALUES
C                           27-32          33-44
C                               R              L (FIRST ZERO, THEN POS.SEQUENCE)
51LINE AEQUR A                                50.
52LINE BEQUR B                               125.
53LINE CEQUR C
C
C TRANSMISSION LINES
C 3456789012345678901234567890123456789012345678901234567890
C                           27-32 33-38 39-44 45-50  CODE IN COLUMN "52"
C                               R     L     C    LE  (LE=LENGTH)
C                                                    (ZERO,POSITIVE SEQUENCE)
-1B500 ALINE A              .55801.6722.01268    90. 0
-2B500 BLINE B              .0310 .5816.01940    90. 0
-3B500 CLINE C
C 120 MILE LINE, FLAT CONFIGURATION
C 3456789012345678901234567890123456789012345678901234567890123456789012345678890
-1SEND AREC  A             .5294 1.7659.01224 120.  0
-2SEND BREC  B             .02499.59614.01914 120.  0
-3SEND CREC  C
C
C TRANSFORMER
C 345678901234567890123456789012345678901234567890
C        3-13   15-20       27-32 33-38 39-44 45-50
C REQUESTWORD     BUS           I  FLUX   BUS R-MAG
  TRANSFORMER                2.33 1137.      X  3.E5
C
C            1-16           17-32
C         CURRENT            FLUX
             2.33          1137.0
             5.44          1250.0
            23.33          1364.0
          1579.00          2274.0
             9999
C TRANSFORMER WINDINGS
```

TABLE 7.5 (Cont'd)

Input Data for Calculating Trapped Charge

```
C COLUMN 1,2: WINDING NUMBER
C 3456789012345678901234567890123456789O
C    3-8  9-14              27-32 33-38 39-44
C   BUS1  BUS2                R-K   L-K TURNS
 1B500 A                        27.55 11.66
 2B26  AB26  B                  .2026    1.
  TRANSFORMER      X                      Y
 1B500 B
 2B26  BB26  C
  TRANSFORMER      X                      Z
 1B500 C
 2B26  CB26  A
BLANK CARD TERMINATING BRANCH CARDS
C
C SWITCH CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24      25-34      35-44      45-54      55-64      65-74
C                                                       (OUTPUT OPTION IN COLUMN 80)
C   NODE NAMES                             IE FLASHOVER   SPECIAL   REFERENCE
C                 TIME TO    TIME TO       OR   VOLTAGE   REQUEST SWITCH-NAME
C   BUS1  BUS2      CLOSE       OPEN   NSTEP                  WORD  BUS5  BUS6
  B500 ASEND A        -1.       .020
  B500 BSEND B        -1.       .020
  B500 CSEND C        -1.       .020
  REC  AFAULTA       -.01      .0960                                           1
BLANK CARD TERMINATING SWITCH CARDS
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C   3-8        11-20     21-30     31-40     41-50     51-60     61-70     71-80
C   NODE   AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1   TIME-T1   T-START    T-STOP
C   NAME                 IN HZ      DEGR             SECONDS   SECONDS   SECONDS
14EQUL A      18863.      60.0        0.                          -1.0
14EQUL B      18863.      60.0      -120.                         -1.0
14EQUL C      18863.      60.0      -240.                         -1.0
C REMOTE SOURCE
14EQUR A     380281.      60.0       30.                          -1.0
14EQUR B     380281.      60.0      -90.                          -1.0
14EQUR C     380281.      60.0     -210.                          -1.0
C
BLANK CARD TERMINATING SOURCE CARD
C NODE VOLTAGE OUTPUT
C 3456789012345678901234567890123456789O
  B500 AB500 BB500 CSEND ASEND BSEND CREC  AREC  BREC  C
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
C PLOTTING CARDS
  CALCOMP PLOT                 2
C (CASE TITLE UP TO 78 CHARACTERS)
2 SINGLE-PHASE FAULT CLEARING
C THE FOLLOWING IS FORMAT OF THE PLOT REQUEST CARDS
C COLUMN 2,      "1"
C COLUMN 3.       4=NODE VOLTAGE
C                 8=BRANCH VOLTAGE
C                 9=BRANCH CURRENT
C COLUMN 4,       UNITS OF HORIZOTAL SCALE  1=DEGREES
C                                           2=CYCLES
C                                           3=SEC
C                                           4=MSEC
C                                           5=USEC
C COLUNNS 5-7     HORIZONTAL SCALE (UNITS PER INCH)
C COLUMNS 8-11    TIME WHERE PLOT STARTS
C COLUMNS 12-15   TIME WHERE PLOT ENDS
C COLUMNS 16-20   VALUE OF BOTTOM VERTICAL SCALE
C COLUMNS 21-24   VALUE OF TOP VERTICAL SCALE
C COLUMNS 25-48   UP TO FOUR NODE NAMES
C COLUMNS 49-64   GRAPH HEADING LABEL
C COLUMNS 65-80   VERTICAL AXIS LABEL
 144 8.   80.            REC   AREC  BREC  C
 144 8.   80.            SEND ASEND BSEND C
BLANK CARD TERMINATING PLOT REQUESTS
BLANK CARD TERMINATING THE CASE
```

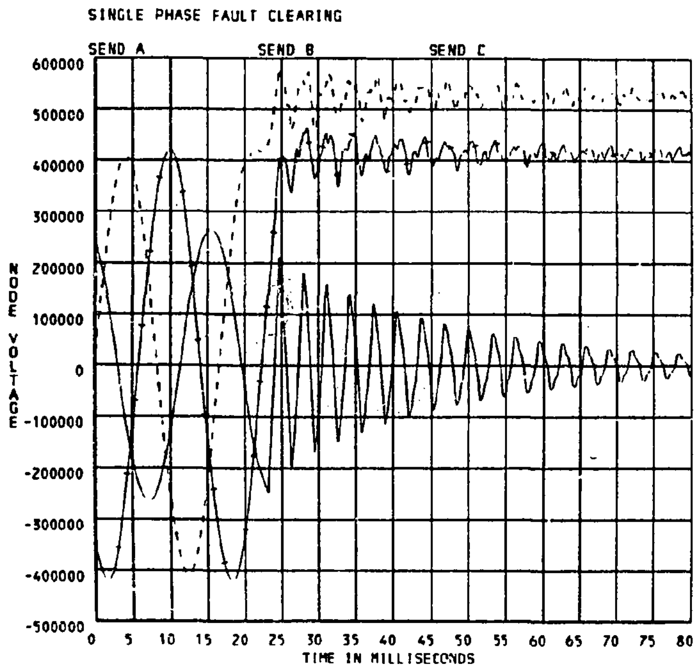


FIGURE 7.10. Fault Clearing, Sending End Voltages

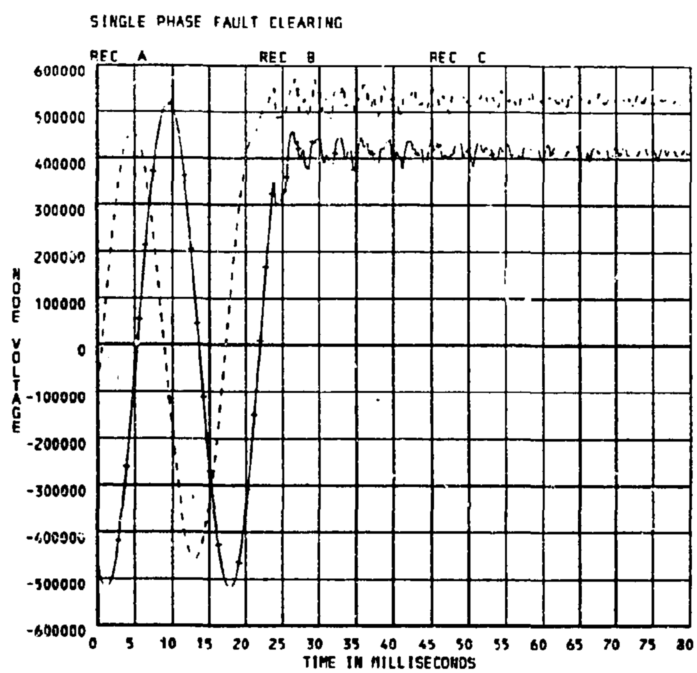


FIGURE 7.11. Fault Clearing, Receiving End Voltages

Figure 7.10 shows the sending end line voltage for the case where the fault was applied for the entire simulation. The frequency of the Phase A voltage oscillations after breaker opening corresonds to the surge travel time on the 120-mile line. This voltage is coupled to the two unfaulted Phases B and C. The trapped charges on Phases B and C are approximately 525 kV and 415 kV, respectively, as d.c. steady-state is approached. The trapped charges expressed in per-unit are 1.29 and 1.02, respectively (1 per-unit = 408 kV). The receiving end voltages in Figure 7.11 approach these same d.c. trapped voltages.

Because it is not possible to predict in advance the switch operating times which result in the maximum switching overvoltage, probability cases are performed with a set of random switching operations in each case. This produces a probability distribution of switching overvoltages which can be compared to the probability distribution of insulation strength. The result is a switching surge flashover rate per 100 operations (SSFOR), which can be used as a figure of merit for the line design.

For each reclosing, several random numbers are selected. Using the uniform distribution determined by the width of the aiming point window, an aiming point is determined. Using the statistical closing parameters of the Auxiliary and Main contacts, the closing times for each contact are determined. Each set of contact closing times results in different switching overvoltages. In order to determine the statistical character of the switching overvoltages, 200 reclosing operations were simulated. It has been found in TNA studies (Reference 14) that 200 simulations give a good representation of the overvoltages, and that more simulations have only a small effect on the overvoltages. Input data for a probability case with 450-ohm preinsertion resistors is given in Table 7.6.

The third Miscellaneous Data Card contains many of the statistical switching parameters. AINCR defines the class size for the overvoltage histograms in per-unit. It is usually equal to .05 or .10 per-unit, to achieve a total of 10 to 20 histogram classes. A value of .10 was used for the case with no surge reduction schemes. A value of .05 was more appropriate for the case with preinsertion resistors because the range of overvoltages is smaller.

TABLE 7.6

Input Data for the 200 Reclosing Operations with Preinsertion Resistors

```
C FILE NAME:  "L500STAT": SIMULATE RECLOSING OF THE 120 MILE LINE. THE
C STATISTICS SWITCHES "MAIN" AND "AUX" CONTROL THE CLOSING. TRAPPED
C CHARGE IS ON THE LINE. 200 CLOSING OPERATIONS WILL BE SIMULATED.
C 450 OHM RESISTOERS USED
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     1-8     9-16    17-24    25-32
C T-STEP   T-MAX   X-OPT    C-OPT
C SECNDS SECONDS    O=MH     O=UF
C                  F(HZ)    F(HZ)
33.30E-6      .07     60.        0
C
C SECOND MISCELLANEOUS DATA CARD
C     1-8     9-16    17-24    25-32    33-40    41-48    49-56    57-64    65-72   73-80
C   PRINT     PLOT NETWORK    PR.SS   PR.MAX    I PUN    PUNCH     DUMP    MULT.  DIAGNOS
C O=EACH  O=EACH    O= NO    O= NO    O= NO    O= NO    O= NO     INTO   NENERG    PRINT
C K=K-TH  K=K-TH    1=YES    1=YES    1=YES    1=YES    1=YES     DISK  STUDIES     O=NO
    5000        1        1        1        1                                   200
C
C IF ON MISC. CARD#2 "NENERG" COL.65-72 IS NONZERO A THIRD MISC.CARD MUST FOLLOW
C
C THIRD MISCELLANEOUS CARD (FOR STATISTICS DATA FOR THE SWITCHES)
C
C ISW     PRINT OUTPUT FOR ALL CLOSING TIMES FOR EVERY ENERGIZATION
C ITEST   EXTRA RANDOMLY SELECTED OFFSET TIME
C IDIST   O= SWITCH CLOSING TIMES WILL HAVE GAUSSIAN DISTRIBUTION
C         1= SWITCH CLOSING TIMES WILL HAVE UNIFORM DISTRIBUTION
C AINCR   PER-UNIT OVERVOLTAGE HISTOGRAM CLASS INCREMENT
C XMAXMX  MAX PER-UNIT OVERVOLTAGE THAT THE COUNTING ALGORITHM WILL CONSIDER
C DEGMIN  MINIMUM DEGREES
C DEGMAX  MAXIMUM DEGREES  DEGMIN AND DEGMAX DEFINE AN AIMING POINT WINDOW
C STATFR   POWER FREQUENCY
C SIGMAX  POINT AT WHICH TAIL OF NORMAL DISTRIBUTION WILL BE TRUNCATED
C NSEED   CONTROL OVER RANDOM SWITCH TIMES
C         O=RERUN WILL PRODUCE DIFFERENT ANSWER SEED WILL DEPEND ON TIME OF DAY
C         1=RERUN WILL PRODUCE THE SAME ANSWER
C
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     1-8     9-16    17-24    25-32    33-40    41-48    49-56    57-64    65-72    73-80
C     ISW    ITEST    IDIST    AINCR   XMAXMX   DEGMIN   DEGMAX   STATFR   SIGMAX    NSEED
        1        0        0      .05       5.       0.     360.      60.       3.        0
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     3-8   9-14  15-20  21-26  27-32  33-38  39-44
C    NODE NAMES    REFERENCE   RES.   IND.   CAP.                 (OUTPUT IN COLUMN 80)
C                    BRANCH            MH     UF                                    I=    1
C    BUS1   BUS2   BUS3   BUS4    OHM    OHM   UMHO                                 V=    2
C                                                                                   I,V   3
C                                                                                   P,E   4
C 34567890123456789012345678901234567890123456789012345678901234567890
C HIGH RESISTANCE FOR PHASE TO PHASE STATISTICS DATA
  REC  AREC  B                10. E9                                                      2
  REC  BREC  C                10. E9                                                      2
  REC  CREC  A                10. E9                                                      2
  SEND ASEND B                10. E9                                                      2
  SEND BSEND C                10. E9                                                      2
  SEND CSEND A                10. E9                                                      2
C PREINSERTION RESISTOR
  B500 AAUX  A                  450.
  B500 BAUX  B                  450.
  B500 CAUX  C                  450.
C LOCAL SOURCE (GENERATOR)
  B26  AEQUL A                          .203
```

TABLE 7.6 (Cont'd)

Input Data for the 200 Reclosing
Operations with Preinsertion Resistors

```
  B26  BEQUL B                      .203
  B26  CEQUL C                      .203
C
C REMOTE SOURCE (MUTUALLY COUPLED)
C 34567890123456789012345678901234567890123456789012345
C                             SEQUENCE VALUES
C                           27-32       33-44
C                               R           L (FIRST ZERO. THEN POS.SEQUENCE)
51LINE AEQUR A                             50.
52LINE BEQUR B                            125.
53LINE CEOUR C
C
C TRANSMISSION LINES
C 345678901234567890123456789012345678901234567890123456789012345
C                           27-32 33-38 39-44 45-50  CODE IN COLUMN "52"
C                               R     L     C    LE  (LE=LENGTH)
C                                                    (ZERO.POSITIVE SEQUENCE)
-1B500 ALINE A              .5580:.6722.01268   90. O
-2B500 BLINE B              .0310 .5816.01940   90. O
-3B500 CLINE C
C 120 MILE LINE
C 345678901234567890123456789012345678901234567890123456789012345
-1SEND AREC  A             .5294 1.7659.01224 120. O
-2SEND BREC  B             .02499.59614.01914 120. O
-3SEND CREC  C
C
C TRANSFORMER
C 3456789012345678901234567890123456789012345678901234
C       3-13   15-20        27-32 33-38 39-44 45-50
C REQUESTWORD    BUS            I  FLUX   BUS R-MAG
  TRANSFORMER                2.33 1137.      X
C
C           1-16            17-32
C        CURRENT             FLUX
            2.33           1137.0
            5.44           1250.0
           23.33           1364.0
         1579.00           2274.0
            9999
C TRANSFORMER WINDINGS
C COLUMN 1,2: WINDING NUMBER
C 3456789012345678901234567890123456789012345678901234
C    3-8  9-14              27-32 33-38 39-44
C   BUS1  BUS2                R-K   L-K TURNS
 1B5CO A                          27.55 11.66
 2B26  AB26  B                    .2026    1.
  TRANSFORMER        X                     Y
 1B500 B
 2B26  BB26  C
  TRANSFORMER        X                     Z
 1B500 C
 2B26  CB26  A
BLANK CARD TERMINATING BRANCH CARDS
C STATISTIC SWITCHES
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14      15-24     25-34                          55-64
C   BUS1  BUS2       MEAN  STANDARD
C                 CLOSING DEVIATION
C                    TIME MAIN.CONT
  B500 ASEND A      .0165     .0014                          STATISTICS
  B500 BSEND B      .0165     .0014                          STATISTICS
  B500 CSEND C      .0165     .0014                          STATISTICS
C
C AUXILIAPY SWITCHES
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C                   15-24     25-34                                        REFERENCE
```

TABLE 7.6 (Cont'd)

Input Data for the 200 Reclosing Operations with Preinsertion Resistors

```
C                    RANDOM  STANDARD                                      SWITCH
C                     DELAY DEVIATION                                 65-70 71-76
C                      TIME AUXILIARY
  AUX   ASEND A     -.010       .0007                         STATISTICSB500 ASEND A
  AUX   BSEND B     -.010       .0007                         STATISTICSB500 BSEND B
  AUX   CSEND C     -.010       .0007                         STATISTICSB500 CSEND C
BLANK CARD TERMINATING SWITCH CARDS
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C     3-8         11-20      21-30      31-40      41-50      51-60      61-70      71-80
C    NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1    TIME-T1    T-START    T-STOP
C    NAME                 IN HZ      DEGR               SECONDS    SECONDS    SECONDS
C LOCAL SOURCE
14EQUL A        18863.      60.0        0.                         -1.0
14EQUL B        18863.      60.0     -120.                         -1.0
14EQUL C        18863.      60.0     ,-240.                        -1.0
C
C REMOTE SOURCE
14EQUR A       380281.      60.0       30.                         -1.0
14EQUR B       380281.      60.0      -90.                         -1.0
14EQUR C       380281.      60.0     -210.                         -1.0
C
BLANK CARD TERMINATING SOURCE CARDS
C INITIAL CONDITIONS ON THE SWITCHED LINE
C 3456789012345678901234567890123456789012345678901234567890
C COLUMN 2: 2 = CARD FOR NODE VOLTAGES
C     3-8            9-23  (FORMAT E15.8)
C    BUS1   INST.VOLT.T=0
 2SEND A       0.
 2SEND B525000.
 2SEND C415000.
 2REC  A       0.
 2REC  B525000.
 2REC  C415000.
C
C COLUMN 2: 3 = CARD FOR LINEAR BRANCH CURRENTS
C 345678901234567890123456789O
C     3-8  9-14            15-29
C    BUS1  BUS2     CURRENT T=0
 3SEND AREC  A
 3SEND BREC  B
 3SEND CREC  C
C
C NODE OUTPUTS
C     3-8  9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C    BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  B500 AB500 BB500 CSEND ASEND BSEND CREC  AREC  BREC  C
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
BLANK CARD TERMINATING PLOT REQUESTS
C OUTPUT FOR THE "STATISTICS" CASE
C COLUMN 2:  O = NODE VOLTAGES
C           -1 = BRANCH VOLTAGES
C 3456789012345678901234567890123456789O
C           3-14 15-20 21-26 27-32 33-38
C     BASE VOLT  BUS1  BUS2  BUS3  BUS4
C REQUEST FOR LINE-TO-GROUND HISTOGRAMS
 0       408269.SEND ASEND BSEND C
 0       408270.REC  AREC  BREC  C
C REQUEST FOR LINE-TO-LINE HISTOGRAMS
-1       408271.SEND ASEND BSEND BSEND CSEND CSEND A
-1       408272.REC  AREC  BREC  BREC  CREC  CREC  A
BLANK CARD TERMINATING STATISTICS OUTPUT
BLANK CARD TERMINATING THE CASE
```

TABLE 7.7

Tabulation of Case Peak Receiving End Line-to-Ground Voltages

A DISTRIBUTION OF PEAK OVERVOLTAGES AMONG ALL OUTPUT NODES ON THE LAST CARD HAVING THE SAME BASE VOLTAGE FOLLOWS. THIS STATISTICAL DISTRIBUTION IS FOR THE MAXIMUM OF THE PEAKS AT ALL OF THESE OUTPUT NODES HAVING BASE VOLTAGE = 0.40827E+06

INTERVAL NUMBER	VOLTAGE IN PER UNIT	VOLTAGE IN PHYSICAL UNITS	FREQUENCY (DENSITY)	CUMULATIVE FREQUENCY	PER CENT .GE. CURRENT VALUE
14	1.30000	0.530751E+06	0	0	100.000
15	1.40000	0.571578E+06	1	1	99.500
16	1.50000	0.612405E+06	2	3	98.500
17	1.60000	0.653232E+06	2	5	97.500
18	1.70000	0.694059E+06	6	11	94.500
19	1.80000	0.734886E+06	5	16	92.000
20	1.90000	0.775713E+06	6	22	89.000
21	2.00000	0.816540E+06	3	25	87.500
22	2.10000	0.857367E+06	2	27	86.500
23	2.20000	0.898194E+06	16	43	78.500
24	2.30000	0.939021E+06	13	56	72.000
25	2.40000	0.979848E+06	16	72	64.000
26	2.50000	0.102067E+07	12	84	58.000
27	2.60000	0.106150E+07	14	98	51.000
28	2.70000	0.110233E+07	11	109	45.500
29	2.80000	0.114316E+07	13	122	39.000
30	2.90000	0.118398E+07	11	133	33.500
31	3.00000	0.122481E+07	12	145	27.500
32	3.10000	0.126564E+07	11	156	22.000
33	3.20000	0.130646E+07	14	170	15.000
34	3.30000	0.134729E+07	10	180	10.000
35	3.40000	0.138812E+07	4	184	8.000
36	3.50000	0.142895E+07	8	192	4.000
37	3.60000	0.146977E+07	4	196	2.000
38	3.70000	0.151060E+07	2	198	1.000
39	3.80000	0.155143E+07	1	199	0.500
40	3.90000	0.159225E+07	0	199	0.500
41	4.00000	0.163308E+07	1	200	0.000

DISTRIBUTION PARAMETERS FOR THE ABOVE DATA.	GROUPED DATA	UNGROUPED DATA
MEAN =	2.6770000	2.7283115
VARIANCE =	0.2855990	0.2855067
STD DEVIATION =	0.5344146	0.5343283

The first three switch cards in Table 7.6 are for the main contacts. Instead of closing and opening times, the mean closing times and standard deviations around the Aiming Point are input. The next three switch cards are for the auxiliary contacts. Their input parameters are the mean and standard deviations of their closing times relative to their "master switches," namely, the main contacts. These switches are commented out to run the case with no surge reduction measures.

The output of this case begins with a steady-state solution and a base case which has no random switching variation. Then the 200 random shots begin. For each shot, the actual switch closing times and the peak overvoltages are printed. This allows the user to rerun single-shot cases to obtain plotted waveforms.

The EMTP program prints a summary of the overvoltages from which histograms of the voltage distribution are drawn. Such a summary is included in Table 7.7 for the "case peak" receiving end line-to-ground voltages for the case with no surge reduction measures. This summary considers the maximum voltages which appeared phase-to-ground or phase-to-phase for the requested monitoring points during each shot. This grouping is performed automatically by the EMTP according to the statistical output requests which appear at the end of the input file. By specifying slightly different voltage bases on the output request cards, labeled OUTPUT FOR STATISTICS CASE, case peak summaries were obtained for the sending end and receiving end overvoltages. Each variable with the same voltage base is grouped into a histogram. The case peak summaries are used in probabilistic insulation design methods, because they describe the stress on any phase of the line during a particular shot. As far as line reliability is concerned, it doesn't matter which phase flashes over. For single pole reclosing, individual phase peaks are used instead of the case peaks.

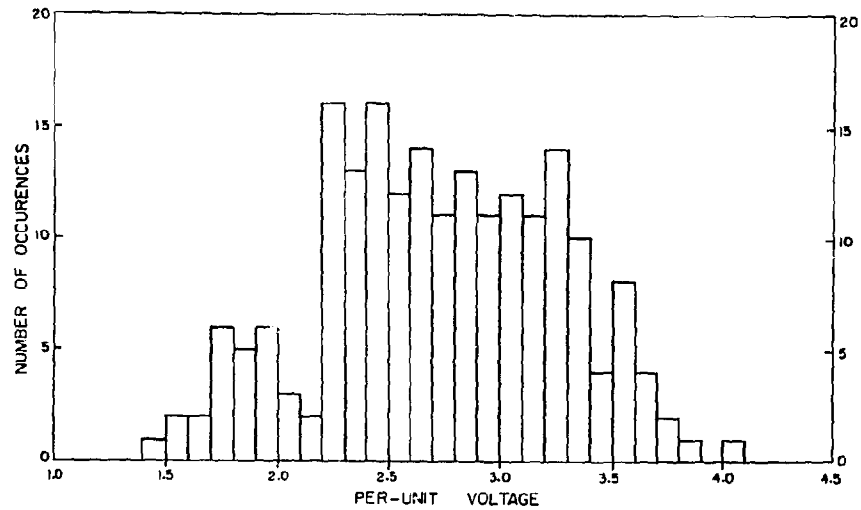
The first and second statistical output request cards define the sending and receiving end phase-to-ground overvoltage histograms, both for individual phases and grouped into case peaks. The third and fourth statistical output request cards define the same type of histograms for phase-to-phase overvoltages. This data will not be used in the Primer, but it may be important in actual studies of transformer-terminated lines.

The reclosing case was run with and without preinsertion resistors. The receiving overvoltages were sharply reduced with the resistors, as expected. Figures 7.12 and 7.13 show the case peak histograms of the switching overvoltages for the receiving end phase-to-ground voltages for the two cases. The per-unit voltages in Table 7.7 represent the lower class boundaries of the histogram. For example, one shot had a peak receiving end voltage between 1.40 and 1.50 per-unit, two shots had peaks between 1.50 and 1.60, etc. These numbers are read from the frequency density column.

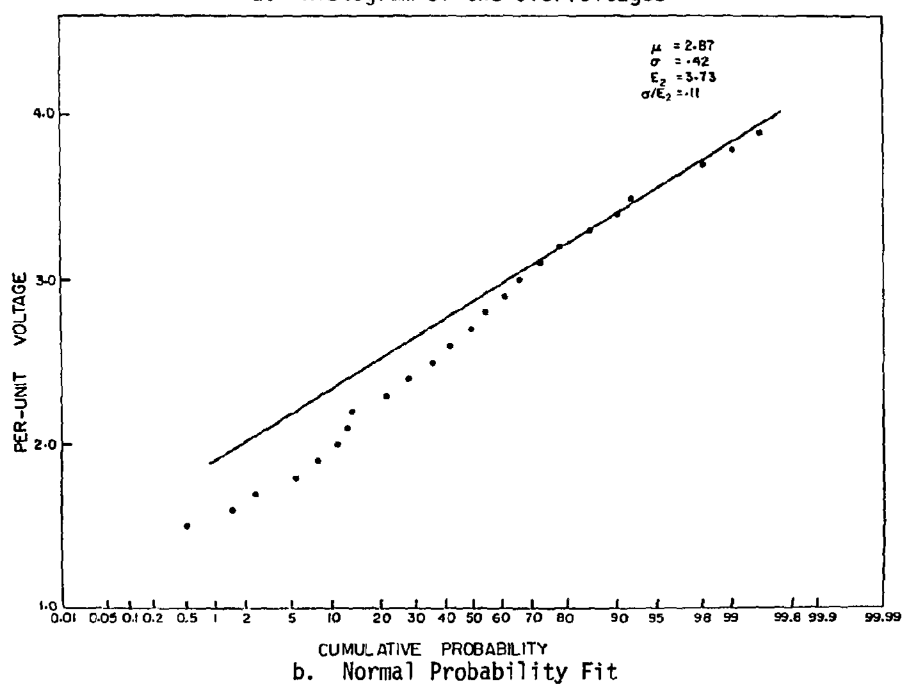
The cumulative probability distributions are also plotted for the above variables on Normal probability paper and are illustrated in Figures 7.12 and 7.13. The plots are generated by using the cumulative frequency column of Table 7.7. A straight line fit is applied to the upper end of the distribution becuase this is the most significant portion of the distribution for insulation coordination purposes. Parameters of each distribution, namely the mean, μ, and the standard derivation, σ, are then determined from the plots. The EMTP can perform this function, i.e., determine the parameters of a Normal distribution fit for the overvoltages, as seen in Table 7.7. Use of this fit for insulation coordination, however, is not recommended since the program tries to fit all the data, rather than the more important upper end of the distribution.

Peak overvoltages at points on the line other than the receiving end are considerably lower, as illustrated in Figure 7.14. A detailed SSFOR calculation would consider the peak voltage at each tower on the line. However, a simple and conservative assumption would be to use the receiving end overvoltages in the design.

A standard statistical parameter used in insulation coordination is the statistical switching overvoltage, E_2. This is an estimated value which 2% of the switching operations will exceed, and it can be read from the plots as the voltage at 98% cumulative probability. E_2 was estimated at 3.73 per-unit without resistors, and 1.79 per-unit with preinsertion resistors. One simple and conservative probabilistic design technique would be to set E_2 equal to V_3, the statistical insulation withstand voltage. V_3 is defined to be three standard deviations below the critical flashover voltage, CFO. Fifty percent of the test shots at the CFO voltage will cause flashover, while fifty percent will not. Reference (14) contains more information on probabilistic line insulation coordination.

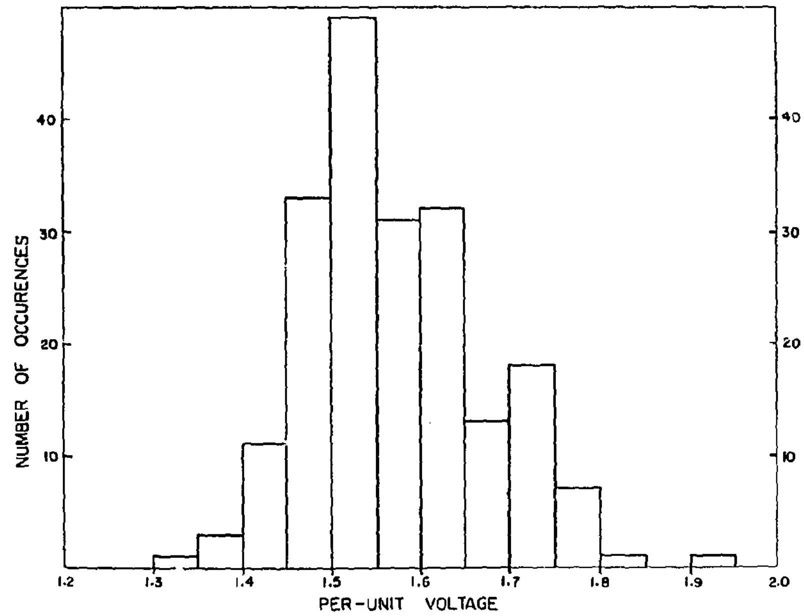


a. Histogram of the Overvoltages

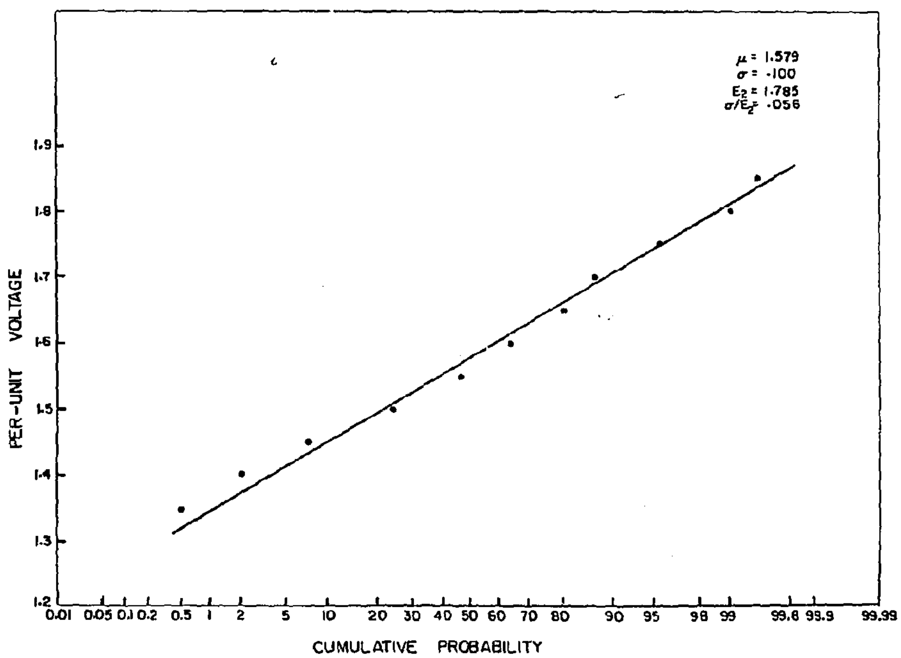


b. Normal Probability Fit

FIGURE 7.12. Case Peaks of the Receiving End Line-to-Ground Voltages with No Surge Reduction Schemes

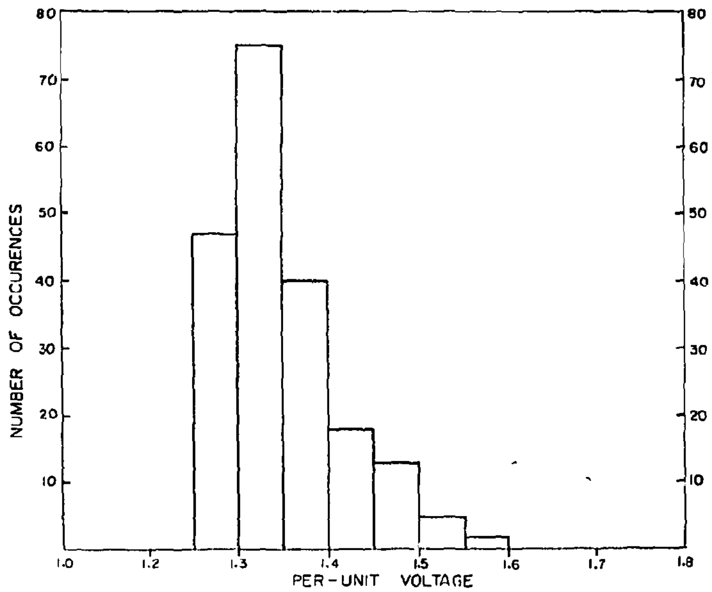


a. Histogram of the Overvoltages

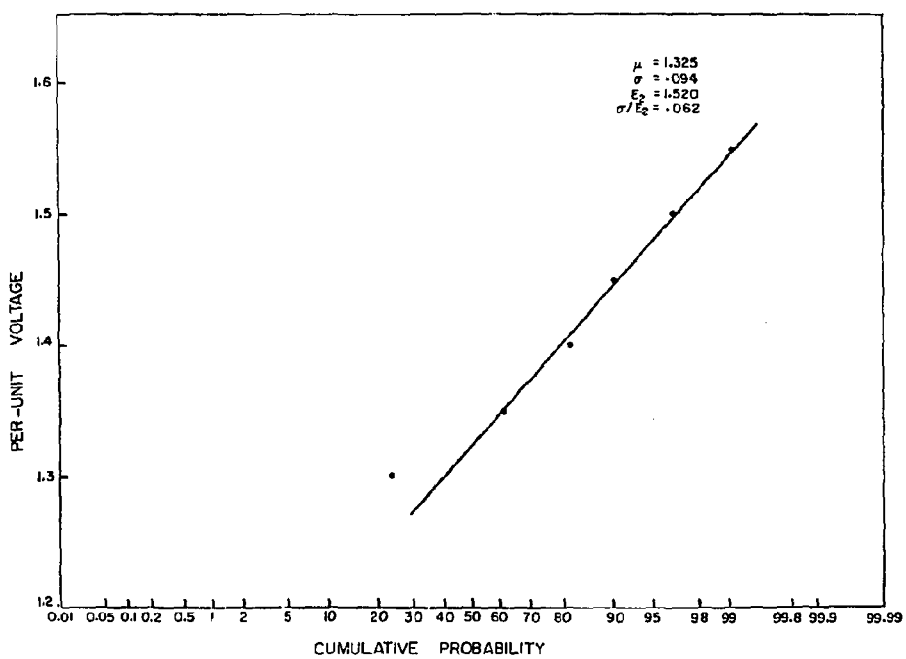


b. Normal Probability Fit

FIGURE 7.13. Case Peaks of the Receiving End Line-to-Ground Voltages with Preinsertion Resistors



a. Histogram of the Overvoltages



b. Normal Probability Fit

FIGURE 7.14. Case Peaks of the Sending End Line-to-Ground Voltages with No Surge Reduction Schemes

The line will be assumed to be at sea level, and it is also assumed that the insulation strike distance will have to be greater than one meter. Under these conditions, the required strike distance in meters is given by:

$$S = \frac{8}{\frac{4140}{CFO} - 1} \tag{7-16}$$

where the CFO is in kV and S is in meters. Our voltage base was 500 kV, or 408.25 kV peak line-to-ground. For the case without resistors:

$$E_2 = 3.73\ (408.25\ \text{kV}) = 1523\ \text{kV} \tag{7-17}$$

$$\sigma_f \text{ assumed to be .05 x CFO, set } V_3 = CFO - 3\ \sigma_f = E_2 \tag{7-18}$$

where σ_f is the standard deviation of the flashover voltage distribution of the line insulation.

$$CFO = E_2/(1 - .15) = 1523\ \text{kV}/.85 = 1792\ \text{kV} \tag{7-19}$$

$$S = \frac{8}{\frac{4140}{1792} - 1} = 6.10\ \text{m} = 20.0\ \text{ft.} \tag{7-20}$$

From Figure 7.6, this strike distance cannot be achieved with the given tower design. For the case with resistors:

$$E_2 = 1.79\ (408.25\ \text{kV}) = 731\ \text{kV} \tag{7-21}$$

$$CFO = 731/.85 = 860\ \text{kV} \tag{7-22}$$

$$S = \frac{8}{\frac{4140}{860} - 1} = 2.10\ \text{m} = 6.9\ \text{ft.} \tag{7-23}$$

This distance from phase conductor to tower structure is more practical. To determine the number of standard 5-3/4-inch insulators in the string, the strike distance is multiplied by 1.05 and divided by .146 m, the length of one insulator.

$$\#\ \text{ins} = \frac{2.1\ \text{m}\ (1.05)}{.146\ \text{m/ins}} = 15.1\ \text{insulators} \tag{7-24}$$

Based on the study, 15-insulator strings and 450-ohm preinsertion resistors would be recommended to satisfy switching surge requirements. The design criteria of $V_3 = E_2$ is targeted for one flashover per 100 switching operations, but empirical evidence suggests that all switching surge outage rate calculations have been conservative. See References (14) and (15). In the final line design, lightning and contamination requirements must be considered. These will dictate the use of more than 15 insulators per string on typical 500-kV lines.

The highest recorded receiving end voltage occurred in the 190th reclosing simulation without preinsertion resistors, and in the 146th reclosing operation with resistors. Actual contact operating times and pole spans are shown in Table 7.8.

TABLE 7.8

Closing Times in Milliseconds which
Resulted in the Highest Receiving End Overvoltage

	With Resistors		Without Resistors
	Auxiliary Contact	Main Contact	Main Contact
Phase A................	13.7754	23.6155	32.2316
Phase B................	17.4987	26.6852	31.2096
Phase C................	16.3491	26.5176	33.1682
Pole Span..............	3.723	3.070	1.959

The recorded sending end and receiving end voltages for the closing times of Table 7.8 are given in Table 7.9.

TABLE 7.9

Overvoltages at Sending and
Receiving Ends in kV (and Per-Unit)

	Sending End	Receiving End
With Resistors		
Phase A................	467.0 (1.14)	681.9 (1.67)
Phase B................	636.6 (1.56)	782.5 (1.92)
Phase C................	526.6 (1.29)	- 632.6 (1.55)
Without Resistors		
Phase A................	772.4 (1.89)	909.2 (2.23)
Phase B................	1116.8 (2.74)	-1419.0 (3.48)
Phase C................	- 982.2 (2.41)	-1643.1 (4.02)

The Cray 1S running times for these EMTP cases are as follows:

	Single Shot	Probability Case
Fault Clearing...............	.6	---
Without Resistors...........	3.6	374
With Resistors...............	3.7	465

Suggested investigation:

1. Vary the preinsertion resistor size, using 200 ohms and 650 ohms, for example.

2. Perform a line energization probability case with no trapped charge.

Section 8

CASE 8: SURGE ARRESTERS

The system described in Case 7 and shown in Figure 7.9 was used to illustrate the use of metal oxide surge arresters. These are employed as surge reduction measures similar to preinsertion resistors. A single reclosing case was simulated with 396-kV metal oxide surge arresters installed at each end of the switched line. The EMTP can model these arresters with a single exponential VI characteristic. No series or shunt gaps were modelled. A VI characteristic is defined based on a reference or base voltage, which is determined by the arrester rating in kV crest.

$$I = 2500 \left(\frac{V}{V_{ref}}\right)^{26} \tag{8-1}$$

$$V_{ref} = 1.39 \sqrt{2}\ (396{,}000) = 779{,}000 \tag{8-2}$$

The VI characteristic defined by equation 8-1 is presented in Table 8.1, along with the range of switching surge protective levels and 8 x 20 discharge voltages for three surge arrester manufacturers. It must be realized that the surge arrester discharge voltage depends on the steepness of the discharge current waveform as well as its magnitude. The peak voltage usually occurs after the peak current. Published discharge voltages for 8 x 20 current waveforms are higher than switching surge discharge voltages, but lower than typical lightning surge discharge voltages which have comparable current magnitudes but shorter wavefronts. Switching surges have much longer wavefronts and current magnitudes which usually do not exceed a few hundred amperes. Some arresters have series gaps or gaps which shunt part of the metal oxide.

The model of equation 8-1 and Table 8.1 may be adequate for most switching surge studies. Its accuracy may be improved by adding more exponential VI segments, shunt gaps, series gaps, and/or lumped RLC circuits to simulate the dynamics discussed above. Consult the Application Guide for more information.

The input file for the arrester case is presented in Table 8.2. The arrester connections are included with the branch cards, but the VI characteristics are defined after the initial conditions and before the node voltage output requests.

TABLE 8.1

396-kV Metal Oxide Surge Arrester VI Characteristics

I [Amperes]	V [kV] Equation 8-1	Manufacturers
100	688.3	Switching Surge Protective Level 744 to 815
300	718.0	
500	732.2	
1000	752.0	
1500	763.8	776 to 807
3000	784.5	812 to 838
5000	800.0	843 to 865
10000	821.7	890 to 912
20000	843.9	947 to 968
40000	866.7	1046 to 1053

The sending and receiving end arresters are considered to be two separate three-phase components due to the EMTP's method of simulating nonlinearities. Also, a pre-existing voltage is defined for each arrester corresponding to the trapped charge.

The switched line was split into five 24-mile sections to obtain the profile of peak voltages along the line. The intermediate nodes are labelled PNT1, PNT2, PNT3, and PNT4 from sending end to receiving end. Additional initial condition cards are required for the extra nodes and line sections. The time step for this case was chosen as one tenth that used for the probability runs to avoid possible instability of the arrester model.

The arrester's switching surge discharge voltage will be determined by the point at which the slope of its VI characteristic equals the line surge impedance. Higher initial currents and voltages can occur if the "open circuit voltage," or the receiving end voltage without arresters, is very large. Using a single phase analysis with the positive sequence surge impedance, the discharge voltage can be estimated.

$$I = 2500\ (V/779000)^{26} \tag{8-3}$$

$$V = 576564\ I^{1/26} \tag{8-4}$$

$$\frac{dV}{dI} = 22176\ I^{-25/26} \tag{8-5}$$

TABLE 8.2

Input Data for the Arrester Case

```
C FILE NAME:  "L500ARR": SIMULATE RECLOSING OF THE 120 MILE LINE. THE
C STATISTICS SWITCHES "MAIN" AND "AUX" CONTROL THE CLOSING. TRAPPED
C CHARGE IS ON THE LINE. 200 CLOSING OPERATIONS WILL BE SIMULATED.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8    9-16   17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C                  F(HZ)   F(HZ)
33.30E-7     .07     60.       0
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8    9-16   17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C O=EACH  O=EACH   O= NO   O= NO   O= NO   O= NO   O= NO    INTO  NENERG   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
   25000       9       1       1       1                       1     000
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.                  (OUTPUT IN COLUMN 80)
C                   BRANCH          MH    UF                                  I=   1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                                  V=   2
C                                                                             I,V  3
C                                                                             P,E  4
C 34567890123456789012345678901234567890123456789O
C LOCAL SOURCE (GENERATOR)
  B26   AEQUL A                   .203
  B26   BEQUL B                   .203
  B26   CEQUL C                   .203
C
C REMOTE SOURCE (MUTUALLY COUPLED)
C 3456789012345678901234567890123456789012345
C                            SEQUENCE VALUES
C                          27-32       33-44
C                              R           L (FIRST ZERO, THEN POS.SEQUENCE)
51LINE AEQUR A                            50.
52LINE BEQUR B                           125.
53LINE CEQUR C
C
C TRANSMISSION LINES
C 345678901234567890123456789012345678901234567890
C                          27-32 33-38 39-44 45-50  CODE IN COLUMN "52"
C                              R     L     C    LE  (LE=LENGTH)
C                                                   (ZERO,POSITIVE SEQUENCE)
-1B500 ALINE A             .55801.6722.01268   90. 0
-2B500 BLINE B             .0310 .5816.01940   90. 0
-3B500 CLINE C
C 120 MILE LINE, FLAT CONFIGURATION
C 3456789012345678901234567890123456789012345678901234567890
-1SEND APNT1 A            .5294 1.7659.01224 24.    0
-2SEND BPNT1 B            .02499.59614.01914 24 .   0
-3SEND CPNT1 C
-1PNT1 APNT2 ASEND APNT1 A
-2PNT1 BPNT2 B
-3PNT1 CPNT2 C
-1PNT2 APNT3 ASEND APNT1 A
-2PNT2 BPNT3 B
-3PNT2 CPNT3 C
-1PNT3 APNT4 ASEND APNT1 A
-2PNT3 BPNT4 B
-3PNT3 CPNT4 C
-1PNT4 AREC  ASEND APNT1 A
```

TABLE 8.2 (Cont'd)

Input Data for the Arrester Case

```
-2PNT4 BREC  B
-3PNT4 CREC  C
C LINE END ARRESTERS  396-KV MOV
C NODE CONNECTIONS INPUTTED WITH DUMMY CHARACTERISTICS HERE
C 5555. CODE REFERS TO ACTUAL CHARACTERISTICS LOCATED
C BEFORE NODE VOLTAGE OUTPUT REQUESTS
C
92REC  A                   5555.
              -1.            -1.
               1.             1.
            9999.
92REC  B       REC  A      5555.
92REC  C       REC  A      5555.
92SEND A       REC  A      5555.
92SEND B       REC  A      5555.
92SEND C       REC  A      5555.
C
C
C TRANSFORMER
C 3456789012345678901234567890123456789012345678901234567890
C           3-13  15-20        27-32 33-38 39-44 45-50
C REQUESTWORD      BUS             I   FLUX   BUS R-MAG
  TRANSFORMER                   2.33 1137.      X
C
C             1-16             17-32
C          CURRENT              FLUX
              2.33            1137.0
              5.44            1250.0
             23.33            1364.0
           1579.00            2274.0
              9999
C TRANSFORMER WINDINGS
C COLUMN 1,2: WINDING NUMBER
C 3456789012345678901234567890123456789012345678901234567890
C    3-8  9-14                 27-32 33-38 39-44
C   BUS1  BUS2                   R-K   L-K TURNS
 1B500 A                            27.55 11.66
 2B26  AB26  B                      .2026    1.
  TRANSFORMER         X                       Y
 1B500 B
 2B26  BB26  C
  TRANSFORMER         X                       Z
 1B500 C
 2B26  CB26  A
BLANK CARD TERMINATING BRANCH CARDS
  B500 ASEND A   .0322316      1.0
  B500 BSEND B   .0312096      1.0
  B500 CSEND C   .0331682      1.0
BLANK CARD TERMINATING SWITCH CARDS
C SOURCE CARDS
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C     3-8        11-20     21-30     31-40     41-50     51-60     61-70     71-80
C    NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1   TIME-T1   T-START    T-STOP
C    NAME                  IN HZ      DEGR             SECONDS   SECONDS   SECONDS
C LOCAL SOURCE
14EQUL A        18863.      60.0        0.                          -1.0
14EQUL B        18863.      60.0     -120.                          -1.0
14EQUL C        18863.      60.0     -240.                          -1.0
C
C REMOTE SOURCE
14EQUR A       380281.      60.0       30.                          -1.0
14EQUR B       380281.      60.0      -90.                          -1.0
14EQUR C       380281.      60.0     -210.                          -1.0
C
```

TABLE 8.2 (Cont'd)

Input Data for the Arrester Case

```
BLANK CARD TERMINATING SOURCE CARDS
C INITIAL CONDITIONS ON THE SWITCHED LINE
C 345678901234567890123456789012345678901234567890
C COLUMN 2: 2 = CARD FOR NODE VOLTAGES
C     3-8          9-23   (FORMAT E15.8)
C    BUS1   INST.VOLT.T=0
 2SEND A       0.
 2SEND B525000.
 2SEND C415000.
 2REC  A       0.
 2REC  B525000.
 2REC  C415000.
 2PNT1 A       0.
 2PNT1 B525000.
 2PNT1 C415000.
 2PNT2 A       0.
 2PNT2 B525000.
 2PNT2 C415000.
 2PNT3 A       0.
 2PNT3 B525000.
 2PNT3 C415000.
 2PNT4 A       0.
 2PNT4 B525000.
 2PNT4 C415000.
C
C COLUMN 2: 3 = CARD FOR LINEAR BRANCH CURRENTS
C 34567890123456789012345678 90
C     3-8   9-14          15-29
C    BUS1  BUS2       CURRENT T=0
 3SEND APNT1 A
 3SEND BPNT1 B
 3SEND CPNT1 C
 3PNT1 APNT2 A
 3PNT1 BPNT2 B
 3PNT1 CPNT2 C
 3PNT2 APNT3 A
 3PNT2 BPNT3 B
 3PNT2 CPNT3 C
 3PNT3 APNT4 A
 3PNT3 BPNT4 B
 3PNT3 CPNT4 C
 3PNT4 AREC  A
 3PNT4 BREC  B
 3PNT4 CREC  C
C ZINC OXIDE CHARACTERISTICS     I=K*(V/VREF)**Q FOR V > VMIN*VREF
C                                I=V/R FOR V < VMIN*VREF
C PHASE NUMBERING
C DEFINES TWO THREE-PHASE
C DEVICES AT EACH LINE END
C PHASE NUMBER           K                 Q                  VMIN             V(0-)   VREF
C
        -1           2500.             26.                 .5                 0. 779000.
        -2           2500.             26.                 .5            525000. 779000.
        -3           2500.             26.                 .5            415000. 779000.
        -1           2500.             26.                 .5                 0. 779000.
        -2           2500.             26.                 .5            525000. 779000.
        -3           2500.             26.                 .5            415000. 779000.
        20
C
C NODE OUTPUTS
C     3-8   9-14  15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C    BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9  BUS10 BUS11 BUS12 BUS13
  SEND ASEND BSEND C
  PNT1 APNT1 BPNT1 CPNT2 APNT2 BPNT2 CPNT3 APNT3 BPNT3 CPNT4 APNT4 BPNT4 C
  REC  AREC  BREC  C
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
```

TABLE 8.2 (Cont'd)

Input Data for the Arrester Case

```
  CALCOMP PLOT                     2
C (CASE TITLE UP TO 78 CHARACTERS)
2 RECLOSING WITH LINE-END ARRESTERS
C THE FOLLOWING IS FORMAT OF THE PLOT REQUEST CARDS
C COLUMN 2,      "1"
C COLUMN 3,       4=NODE VOLTAGE
C                 8=BRANCH VOLTAGE
C                 9=BRANCH CURRENT
C COLUMN 4,       UNITS OF HORIZOTAL SCALE  1=DEGREES
C                                           2=CYCLES
C                                           3=SEC
C                                           4=MSEC
C                                           5=USEC
C COLUNNS 5-7     HORIZONTAL SCALE (UNITS PER INCH)
C COLUMNS 11-15   TIME WHERE PLOT ENDS
C COLUMNS 16-20   VALUE OF BOTTOM VERTICAL SCALE
C COLUMNS 21-24   VALUE OF TOP VERTICAL SCALE
C COLUMNS 25-48   UP TO FOUR NODE NAMES
C COLUMNS 49-64   GRAPH HEADING LABEL
C COLUMNS 65-80   VERTICAL AXIS LABEL
 144 8.     80.0         SEND A
 144 8.     80.0         SEND B
 144 8.     80.0         SEND C
 144 8.     80.0         PNT1 A
 144 8.     80.0         PNT1 B
 144 8.     80.0         PNT1 C
 144 8.     80.0         PNT2 A
 144 8.     80.0         PNT2 B
 144 8.     80.0         PNT2 C
 144 8.     80.0         PNT3 A
 144 8.     80.0         PNT3 B
 144 8.     80.0         PNT3 C
 144 8.     80.0         PNT4 A
 144 8.     80.0         PNT4 B
 144 8.     80.0         PNT4 C
 144 8.     80.0         REC  A
 144 8.     80.0         REC  B
 144 8.     80.0         REC  C
BLANK CARD TERMINATING PLOTTED OUTPUT
BLANK CARD TERMINATING THE CASE
```

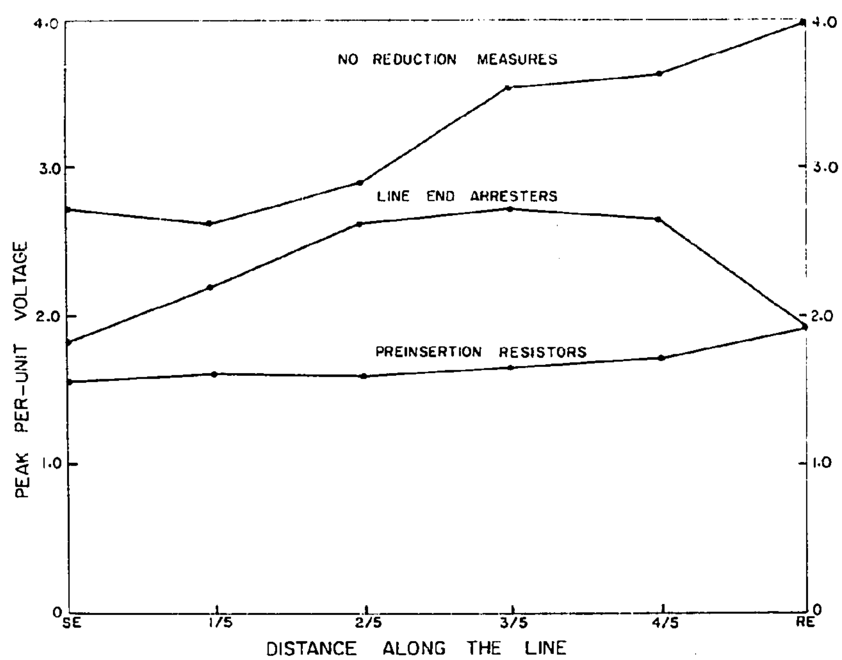


FIGURE 8.1. Line Overvoltage Profiles

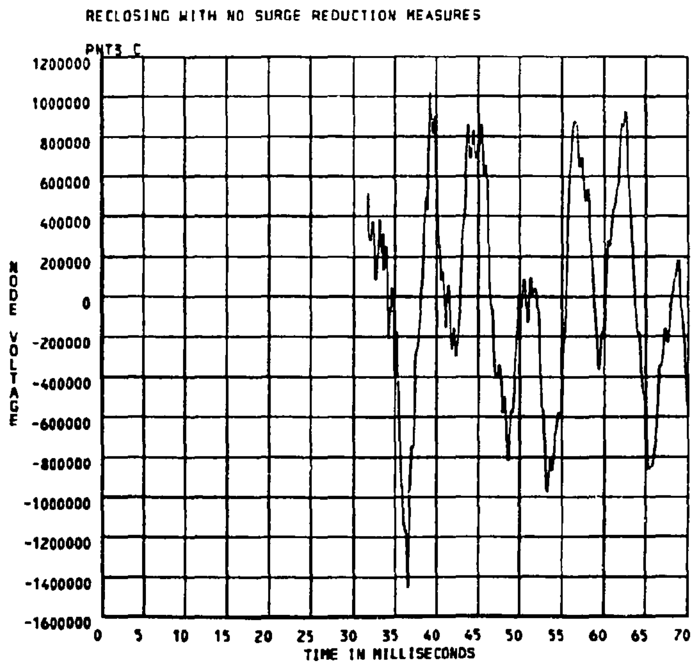


FIGURE 8.2. Phase C Voltage at the Fourth Metering Point (PNT3) with No Surge Reduction Measures

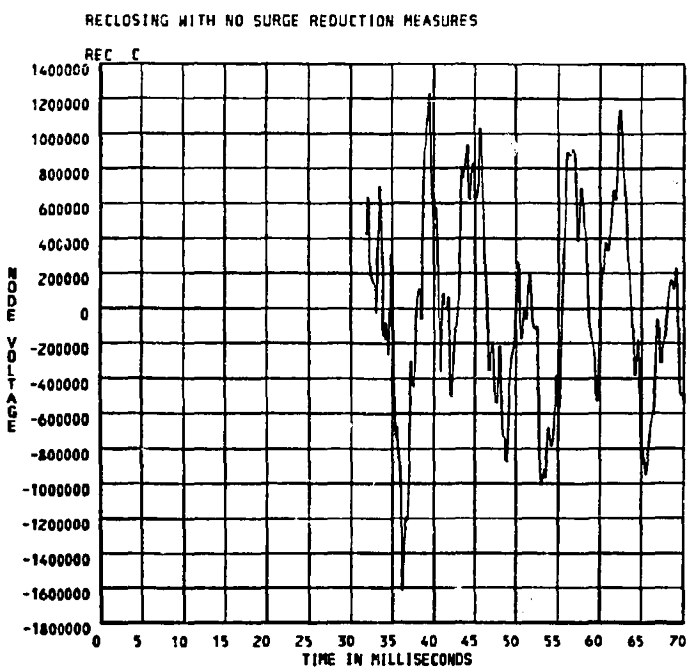


FIGURE 8.3. Phase C Voltage at the Receiving End with No Surge Reduction Measures

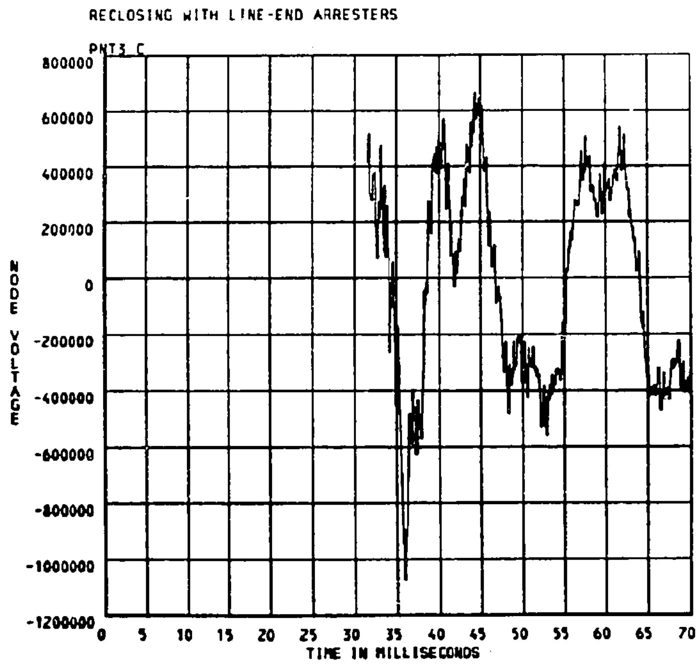


FIGURE 8.4. Phase C Voltage at the Fourth Metering Point (PNT3) with Line-End Surge Arresters

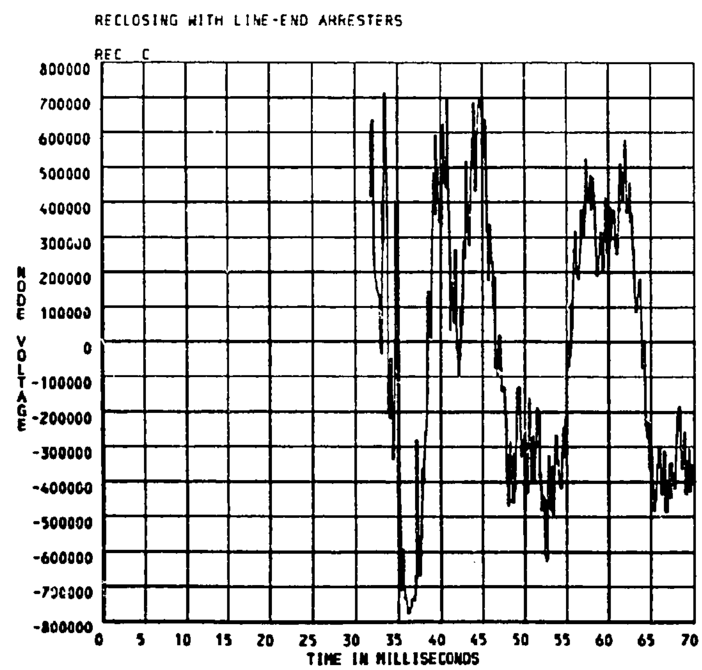


FIGURE 8.5. Phase C Voltage at the Receiving End with Line-End Surge Arresters

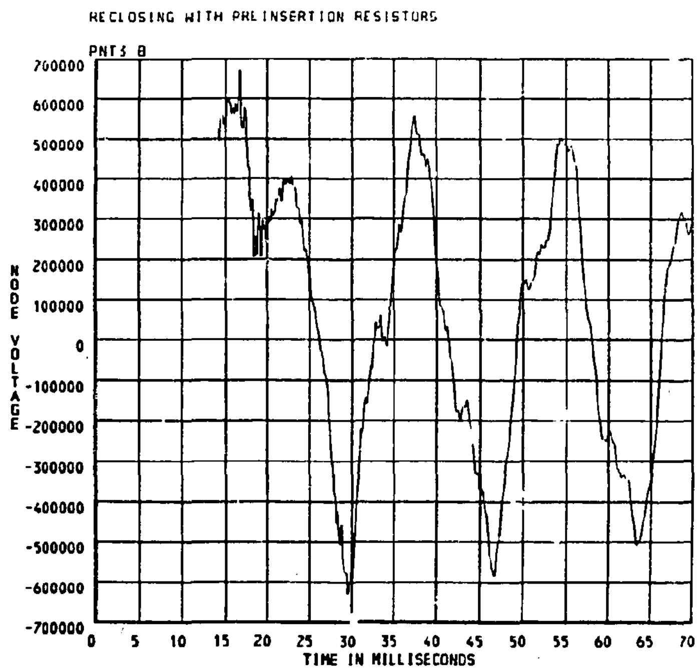


FIGURE 8.6. Phase B Voltage at the Fourth Metering Point (PNT3) with Preinsertion Resistors

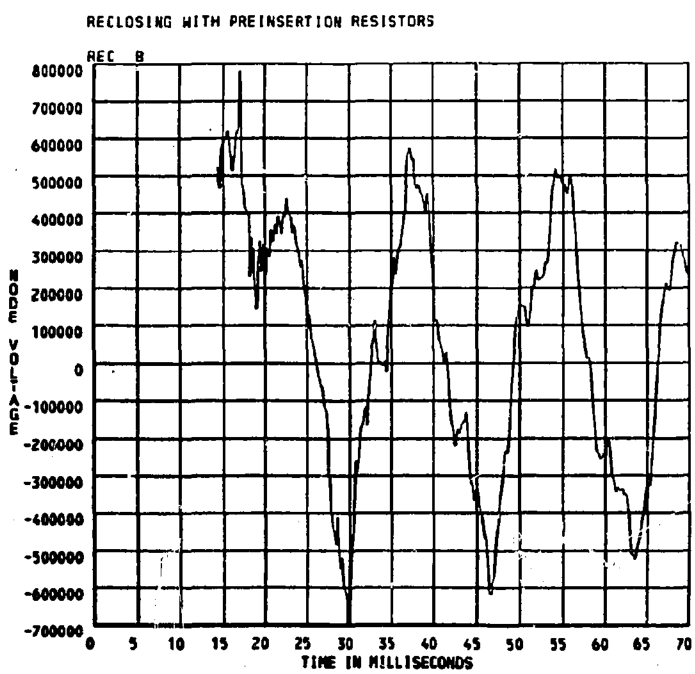


FIGURE 8.7. Phase B Voltage at the Receiving End with Preinsertion Resistors

$$\text{at } \frac{dV}{dI} = 288 \text{ ohms}, \; I = 91.61 \text{ amps} \tag{8-6}$$

$$V_{discharge} = 576564 \; (91.61)^{1/26} = 685.97 \text{ kV (1.68 per-unit)} \tag{8-7}$$

The receiving end overvoltage without arresters or resistors can be as high as 4.02 per-unit, or 1643.1 kV. The actual peak arrester voltage could be estimated by:

$$I = \frac{E_{oc} - V_{discharge}}{Z} = \frac{1643.1 - 685.97}{288} = 3323 \text{ amps} \tag{8-8}$$

$$V = 576564 \; (3323)^{1/26} = 787.6 \text{ kV (1.93 per-unit)} \tag{8-9}$$

In some cases, it may appear that arresters are more effective than preinsertion resistors. However, they only operate at the line ends. Reflected waves from the receiving end arresters travel back to the source, and are added to the remaining incoming surge. Typically, peak overvoltages are higher at interior points on the line than at the arrester locations.

The appendix to Reference (15) derives an equation for approximating the peak voltage at an interior point of a line where line-end arresters have been employed.

$$E_M = E_I + \frac{e_{A1} - i_{A1} Z_c \pm V_d}{2} \tag{8-10}$$

where E_M = maximum peak voltage on the line.

E_I = input surge voltage.

e_{A1}, i_{A1} = voltage and current values from equations 8-6 and 8-7.

Z_c = line surge impedance.

V_d = trapped charge voltage.

The negative sign for V_d is used if E_I is of the same polarity as V_d. The maximum voltage at the receiving end with no surge reduction measures occurred on Phase C. The main breaker contacts closed at 33.2 milliseconds as noted in Table 7.8. The Phase C sending end bus voltage at the instant of closure can be calculated from the phasor solution, which states that the steady-state node voltage at "B500 C" is 397.9 kV at an angle of 150 degrees.

$$V_c = 397.9 \cos [150^0 + 360^0 (33.2 \text{ msec}/16.67 \text{ msec})] = -333.6 \text{ kV} \qquad (8\text{-}11)$$

The input surge voltage is the difference between V_c and the initial trapped charge of 415 kV. Therefore, E_I = -748.6 kV and the positive sign is used in equation 8-10 because E_I and V_d are of opposite polarity. An estimated value of E_M is:

$$E_M = 748{,}600 + \frac{685{,}970 - 91.61\ (288) + 415{,}000}{2}$$

$$= 1286 \text{ kV} = 3.15 \text{ per-unit} \qquad (8\text{-}12)$$

Three cases were performed with switch closing times taken from Table 7.8. The case with line-end arresters was run with the same switching times as the case with no surge reduction measures. This will not necessarily produce the highest overvoltage possible with line-end arresters, but it should be very close. A probability case with arrester models will use more CPU time than the cases in Section 7 for two reasons:

1. The nonlinear arrester model adds to the computational effort at each time step.
2. A shorter time step must be used to obtain accurate results with nonlinear models than would otherwise be the case.

The arrester case was run with a time step of 3.33 microseconds, while the cases with no surge reduction measures and with preinsertion resistors were run with time steps of 33.3 microseconds, as in Case 7. The peak voltage results are presented in Table 8.3. There are slight differences from Table 7.9 because the 120-mile line length has been broken into 5 sections with only 4 time steps per section. Equation 8-9 accurately predicted the peak receiving end voltage, but equation 8-12 was somewhat conservative in predicting the peak voltage on the line.

TABLE 8.3

Peak Overvoltage Results in Per-Unit

Case	SEND	PNT3	REC
No Reduction Measures	2.72	3.54	3.96
Line-End Arresters	1.82	2.71	1.91
Preinsertion Resistors	1.56	1.65	1.91

Figure 8.1 shows the overvoltage profile for the arrester case, and also for the cases with preinsertion resistors and with no surge reduction means. If the design rule $V_3 = E_2$ is used for a probability case with arresters, the proper value of E_2 should be the maximum recorded value along the line's profile. Such a design criterion may lead to a larger number of insulators than those allowed by the use of preinsertion resistors. Reference (16) describes the use of line-end arresters in line designs.

Figures 8.2 through 8.7 show the peak voltages at a point 74 mi from the sending end (PNT3), and at the receiving end.

The Cray 1S running times for these EMTP cases are as follows:

	CP Time In Seconds
No Reduction Measures...........	3.6
Preinsertion Resistors..........	3.7
With Arresters..................	60.4

Suggested investigations:

1. Obtain an overvoltage profile for a case with both arresters and preinsertion resistors.
2. Vary the time step in the case with arresters. Also plot the arrester discharge currents.
3. Estimate the value of E_2 with line-end arresters and calculate the required number of insulators per string.

Section 9

CASE 9: POTENTIAL TRANSFORMER FERRORESONANCE

This study's objective is to solve an operating problem caused by nonlinear ferroresonance between a potential transformer (PT) and an open circuit breaker's grading capacitance. The ferroresonance leads to very large power frequency overvoltages on the PT bus and subsequent insulation failures. The EMTP outputs of interest are plotted PT bus voltages, although the evaluation of the output is more qualitative than quantitative in this case. The result of each case will be that ferroresonance either does or does not occur, or that stability appears to be marginal. The actual peak voltages are not so important. Reference (17) provides more detailed information about this problem.

The phenomena being simulated is highly nonlinear, and proper time-step selection is important to obtaining an accurate numerical solution. Some experimentation with the step size may be necessary. The main EMTP model used in this study is the saturable TRANSFORMER branch type.

A typical breaker-and-a-half substation arrangement is shown in Figure 9.1. A fault on Bus 2 is cleared by circuit breaker A, which is the last breaker to open, and one might expect that the bus voltage is zero after the breaker opens. However, most modern EHV puffer circuit breakers have capacitors across the interrupters to grade the voltage and to slope off the transient recovery voltage. After these breakers open, the bus is still capacitively connected to the source. Depending on the ratio of bus capacitance to open breaker capacitance, a relatively high voltage can appear on the bus.

A simplified circuit representing one open circuit breaker connected to a 345-kV bus is shown in Figure 9.2. The other circuit breakers have been isolated by open disconnect switches. With typical values of 650 pF for the breaker capacitance and 150 pF for the bus capacitance, there is a capacitively coupled 60-Hz voltage on the supposedly deenergized bus, with magnitude equal to 81.5% of the source voltage. This voltage can be large enough to saturate a PT's magnetizing impedance.

When the last breaker in Figure 9.1 or Figure 9.2 opens, there will be a near-peak voltage trapped on the bus capacitance because of the PT's small MVA rating and large magnetizing impedance. This trapped charge decays at a low frequency, and may be considered to be d.c. for a simple analysis. The d.c. voltage saturates

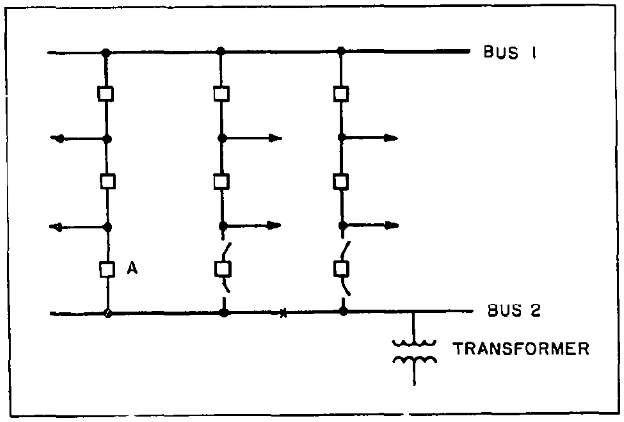


FIGURE 9.1. Typical Breaker-and-A-Half Substation Arrangement

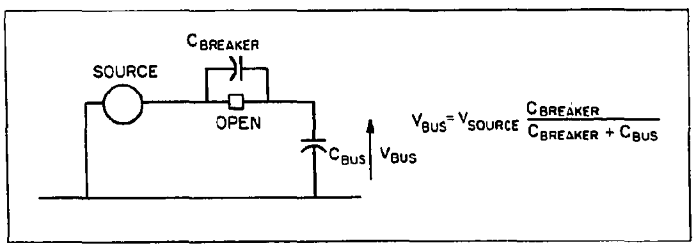


FIGURE 9.2. Simplified Circuit

the transformer. With a new saturated magnetizing inductance in the circuit, the trapped charge will decay rapidly and initiate an LC circuit oscillation until enough flux has been added to the core to cause saturation in the opposite direction. On a truly deenergized transformer, these trapped charge oscillations will appear as square waves with steadily decreasing magnitudes and increasing periods. See Figure 9.3.

With a coupled 60-Hz voltage on the bus as shown in Figure 9.2, there may be enough added energy to supply the transformer losses and sustain the trapped charge oscillations. This situation is known as ferroresonance, with typical waveforms as shown in Figure 9.4. This waveform is a combined trapped charge oscillation with 60-Hz coupled voltage. Since the 60-Hz coupled voltage is required to sustain the trapped charge oscillations, the oscillations must occur

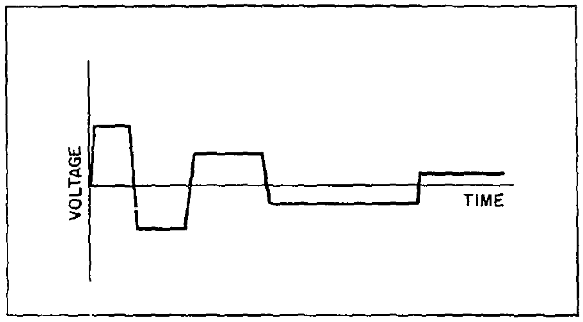


FIGURE 9.3. Square Wave Voltage Oscillations of Deenergized Transformer

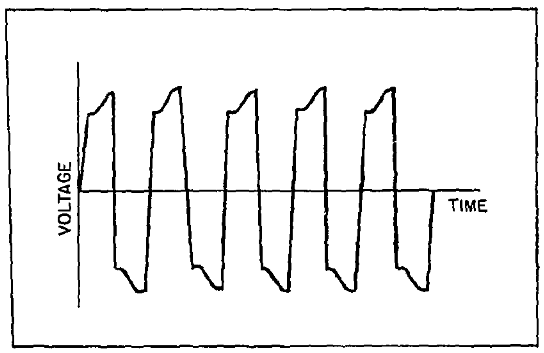


FIGURE 9.4. Typical Ferroresonant Voltage Waveform

at half cycle, one and one half cycle, etc., intervals. The most commonly observed oscillation frequencies are 60 Hz and 20 Hz. Any odd subharmonic of 60 Hz is theoretically possible, whereas ferroresonance above the power frequency cannot occur.

There are several possible solutions to this particular ferroresonance problem:

1. Use Coupling Capacitor Potential Devices (CCPD) rather than PT's. These devices do not have a non-linear magnetizing inductance.
2. Add bus capacitance to reduce the 60-Hz coupled voltage.
3. Add lossy elements to the PT bus.

The third option will be explored here.

PT's generally have a 115 volt line-to-ground wye secondary and a 115 volt line-to-line delta secondary. The delta secondary has an open corner to provide a zero sequence voltage measurement for relaying. The open corner develops 3 E_0, where E_0 is the system zero sequence voltage. To eliminate ferroresonance, a resistor could be added to the open corner of the delta, or a three-phase switched resistor could be added to the wye secondary.

The wye resistors would be switched in soon after the PT is "deenergized." An approximate formula for the maximum resistor size is

$$R_c = X_c \bar{V}_s \tag{9-1}$$

where $\bar{V}_s$ is the per-unit saturated PT voltage, and X_c is the breaker capacitance on a 115-volt base.

The delta resistor is effective only if there is a zero sequence voltage present. There will normally be a small zero sequence unbalance in the system, and there will also be a zero sequence unbalance if the non-linear ferroresonance occurs. The maximum delta resistor size must be determined by experimentation. The resistance should not be less than one ohm, since it will be in the relaying circuit at all times. A one-ohm resistor reduces the measured 3 E_0 by approximately 10%. The delta resistor is not effective in all cases, but it would be simpler and cheaper than the switched wye resistors.

The transformer model is the critical feature of this simulation. EMTP transformer models consist of separate elements to account for the turns ratios and leakage impedances, the core, and the capacitive coupling. These elements may be set up and used independently of one another. Terminal capacitances were used in Case 1 to account for transformer electrostatic coupling. One of the options for modeling the turns ratios and leakage impedances was illustrated in Case 7. In this case, attention will be focused on the core model.

The PT leakage impedances are low and unimportant to the simulation. The turns ratio is 1800 on the 345-kV primary to 1 on the delta and wye secondaries. The nominal secondary voltages are thus 115 volts and 199 volts line-to-line. A .001-ohm leakage inductance is placed in each branch of the star equivalent circuit, with zero winding resistance. The input for this element is shown in

Table 9.1. The EMTP coverts these turns ratios and star equivalent leakage impedances into an admittance matrix for each phase or leg of the PT.

Note the arrangement of node names for each phase. Winding 1 is connected from one 345-kV bus phase to ground, resulting in a three-phase wye-grounded connection. Similarly, winding 2 results in a three-phase wye-grounded secondary. Winding 3 forms an open delta secondary. A closed delta secondary would result by changing THREO to DELTAA on Phase A's winding 3, and connecting Phase C's winding 3 from DELTAC to DELTAA, rather than from DELTAC to ground. Closed delta windings must have a connected load or other path to ground so that their terminal voltages are mathematically defined. If there is no load to be connected, as is the case on many delta tertiary windings, it is sufficient to simply ground one corner of the delta, provided the delta terminal voltages are not of interest. The delta winding currents and the other terminal voltages would still be correct because there is only one connection to ground on the delta winding.

Since ferroresonance is a low frequency phenomenon, the PT electrostatic coupling is unimportant to this simulation and will not be modeled.

The core model will consist of a detailed saturation characteristic. The EMTP models saturation as a piecewise linear function of flux linkage in volt-seconds vs. current in amperes. Transformer manufacturers normally give saturation curves in units of voltage vs. current, based on tests at power frequency. A conversion of voltage to flux linkage is given by

$$\Psi_{peak} = \frac{\sqrt{2}}{\sqrt{3}} \frac{V_{rms\ L-L}}{377} \qquad (9\text{-}2)$$

for 60-Hz transformers. This formula can be applied to the manufacturer's data to perform a point-by-point conversion. However, because the saturation characteristic is nonlinear, a constant $\sqrt{2}$ scaling factor between peak and rms magnetizing current is only approximate. The EMTP contains an auxiliary conversion program which was used in this case. Its use is covered in the Application Guide.

The manufacturer's data for the PT saturation characteristic is presented in Table 9.2, together with the results of the conversion to peak flux linkage and current. The curves of 60-Hz rms voltage vs. current and peak flux linkages vs. current are plotted in Figure 9.5. The characteristic is linear up to .59 per-unit voltage. In the steady-state, the characteristic is represented by a single slope which passes through the .59 per-unit point. The error in current at 1 per-unit voltage is very low. The saturated voltage at 60-Hz is approximately 396.8 kV/345 kV or 1.15 per-unit.

Figure 9.5 also shows two EMTP flux linkage vs. current characteristics. One is obtained by multiplying the manufacturer's rms current data by $\sqrt{2}$. The other is obtained by the EMTP auxiliary program. Except for the first current point at .59 per-unit voltage, the currents on this curve for a given value of flux linkage are higher than on the approximate curve. If 1.0 per-unit voltage is applied to this second curve, a .0187 Ampere rms magnetizing current will flow, which matches the manufacturer's measured data. The rms magnetizing current produced by the approximate curve will be less than the correct value.

While the difference in flux linkage between the two curves given a value of current is small, the difference in current given flux linkage is very significant. The PT ferroresonance is driven by a stiff voltage source, so the EMTP auxiliary program's model is more appropriate and will produce more pessimistic results than the approximate curve.

The representation of flux linkage vs. current rather than voltage vs. current is closer to the physical characteristics of the core. A high magnitude voltage at high frequency has a low flux linkage and may not saturate the core. However, a low frequency or d.c. voltage has a high flux linkage even if the voltage magnitude is small, and the core will be saturated.

Core losses can be represented with a linear resistance in parallel with the saturation characteristic. This combination results in a hysteresis characteristic which approximates the actual core behavior. In this case, core losses were neglected as a conservative assumption. The user is encouraged to simulate core losses to determine their effect on the ferroresonance.

Input cards for the transformer are shown in Table 9.1. The first TRANSFORMER request card contains the coordinates of the linear characteristic used for the core in steady-state calculations, and the linear core loss resistance. The bus name on this card identifies the star point at which the saturation and core loss elements are connected. It may be used as a reference branch on subsequent TRANSFORMER cards. The next set of cards contain the peak current-peak flux linkage points which defined the saturation characteristic, terminated by a "9999" card. Three winding cards follow as described in Case 7. The next two

TRANSFORMER cards reference the exciting branches connected to node X, so that the current-flux linkage points need not be input again. These new exciting branches are connected to nodes Y and Z.

TABLE 9.1

Input Data for the PT Ferroresonance Case

```
C FILE NAME: "PT3": SIMULATE FERRORESONANCE ON A POTENTIAL
C TRANSFORMER CONNECTED TO A 345-KV BUS THROUGH AN SF6 BREAKER WITH
C VOLTAGE GRADING CAPACITORS.
C FIRST MISCELLANEOUS DATA CARD
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    1-8    9-16   17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    0=MH    0=UF
C                  F(HZ)   F(HZ)
  25.E-6      .2     60.       0
C
C SECOND MISCELLANEOUS DATA CARD
C    1-8    9-16   17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C  PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT. DIAGNOS
C 0=EACH  0=EACH   0= NO   0= NO   0= NO   0= NO   0= NO    INTO  ENERG.   PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    0=NO
    3000       5       1       1       1       0       0       1
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8  9-14 15-20 21-26 27-32 33-38 39-44
C   NODE NAMES   REFERENCE  RES.  IND.  CAP.                  (OUTPUT IN COLUMN 80)
C                   BRANCH          MH    UF                                 I=   1
C   BUS1  BUS2  BUS3  BUS4   OHM   OHM  UMHO                                 V=   2
C                                                                            I,V  3
C                                                                            P,E  4
  SRCE ABUS  A                          .00065
  SRCE BBUS  BSRCE ABUS  A
  SRCE CBUS  CSRCE ABUS  A
  BUS  A                                .00015
  BUS  B       BUS  A
  BUS  C       BUS  A
C MUTUALLY COUPLED R,L CIRCUITS
C 3456789012345678901234567890123456789012345678890
C                           27-32 33-38
C                           RO,R1 LO,L1
51THEV ASRCE A                    10.60
52THEV BSRCE B                     6.64
53THEV CSRCE C
C
C TRANSFORMER
C 3456789012345678901234567890123456789012345678890
C        3-13  15-20        27-32 33-38 39-44 45-50
C REQUESTWORD REF.BUS  STEADY I,  FLUX   BUS R-MAG
  TRANSFORMER                .002 439.23     X
C
C           1-16            17-32
C        CURRENT            FLUX
           .0020           439.23
           .0043           549.04
           .0077           604.05
           .0108           658.84
           .0153           680.93
           .0240           713.86
           .0342           732.91
           .0540           755.00
           .0688           774.28
           .1143           793.34
           .1511           807.20
           .1904           818.03
           .2650           834.71
           .3561           845.54
           .5639           859.40
            9999
C TRANSFORMER WINDINGS
```

TABLE 9.1 (Cont'd)

Input Data for the PT Ferroresonance Case

```
C COLUMN 1,2: WINDING NUMBER
C 345678901234567890123456789012345678901234567890
C     3-8  9-14                 27-32 33-38 39-44
C    BUS1  BUS2                   R-K   L-K TURNS
 1BUS  A                              .00100 1800.
 2WYE  A                              .00100    1.
 3THREO DELTAB                        .00100    1.
  TRANSFORMER         X                         Y
 1BUS  B
 2WYE  B
 3DELTABDELTAC
  TRANSFORMER         X                         Z
 1BUS  C
 2WYE  C
 3DELTAC
C LOAD RESISTANCE TO ELIMINATE FERRORESONANCE
C CONNECTED IN OPEN DELTA CORNER
C
C THREO                     1.0
C CONNECTED ON PT WYE SECONDARY
C
C WYE   ALOAD A             1.5
C WYE   BLOAD BWYE  ALOAD A
C WYE   CLOAD CWYE  ALOAD A
BLANK CARD TERMINATING BRANCH CARDS
C SWITCH CARDS
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C    3-8  9-14      15-24      25-34      35-44      45-54      55-64      65-74
C                                                          (OUTPUT OPTION IN COLUMN 80)
C    NODE NAMES                            IE FLASHOVER    SPECIAL    REFERENCE
C                 TIME TO    TIME TO       OR   VOLTAGE    REQUEST SWITCH-NAME
C    BUS1  BUS2     CLOSE       OPEN    NSTEP                 WORD  BUS5  BUS6
  SRCE ABUS  A        -1.       .020                                              3
  SRCE BBUS  B        -1.       .020                                              3
  SRCE CBUS  C        -1.       .020                                              3
C LOAD A            .040        1.00
C LOAD B            .040        1.00
C LOAD C            .040        1.00
BLANK CARD TERMINATING SWITCH CARDS
C SOURCE CARDSS
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C COLUMN 1,2: TYPE OF SOURCE 1 - 17,(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: O=VOLTAGE SOURCE, -1=CURRENT SOURCE
C     3-8         11-20    21-30     31-40     41-50     51-60     61-70     71-80
C    NODE    AMPLITUDE FREQUENCY TO IN SEC   AMPL-A1   TIME-T1   T-START    T-STOP
C    NAME                 IN HZ       DEGR               SECONDS   SECONDS   SECONDS
14THEV A      281691.      60.0        0.                            -1.0
14THEV B      281691.      60.0      240.                            -1.0
14THEV C      281691.      60.0      120.                            -1.0
BLANK CARD TERMINATING SOURCE CARDS
C NODE VOLTAGE OUTPUT
C 34567890123456789012345678901234567890123456789012345678901234567890123456789O
C    3-8   9-14 15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C    BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  BUS  ABUS  BBUS  C
BLANK CARD TERMINATING NODE VOLTAGE OUTPUT
  CALCOMP PLOT
 2 PT FERRORESONANCE WITH NO COUNTERMEASURES
 143.02     .200          BUS  A
 143.02     .200          BUS  B
 143.02     .200          BUS  C
BLANK CARD TERMINATING PLOTTING
BLANK CARD TERMINATING THE CASE
```

TABLE 9.2

PT Saturation Curve

Manufacturer's Data		EMTP Model	
L-L Voltage In kV RMS	Magnetizing Current In A rms x $\sqrt{2}$	Peak Flux In V-Sec	Peak Magnetizing Current In Amperes
202.8	.0020	439.26	.0020
253.5	.0035	549.07	.0043
278.9	.0055	603.98	.0077
304.2	.0080	658.85	.0108
314.4	.0100	680.85	.0153
329.6	.0150	713.79	.0240
338.4	.0200	733.01	.0342
348.6	.0300	754.97	.0540
357.5	.0400	774.19	.0688
366.3	.0600	793.41	.1143
372.7	.0800	807.14	.1511
377.7	.1000	818.12	.1904
385.4	.1400	834.59	.2650
390.4	.1800	845.57	.3561
396.8	.3000	859.30	.6639

Equivalent source reactances of 6.64 ohms and 10.6 ohms were assumed for the positive and zero sequences, respectively. These are equivalent to three-phase fault and line-to-ground fault currents of 30 kA and 25 kA, respectively.

It is assumed that the grading capacitor across the open breaker has a value of 650 pF. The capacitance of the 345-kV PT bus was assumed to be 150 pF.

To estimate the maximum size of wye-connected resistor using equation 9-1, the effective saturated voltage as modeled is approximately 396.8 kV, or 1.15 per-unit. The breaker capacitive reactance is 4.08 MΩ on a 345-kV base, or 1.26 ohms after an 1800:1 voltage transformation. The estimated critical resistance is then 1.15 x 1.26 or 1.45 ohms.

Figure 9.6 shows the circuit and node names as represented in the EMTP.

Table 9.1 shows the input data for a case without load resistors. A time step smaller than one degree at 60 Hz is needed, even though ferroresonance is a low-frequency phenomena, because the simulation is highly nonlinear.

Figure 9.7 shows ferroresonance occurring after the breaker contacts part at 20 milliseconds. Ferroresonance begins immediately after the breaker opens, at a frequency of 20 Hz. Figure 9.8 shows the PT magnetizing current during ferroresonance. The large current pulses accompany opposite-polarity changes in the core saturation.

In Figure 9.9, 1.5-ohm resistors are switched into the PT wye secondary at 40 milliseconds. Phase B shows the onset of ferroresonance, although the peak voltage magnitude is less than 1 per unit after the resistors are switched in, compared to 2.25 per unit in Figure 9.7. Phase A of the PT bus was stable for this case as shown in Figure 9.10. The Phase C voltage began ferroresonance, but was stabilized after the resistors were switched in, as shown in Figure 9.11. Note that the simulated 1.5-ohm resistors are slightly larger than the estimated 1.45 ohms. However, this situation may be acceptable due to the low voltage magnitudes.

In Figure 9.12, 1-ohm resistors are switched into the wye secondary. Ferroresonance begins in Phases B and C immediately after the breaker opens, but all phases are stable once the resistors are switched in. In Figures 9.9 through 9.12, the 60-Hz coupled voltage is less than the expected value of .81 per unit because of the load resistors.

Figures 9.13 and 9.14 show that the delta resistors are ineffective in this case. Values of 1 ohm and .5 ohms were investigated.

These EMTP cases ran in approximately 8 seconds on a CRAY 1S computer.

Suggested investigations:

- Explore the effect of time step size in the first case without load resistors. Ferroresonance is a highly nonlinear phenomena, and a proper step size is crucial to obtaining a valid numerical solution.
- Increase the 150 pF bus capacitance in the case without load resistors.
- Add transformer core and winding losses to the case without load resistors.
- With one ohm in the delta corner, find out what amount of system zero sequence voltage unbalance is needed to make this solution effective.

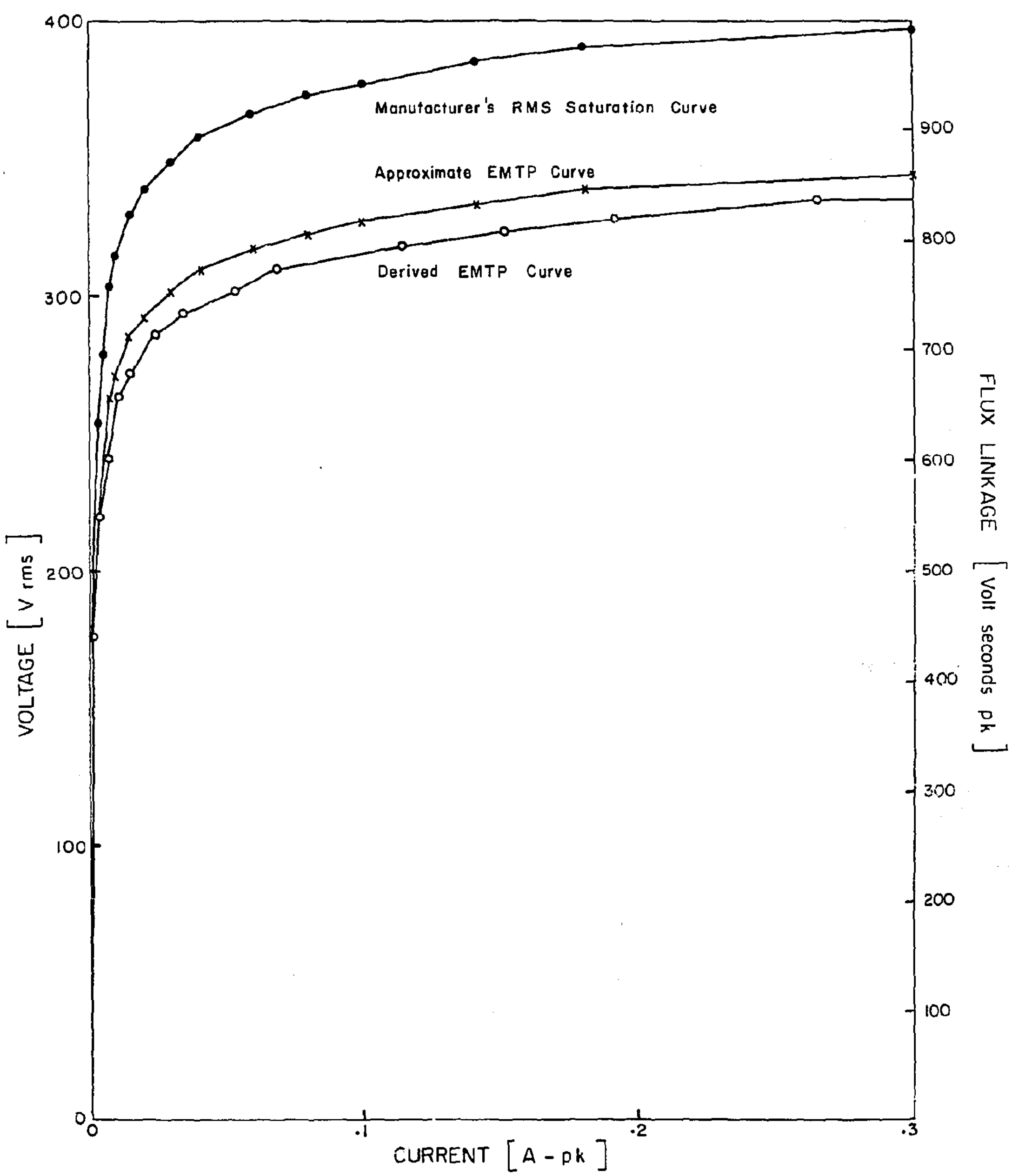


FIGURE 9.5. PT Saturation Characteristic

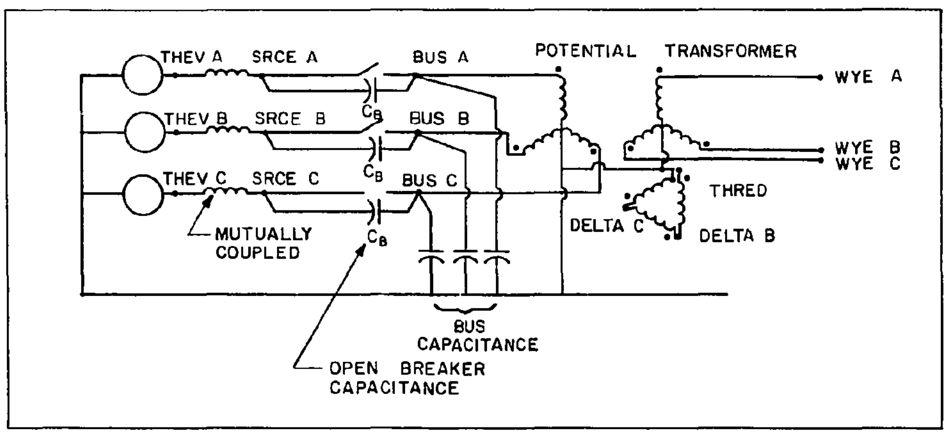


FIGURE 9.6. Circuit Diagram and Node Names

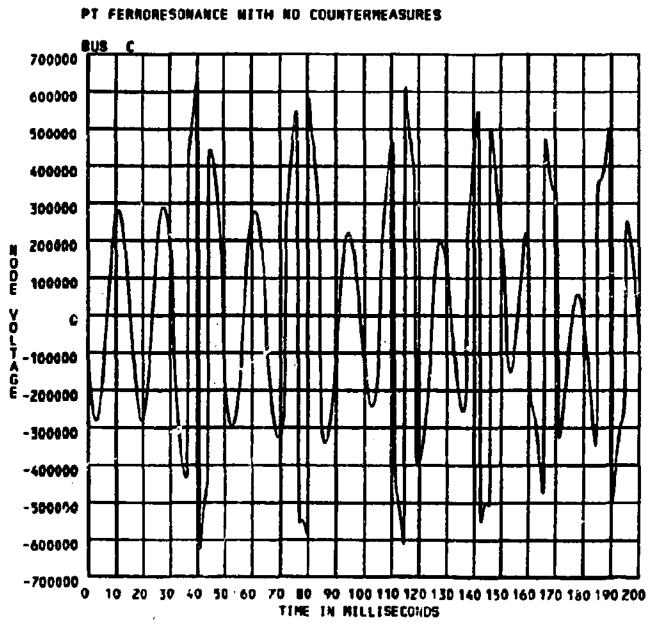


FIGURE 9.7. Phase C PT Bus Voltage with No Load Resistors

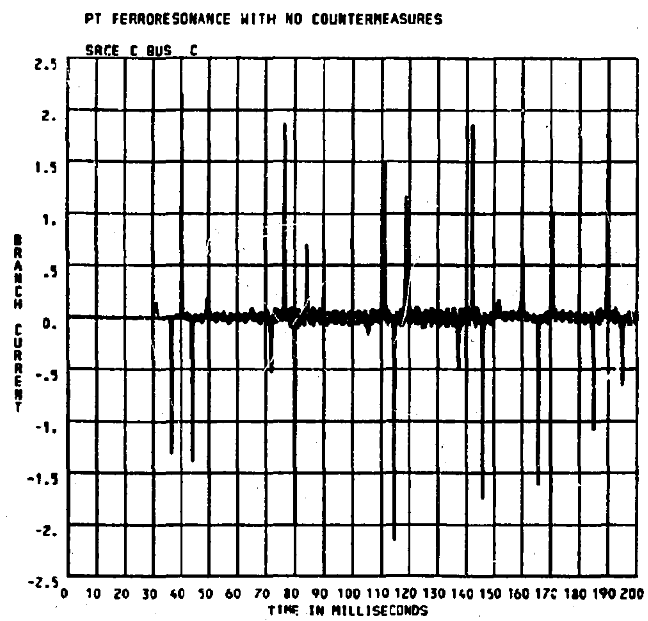


FIGURE 9.8. Phase C Magnetizing Current with No Load Resistors

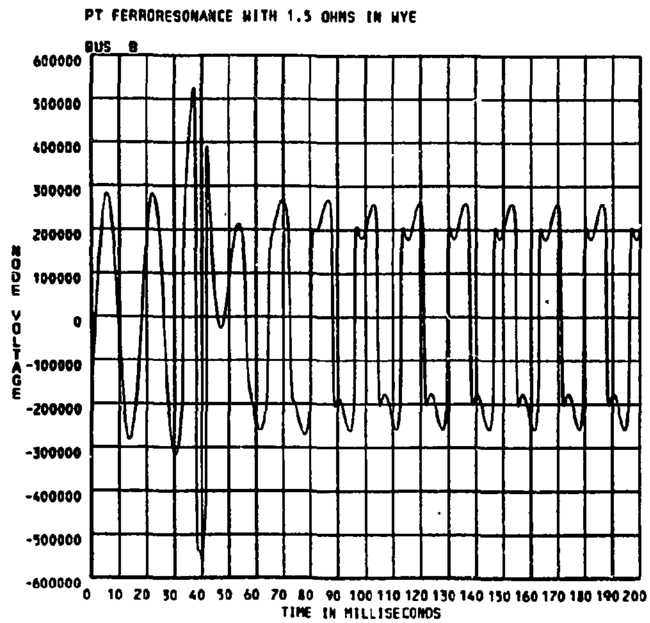


FIGURE 9.9. Phase B PT Bus Voltage with 1.5 Ohms in Wye

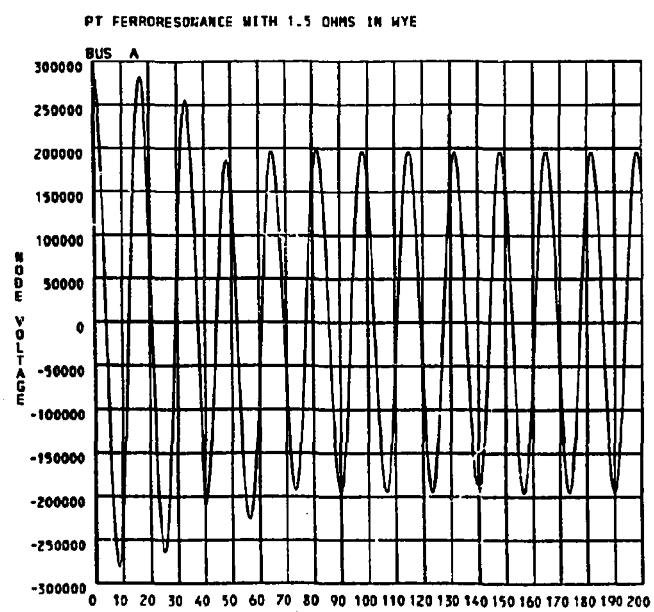


FIGURE 9.10. Phase A PT Bus Voltage with 1.5 Ohms in Wye

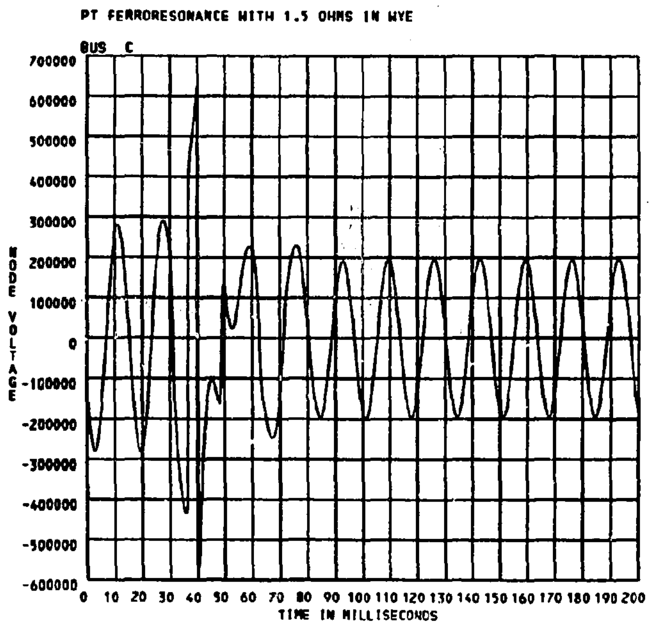


FIGURE 9.11. Phase C PT Bus Voltage with 1.5 Ohms in Wye

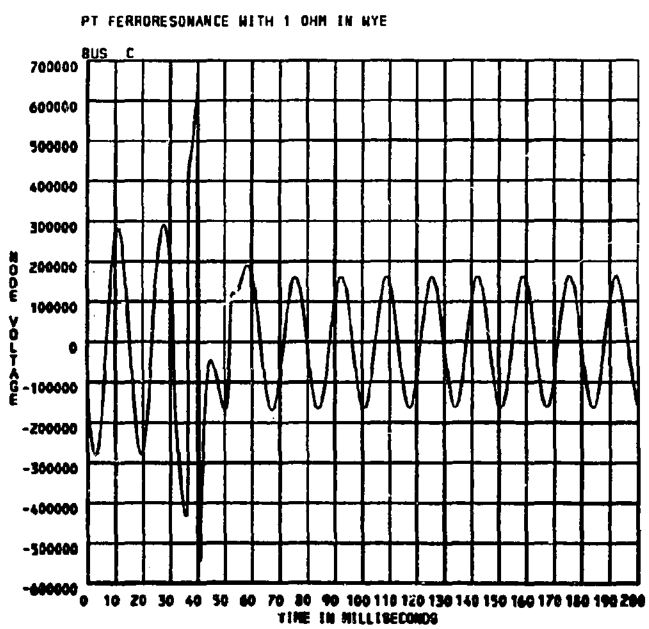


FIGURE 9.12. Phase C PT Bus Voltage with 1.0 Ohms in Wye

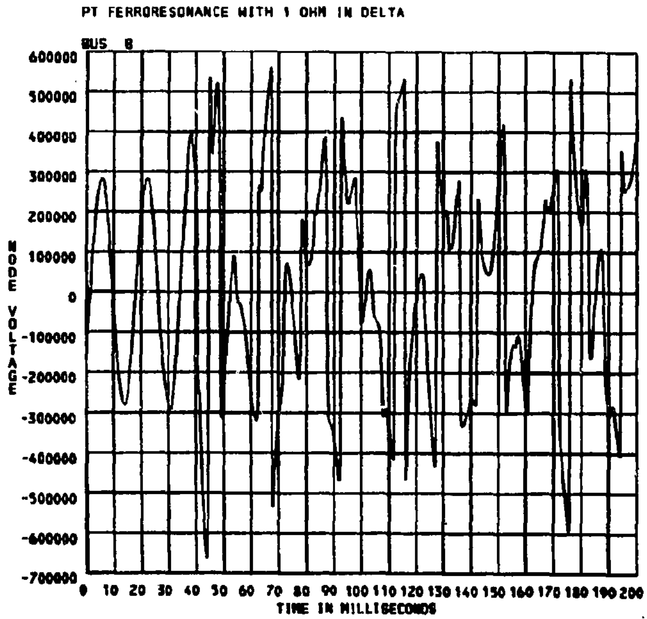


FIGURE 9.13. Phase B PT Bus Voltage with 1.0 Ohms in Delta

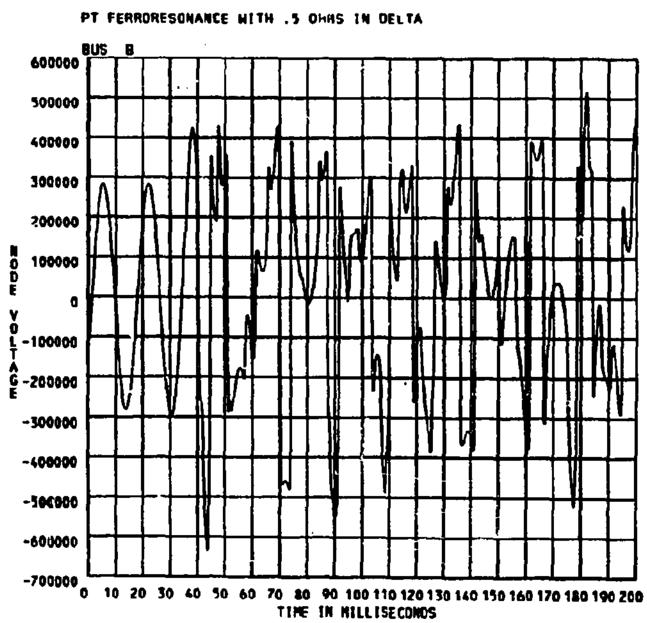


FIGURE 9.14. Phase B PT Bus Voltage with .5 Ohms in Delta

Section 10

CASE 10: SUBSYNCHRONOUS RESONANCE STUDIES

The primary objective of this study is to determine countermeasures for unstable shaft torsional oscillations in turbine-generator units. Plots of the mechanical shaft torques are the EMTP outputs of most interest. New EMTP models introduced in this study include the three-phase synchronous machine and sparkover gaps.

Subsynchronous resonance (SSR) is an unstable exchange of energy between the mechanical shaft system of a turbine-generator (TG) and the series capacitor compensated transmission system to which it is connected. This interaction occurs at natural frequencies less than the power frequency, hence, the term "subsynchronous." The series compensation may be expressed as a percentage of the line impedance, and it is always less than 100%. The resulting natural frequency of the series LC circuit is given by $60 \sqrt{\% \text{ comp}/100}$, and it is always less than 60 Hz. Similarly, the TG shaft system has natural frequencies less than 60 Hz. Oscillations involving the series capacitors and the TG shaft system give rise to SSR.

Two shaft failures were attributed to SSR in 1970, and since then much effort has been made to develop SSR countermeasures and analysis techniques. No failures attributed to SSR have occurred since 1970, but SSR studies are now a common aspect of system planning in the Western United States and in other countries which use series capacitors.

SSR can occur in two manifestations, namely self-excitation and torque amplification. Self-excitation occurs when a small perturbation in the system leads to an unstable buildup of shaft torque oscillations, occurring over a period of several seconds or longer. Torque amplification occurs after large disturbances such as fault initiation and clearing. The system may eventually be stable, but transient shaft torques can still reach high levels and cause significant fatigue loss-of-life. A third aspect of SSR, which is electrical self-excitation or the induction generator effect, has been eliminated in practical cases by the use of machine damper windings.

The sample study presented here is based on a benchmark system for SSR studies documented in Reference (18). Further information on SSR can be obtained from Reference (19).

Self-excitation is most conveniently analyzed in the frequency domain, either by directly calculating eigenvalues or by approximating them with a frequency scanning technique. However, use of the EMTP to obtain similar results will be illustrated. At present, torque amplification studies can only be made by using the EMTP or a similar time domain program. This type of study will also be illustrated here.

The primary EMTP model feature introduced here is the synchronous machine model with a lumped mass mechanical system. This capability was originally developed for SSR studies. For torque amplification studies, a flashover gap model is also introduced.

The machine model data is input with the other sources. Conventional two-axis stability data describes the electrical portion of the model. The mechanical data is input as lumped inertias, springs, and damping coefficients in English units. The outputs are in physical units, similar to other EMTP models. A post processing program is used in the study to rescale the shaft torques to per-unit values.

From Reference (18), the machine's electrical data is presented in Table 10.1.

TABLE 10.1

TG Electrical Parameters

600 MVA, 22 KV rating

$X_L = X_0 =$ .14		
$R_a =$ .0045		
$X_d =$ 1.65	T'_{do}	= 4.5 seconds
$X'_d =$ .25	T''_{do}	= .04 seconds
$X''_d =$ .20	T'_{qo}	= .55 seconds
$X_q =$ 1.59	T''_{qo}	= .09 seconds
$X'_q =$ .46		
$X''_q =$ .20		

The shaft system data, in units accepted by the EMTP, is presented in Table 10.2.

TABLE 10.2

TG Mechanical Parameters

Mass	Inertia [million lbm-ft^2]	Damping [lbf-ft-sec/rad]	Spring [million lbf-ft/rad]
Exciter (EXC)	.001383	4.3	
			4.39
Generator (GEN)	.176204	547.9	
			97.97
Low Pressure (LP) Turbine	.310729	966.2	
			50.12
High Pressure (HP) Turbine	.049912	155.2	

Damping is the result of a mass's deviation from synchronous speed in radians per second. The machine has 2 poles, and each turbine is assumed to develop 50% of the mechanical power.

Analogous to a transmission line which has several independent travelling wave modes, the shaft system's natural frequencies and mode shapes can be calculated by solving an eigenvalue problem. The first mode always occurs at 0 Hz, and plays no part in SSR studies. The remaining modal frequencies for the unit studied are 24.65 Hz, 32.39 Hz, and 51.10 Hz. If the damping values from Table 10.2 are considered, each of the three modes has a damping coefficient σ = .05 rad/sec. In terms of the time periods usually simulated on the EMTP, this damping is very small and is often omitted.

Based on frequency domain analyses documented in Reference (18), a 55% compensation level was chosen for the series compensated line to achieve maximum undamping at the first mechanical mode frequency of 24.65 Hz. The energy exchange occurs in the machine air gap at complementary mechanical and electrical frequencies. The relevant electrical natural frequency is, therefore, 60-24.65 = 35.35 Hz. For this mode of oscillation to be stable, a modal damping of .40 rad/sec would have to be present according to Reference (18). This is eight times the natural damping assumed in Table 10.2.

The electrical system data are given in Figure 10.1, with the impedances in physical ohms. The machine is operated at rated terminal voltage and no load. It is necessary to provide values of field current to produce rated voltage on the air gap line and 1.2 per-unit voltage on the saturation characteristic. These values were estimated as 1970 amperes and 2600 amperes, respectively, based on similar size machines.

The machine and system input data are shown in Table 10.3. The delta-wye stepup transformer requires a 30 degree difference between generator terminal voltage and infinite source voltage to achieve zero power flow over the lines. On the delta side, the line-to-ground leakage impedance is multiplied by three to account for the delta connection. The switches shown in Table 10.3 initiate a three-phase fault on the remote line end bus starting at time zero and clear it within one half cycle.

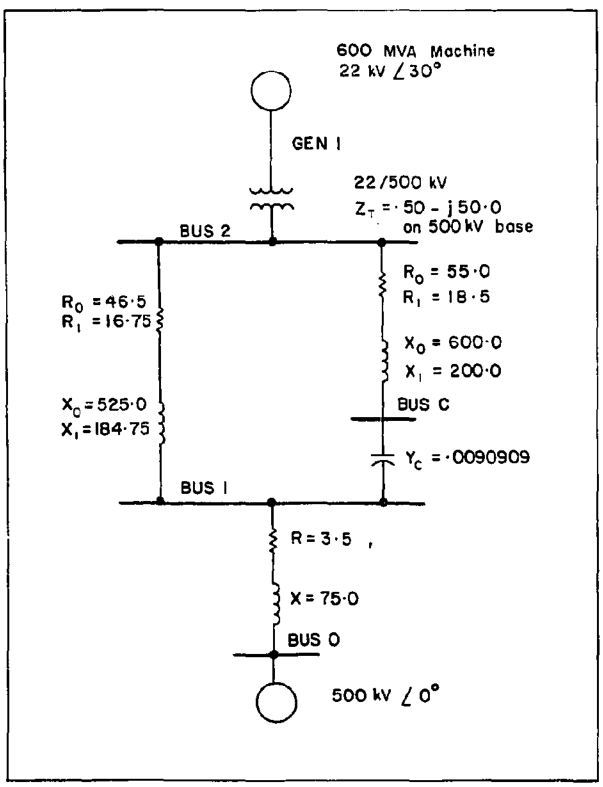


FIGURE 10.1. Second IEEE Benchmark System for SSR Studies

TABLE 10.3

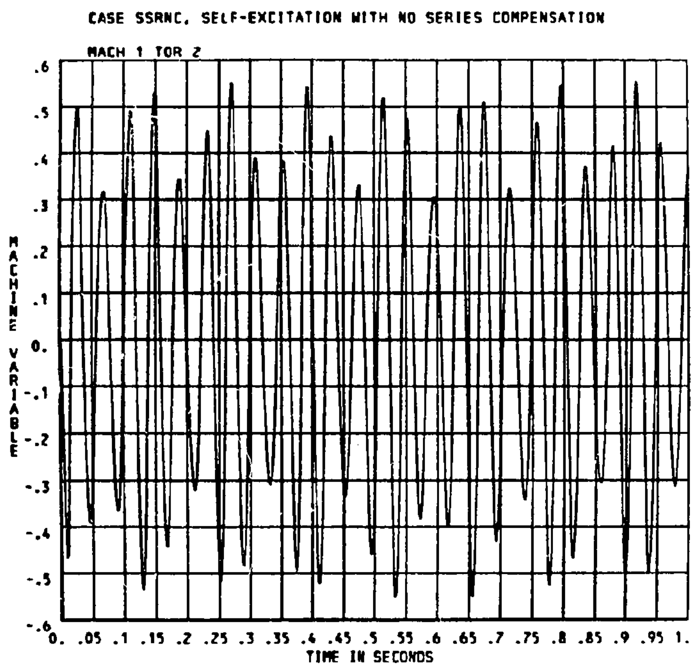
EMTP Input Data for Self-Excitation Case

```
C FILENAME: "SSRD": SIMULATES SELF-EXCITATION PROBLEMS IN IEEE
C SECOND BENCHMARK SYSTEM FOR SSR STUDIES. 55% SERIES COMPENSATION.
BEGIN NEW DATA CASE
C DELTA T    TMAX    FREQUENCY FOR XL AND YC
 200.E-6       1.       60.       60.
C OUTPUT CONTROL PARAMETERS
   20000         9         1         1         1         0         0         1
C UNCOMPENSATED TRANSMISSION LINE
C                            RO AND R1     XO AND X1
51BUS2 ABUS1 A                 46.5          525.0
52BUS2 BBUS1 B                16.75         184.75
53BUS2 CBUS1 C
C COMPENSATED LINE
C                               RO AND R1        XO AND X1
51BUS2 ABUSC A                  55.0         600.0
52BUS2 BBUSC B                  18.5         200.0
53BUS2 CBUSC C
C 55 % SERIES CAPACITORS
C                                           MICROMHOS                     VOLTAGE OUTPUT
  BUSC ABUS1 A                              9090.9                                     2
  BUSC BBUS1 B                              9090.9                                     2
  BUSC CBUS1 C                              9090.9                                     2
C SOURCE IMPEDANCE TO INFINITE BUS
C                               RSELF,XSELF - RO=R1 AND XO=X1
  BUS1 ABUSO A                  3.5  75.0
  BUS1 BBUSO B                  3.5  75.0
  BUS1 CBUSO C                  3.5  75.0
C GENERATOR STEPUP TRANSFORMER (NO MAGNETIZING IMPEDANCE)
  TRANSFORMER                               WNDG1
            9999
C                                 R      X      N
 1GEN1 AGEN1 B                .0015  .1452   22.0
 2BUS2 A                         .25   25.0288.67
C SECOND AND THIRD TRANSFORMER WINDINGS USE SAME DATA
  TRANSFORMER   WNDG1                       WNDG2
 1GEN1 BGEN1 C
 2BUS2 P
  TRANSFORMER   WNDG1                       WNDG3
 1GEN1 CGEN1 A
 2BUS2 C
C CONNECTIVITY CAPACITORS FOR GENERATOR TERMINALS AND DELTA WINDING
C                                           MICROMHOS
  GEN1 A                                    10.0
  GEN1 B                                    10.0
  GEN1 C                                    10.0
BLANK CARD ENDING BRANCH DATA
C FAULT SWITCHES
C             CLOSING TIME    CLEARING TIME
  BUS1 A             .00         .0002
  BUS1 B             .OC         .0002
  BUS1 C             .00         .0002
BLANK CARD ENDING SWITCH DATA
C INFINITE BUS SOURCE VOLTAGE
C                 UDE         FREQUENCY   PHASE ANGLE              ACTIVE IN S.S.
14BUSO A   408248.290          60.          0.                          -1.0
14BUSO B   408248.290          60.        240.                          -1.0
14BUSO C   408248.290          60.        120.                          -1.0
C GENERATOR INPUT DATA
C    PEAK TERMINAL VOLTS, FREQUENCY, ANGLE
59GEN1 A   17962.9248          60.       -30.
59GEN1 B
59GEN1 C
C CONTROL CARD TO OPTIMIZE UNSPECIFIED MODEL PARAMETERS
PARAMETER FITTING               2.0
C                                      RATED MVA AND KV        FIELD CURRENT
 4  2  1    2                          600.          22.      1970.       1970.       2600.
C        RA           XL           XD           XQ           XD'          XQ'         XD''         XQ''
      .0045          .14         1.65         1.59          .25          .46          .20          .20
C       TDO'         TQO'        TDO''        TQO''          XO
         4.5          .55          .04          .09          .14
```

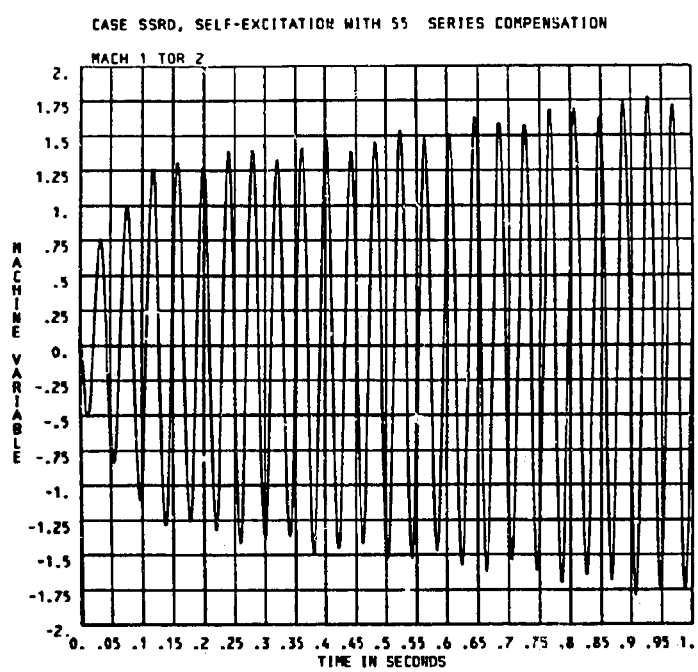
TABLE 10.3 (Cont'd)

EMTP Input Data for Self-Excitation Case

```
C SHAFT SYSTEM DATA
C MASS NUMBER    TORQUE INERTIA     SPEED DEV.              SPRING
C                 FRACTION          DAMPING                 CONSTANT
 1                       .001383                             4.39
 2                       .176204                            97.97
 3                  .5   .310729                            50.12
 4                  .5   .049912
BLANK CARD ENDING MASS DATA
C OUTPUT DATA REQUESTS FOR THE GENERATOR
C GROUP 1 = ELECTRICAL VARIABLES
C  1=ID, 2=IQ, 3=IO, 4=IF, 5=IKD, 6=IG, 7=IKQ, 8=IA, 9=IB
C  10=IC, 14=TQ GEN
  1          1     2     3     4     5     6     7     8     9
  1         10    14
C GROUP 2 = MECHANICAL ANGLES
C  SECOND MASS (GENERATOR ROTOR)
  2          2
C GROUP 3 = MECHANICAL SPEED DEVIATIONS
C  SECOND MASS (GENERATOR ROTOR)
  3          2
C GROUP 4 = SHAFT TORQUES
C  ALL THREE SHAFTS
  4          1     2     3
C GROUP 5 = STEADY STATE OUTPUTS
C  1 = MACHINE PARAMETERS
C  2 = INITIAL CONDITIONS
  5          1     2
BLANK CARD ENDING OUTPUT
C END OF GENERATOR INPUT DATA
  FINISH
BLANK CARD ENDING ALL SOURCE DATA
  GEN1 AGEN1 BGEN1 CBUS2 ABUS2 BBUS2 C
BLANK CARD ENDING NODE VOLTAGE OUTPUT REQUESTS
  CALCOMP PLOT
 2 SECOND IEEE BENCHMARK SYSTEM, CASE SSRD
 193.10      1.         MACH 1TQ GEN
 193.10      1.         MACH 1TOR 2
BLANK CARD ENDING PLOT REQUESTS
BLANK CARD TERMINATING ALL CASES
```

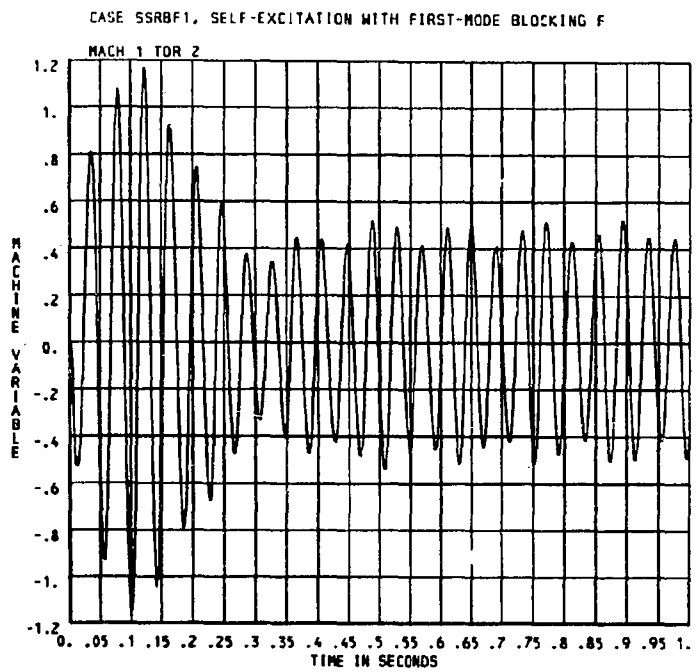


a) No Series Compensation



b) 55% Series Compensation

FIGURE 10.2. GEN-LP Shaft Torques for Self-Excitation Cases



c) 55% Series Compensation With Static Blocking Filter

FIGURE 10.2. (Cont'd). GEN-LP Shaft Torques for Self-Excitation Cases

This scenario is used to investigate self-excitation stability. The frequencies of interest are 60 Hz or less, and .6 seconds of real time are simulated. The time step is accordingly chosen to be somewhat long, 125 microseconds. The main requirement is that the machine model be numerically stable during the simulated period.

The GEN-LP shaft torque, which is denoted "MACH 1 TOR 2" in the list of output variables, is plotted in Figure 10.2 for three self-excitation cases. In the first case, there are no series capacitors. The predominant frequency of oscillation is approximately 25 Hz, because the predominant mode of vibration for this shaft is the first mode. However, the oscillations do not appear to be unstable.

In the second case, with 55% series compensation, the oscillations appear to be growing. This agrees with the prediction of instability from the frequency domain analysis in Reference (18).

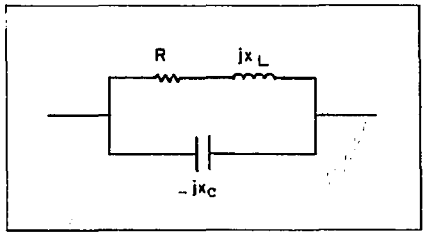


FIGURE 10.3. Static Blocking Filter

The third case illustrates a damped shaft torque for the 55% compensated system with a static filter in series with the generator stepup transformer. This type of filter is usually connected between ground and the transformer neutral terminal in each phase. As a result, the voltage rating requirements of the filter components are minimized. The schematic of this filter is shown in Figure 10.3.

The filter should provide enough positive damping at the torsional mode in question (in our case, 24.65 Hz) and have negligible power loss at 60 Hz. The first step in filter design is to calculate the damping, σ_e, from the electrical system due to modal interaction at the subsynchronous frequency. This parameter is given by:

$$\sigma_e = -\frac{f_e}{8\, f_m\, H_m} \cdot \frac{R_s}{R_s^{\,2} + X_s^{\,2}} \tag{10-1}$$

at resonance X ς 0

$$\sigma_e = -\frac{f_e}{8\, f_m\, H_m} \cdot \frac{1}{R_s} \tag{10-2}$$

H_m = modal inertia

f_e = electrical resonance frequency

f_m = modal frequency ($f_m = 60 - f_e$)

where R_s and X_s are the total resistance and reactance as seen from behind the generator terminals. As may be noted from the equations, σ_e will be negative for positive values of R_s. This indicates negative damping, which will lead to unstable oscillations or self-excitation.

The total damping, σ_t, of the system at any torsional mode is the sum of the mechanical damping provided by turbine and shaft system (σ_m) plus the electrical damping (σ_e).

$$\sigma_t = \sigma_m + \sigma_e \tag{10-3}$$

If the total damping is negative, it is possible to add external system resistance which increases the denominator in equation 10-2. This will decrease the negative value of σ_e in equation 10-3 until it becomes smaller than σ_m. Therefore, even though the electrical system is still acting to undamp the subsynchronous oscillations, the total damping will be positive.

The tuned filter in Figure 10.3 can be designed to increase R_s at the resonant frequency so that the magnitude of σ_e is reduced to the desired level. The minimum value of R_s to provide positive total damping can be calculated by substituting σ_t for σ_e in equation 10-2. This accounts for the beneficial effect of natural mechanical damping.

$$R_S \geq - \frac{f_e}{(\sigma_m + \sigma_e)\ 8\ f_m\ H_m} \tag{10-4}$$

After calculating the net undamping of the turbine generator and the transmission system from an EMTP, Frequency Scan, or Eigenvalue analysis case, the parameters of the filter can be determined, as in the example below.

From Reference (18), assume that $\sigma_m + \sigma_e = -.4$ rad/sec and that the modal inertia = 1.55 p.u.. The quality factor of available reactors = 150. Design to block the first mode (f_m = 24.65 Hz).

Using these values to calculate the filter resistance, we get:

$$R_S = - \frac{(35.35)}{(24.65)(8)(1.55)(-.4)} = .289 \text{ per unit on generator base (22 kV, 600 MVA)} \tag{10-5}$$

Converting to physical units on a 500-kV base

$$R_S = - \frac{500 \times 500 \times .289}{600} = 120\ \Omega \tag{10-6}$$

To achieve stability from self-excited SSR the positive filter resistance should be equal to or larger than 120 Ω, for example, 1000 Ω. The larger filter resistance will result in more damping. The higher resistance will also require lower Q reactors, which may reduce the total filter cost.

The filter model parameters are calculated as follows:

$$X_{L_{60}} = \frac{R_s}{Q} \left(\frac{60}{60 - f_m}\right)^2 \tag{10-7}$$

$$= \frac{1000}{150} \left(\frac{60}{35.35}\right)^2 = j\ 19.2\ \Omega$$

$$X_{C_{60}} = X_{L_{60}} \left(\frac{60 - f_m}{60}\right)^2 \tag{10-8}$$

$$= 19.2 \left(\frac{35.35}{60}\right)^2 = -\ j\ 6.66\ \Omega$$

$$= 150.15\ \mu\text{mhos}$$

$$R = \frac{X_{L_{60}}}{Q} = \frac{19.2}{150} = .128\ \Omega \tag{10-9}$$

The final parameters for the filter are shown in Figure 10.4.

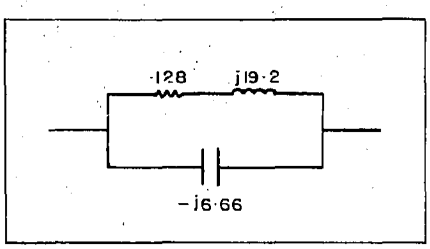


FIGURE 10.4. Filter Parameters for First Mode Damping

The portion of EMTP branch input data for this filter is presented in Table 10.4. The filter is connected from the high-side neutral terminals of the stepup transformer to ground.

To provide complete protection against self-excitation, a filter would be designed for each torsional mode, and all filters would be cascaded in series with the stepup transformer.

To focus on torque amplification problems, the same 55% compensated system was used with sufficient TG damping to eliminate the self-excitation problem. Since .4 rad/sec modal damping is required, the mass speed deviation dampings in Table 10.2 were multiplied by 8 to stabilize the system. A .1 mH three-phase fault was applied on BUS 2, with initiation at 18 milliseconds and a variable clearing time. The fault initiation time corresponds to a negative peak of the phase A generator terminal voltage. It will be shown that the fault clearing time has a significant effect on the ensuing transient torques.

Figure 10.5 depicts a case with the fault cleared after 17 milliseconds. Note that the first mode oscillation frequency of 24.65 Hz has a period of 40.6 milliseconds. The fault initiation and clearing transients represent opposite polarity shocks to the machine air gap torque, and they occur approximately one-half cycle apart at the first mode natural frequency.

For these switching times, the fault initiation and clearing will reinforce the first mode oscillations. The GEN-LP shaft torque builds up to a high level and then becomes marginally stable. The air gap torque and series capacitor voltages both show large forcing functions at the first mode's complementary frequency, which then decay to a low but sustained level. This illustrates transient torque amplification in a stable system.

To convert the shaft torque outputs from million newton-meters to per-unit, the following torque base can be calculated:

$$T_{base} = 3\ (\lambda_{base})(I_{base}) \qquad (10\text{-}10)$$

$$\lambda_{base} = (22000\ \text{volts})/(377\ \sqrt{3}) = 33.692\ \text{volt-sec} \qquad (10\text{-}11)$$

$$I_{base} = \frac{600\ \text{MVA}}{\sqrt{3} \times 22\ \text{kV}} = 15{,}746\ \text{amps} \qquad (10\text{-}12)$$

$$T_{base} = 3(33.692)(15746) = 1.592\text{x}10^6 \text{ nt-m} \tag{10-13}$$

The shaft torques should be per-unitized on their rated torques at full load. Assuming each turbine develops 50% of the power, the HP-LP torque should be per unitized on one-half of the machine base calculated above, while the GEN-LP torque should be based on the full machine torque base.

TABLE 10.4

EMTP Branch Cards for First Mode Blocking Filter

```
C FILENAME: "SSRBF1": SIMULATES FIRST MODE BLOCKING FILTER FOR SELF-
C EXCITATION PROBLEMS IN IEEE SECOND BENCHMARK SYSTEM FOR SSR
C STUDIES
BEGIN NEW DATA CASE
C DELTA T   TMAX   FREQUENCY FOR XL AND YC
 200.E-6      1.     60.      60.
C OUTPUT CONTROL PARAMETERS
   20000       9       1       1       1       0       0       1
C UNCOMPENSATED TRANSMISSION LINE
C                           RO AND R1      XO AND X1
51BUS2 ABUS1 A               46.5         525.0
52BUS2 BBUS1 B              16.75        184.75
53BUS2 CBUS1 C
C 3456789A123456789B123456789C12345K789D123456789E123456789F1C3456789G
C        BLOCKING FILTER #1
C           EFFECTIVE R OF FILTER =1000 OHMS
C        10        20        30        40        50        60        70
  FILTRA                    .1280 19.2
  FILTRB                    .1280 19.2
  FILTRC                    .1280 19.2
  FILTRA                              1501E4
  FILTRB                              1501E4
  FILTRC                              1501E4
C COMPENSATED LINE
C                           RO AND R1      XO AND X1
51BUS2 ABUSC A              55.0          600.0
52BUS2 BBUSC B              18.5          200.0
53BUS2 CBUSC C
C 55 % SERIES CAPACITORS
C                                     MICROMHOS                  VOLTAGE
  BUSC ABUS1 A                        9090.9                                  2
  BUSC BBUS1 B                        9090.9                                  2
  BUSC CBUS1 C                        9090.9                                  2
C SOURCE IMPEDANCE TO INFINITE BUS
C                           RSELF     XSELF - RO=R1 AND XO=X1
  BUS1 ABUSO A               3.5  75.0
  BUS1 BBUSO B               3.5  75.0
  BUS1 CBUSO C               3.5  75.0
C GENERATOR STEPUP TRANSFORMER
  TRANSFORMER                          WNDG1
          9999
C                             R     X     N
 1GEN1 AGEN1 B             .0015 .1452  22.0
 2BUS2 AFILTRA               .25  25.0288.67
C SECOND AND THIRD TRANSFORMER WINDINGS USE SAME DATA
  TRANSFORMER  WNDG1                   WNDG2
 1GEN1 BGEN1 C
 2BUS2 BFILTRB
  TRANSFORMER  WNDG1                   WNDG3
 1GEN1 CGEN1 A
 2BUS2 CFILTRC
C CONNECTIVITY CAPACITORS FOR GENERATOR TERMINALS AND DELTA WINDING
C                                     MICROMHOS
  GEN1 A                              10.0
  GEN1 B                              10.0
  GEN1 C                              10.0
BLANK CARD ENDING BRANCH DATA
```

TABLE 10.5

EMTP Branch and Switch Cards for Series Capacitor Bypass Gaps

```
BEGIN NEW DATA CASE
C DELTA T    TMAX    FREQUENCY FOR XL AND YC
C                    CASE NC
 125.E-6       .6      6C.      60.
C OUTPUT CONTROL PARAMETERS
   20000        5        1        1        1                        1
C UNCOMPENSATED TRANSMISSION LINE
C                                RO AND R1       XO AND X1
51BUS2 ABUS1 A                   46.5       525.0
52BUS2 BBUS1 B                   16.75 .    184.75
53BUS2 CBUS1 C
C COMPENSATED TRANSMISSION LINE
C                                RO AND R1       XO AND X1
51BUS2 ABUSC A                   55.0       600.0
52BUS2 BBUSC B                   18.5       200.0
53BUS2 CBUSC C
C 55 % SERIES CAPACITORS
C                                             MICROMHOS                      VOLTAGE
  BUSC ABUS1 A                              9090.9                                   2
  BUSC BBUS1 B                              9090.9                                   2
  BUSC CBUS1 C                              9090.9                                   2
C BYPASS GAP RINGDOWN CIRCUITS
C
  BUSC ABYPASA                 .02    1.10
  BUSC BBYPASB                 .02    1.10
  BUSC CBYPASC                 .02    1.10
C SOURCE IMPEDANCE TO INFINITE BUS
C                                RSELF      XSELF - RO=R1 AND XO=X1
  BUS1 ABUSO A                    3.5  75.0
  BUS1 BBUSO B                    3.5  75.0
  BUS1 CBUSO C                    3.5  75.0
C GENERATOR STEPUP TRANSFORMER
  TRANSFORMER                               WNDG1
           9999
C                                  R      X      N
 1GEN1 AGEN1 B                 .0015  .1452  22.0
 2BUS2 A                          .25  25.0288.67
C SECOND AND THIRD TRANSFORMER WINDINGS USE SAME DATA
  TRANSFORMER   WNDG1                       WNDG2
 1GEN1 BGEN1 C
 2BUS2 B
  TRANSFORMER   WNDG1                       WNDG3
 1GEN1 CGEN1 A
 2BUS2 C
C CONNECTIVITY CAPACITORS FOR GENERATOR TERMINALS AND DELTA WINDING
C                                           MICROMHOS
  GEN1 A                                    10.0
  GEN1 B                                    10.0
  GEN1 C                                    10.0
C FAULT IMPEDANCE
C
  FAULTA                            .0377
  FAULTB                            .0377
  FAULTC                            .0377
BLANK CARD ENDING BRANCH DATA
C FAULT SWITCHES
C           CLOSING TIME    CLEARING TIME
  BUS2 AFAULTA .018056     .035056                                               1
  BUS2 BFAULTB .018056     .035056                                               1
  BUS2 CFAULTC .018056     .035056                                               1
C BYPASS GAPS
C
  BYPASABUS1 A .001        1.0                   360000.
  BYPASBBUS1 B .001        1.0                   360000.
  BYPASCBUS1 C .001        1.0                   360000.
BLANK CARD ENDING SWITCH DATA
```

The half-peak amplitudes of TOR 2 in Figure 10.5 exceed four per-unit, which is definitely cause for concern in terms of fatigue loss-of-life for the shaft.

Figure 10.6 shows the case repeated with a 40 millisecond fault clearing time. The shocks of fault initiation and clearing now occur one cycle apart at the first mode natural frequency, and thus tend to cancel each other. The shaft torque peak amplitudes are sharply reduced, and in fact the first mode is no longer so predominant. The air gap torque shows no sustained first mode forcing function, but does settle into a low frequency oscillation of the machine inertia against the infinite bus.

One effective way to reduce torque amplification is to bypass series capacitors during faults and reinsert them after the fault is cleared. This practice is also necessary to limit the overvoltage on the capacitors. Sparkover gaps are one means to accomplish this. The lowest practical gap sparkover setting would be approximately twice the voltage across the capacitors when carrying full load current. Assuming a 1000 MW rating for the 500 kV line, a setting can be calculated as follows:

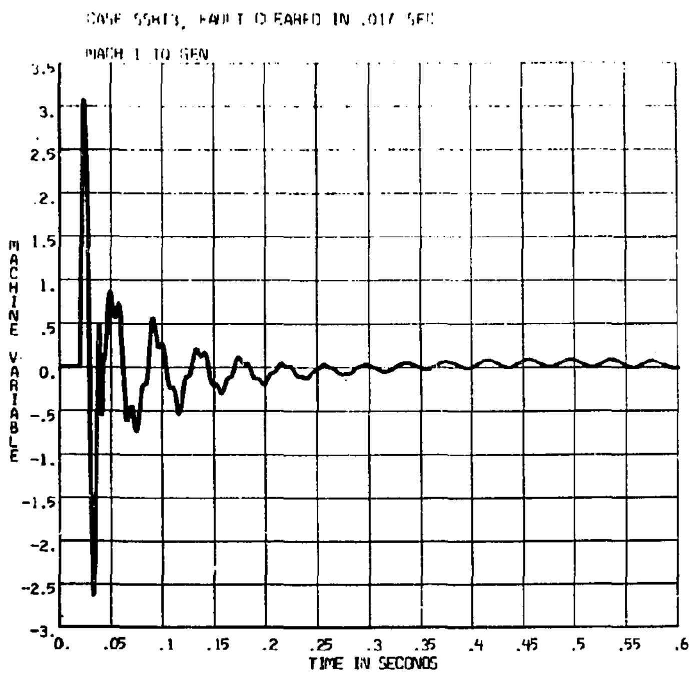
$$I = 1000\ \text{MW}/(500\ \text{kV} \times \sqrt{3}) = 1155\ \text{amps}$$

$$V_{gap} = \frac{2 \times 1155\ \text{amps} \times \sqrt{2}}{9090.9\text{x}10^{-6}\ \text{mhos}} = 360\ \text{kV (peak)}$$

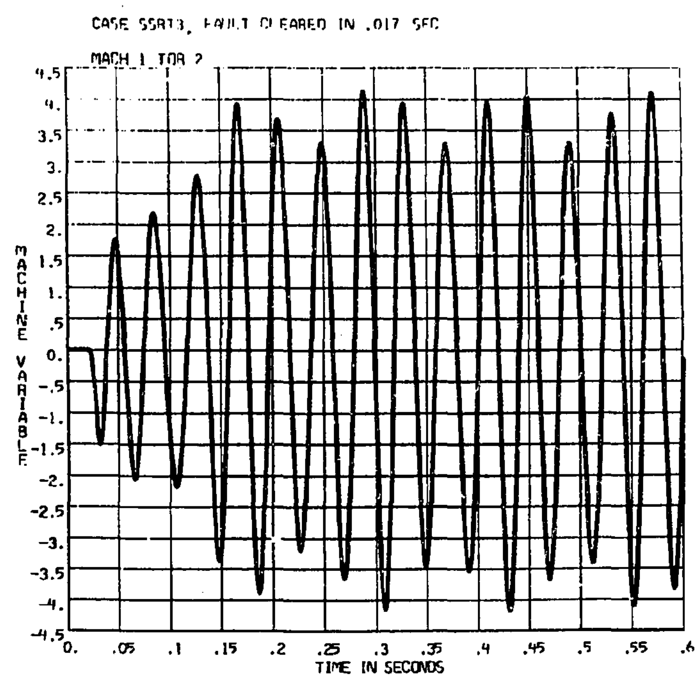
A current-limiting inductor is added in series with the gap to produce a damped 600-Hz ringdown transient after the gap sparks over. The branch and switch cards associated with the bypass gaps are given in Table 10.5.

Repeating the case with a 17 millisecond fault clearing time, the gaps will sparkover because the peak capacitor voltage in Figure 10.5 exceeds 360 kV. Figure 10.7 illustrates the air gap torque and the shaft torque with bypass gaps in place. The first two half cycles of first mode excitation are the same as in Figure 10.5, but then the gaps spark over and the torque amplification is aborted, with ultimate half-peak values less than 1.7 per-unit. Since the capacitors remain bypassed, additional damping of the first mode oscillations can be observed.

These EMTP cases ran in approximately 6 seconds on a Cray 1S computer.

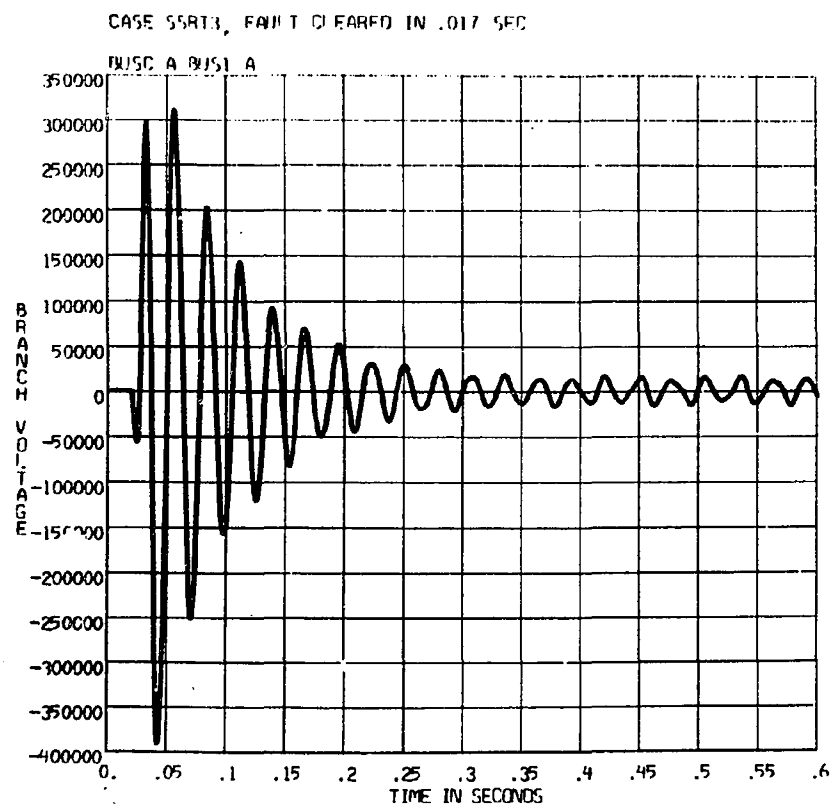


a) air gap torque



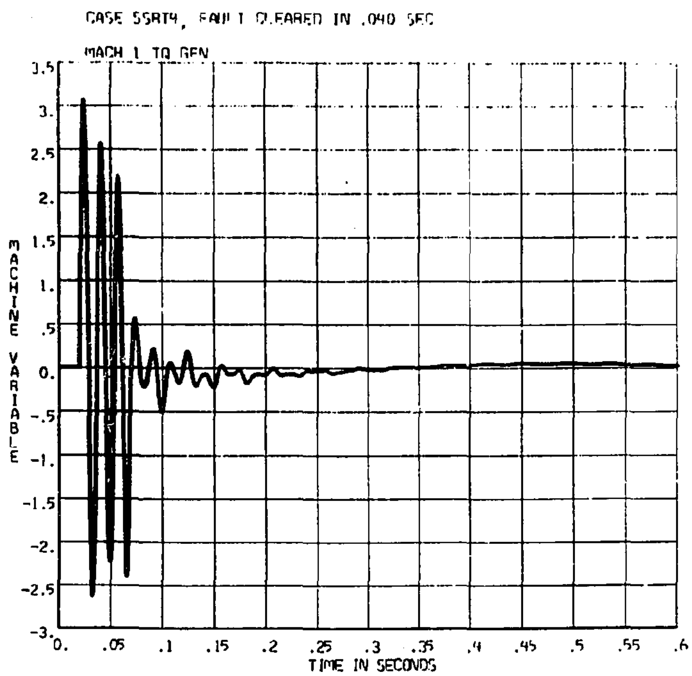
b) GEN-LP torque

FIGURE 10.5. Torque Amplification with Fault Cleared in 17 Milliseconds

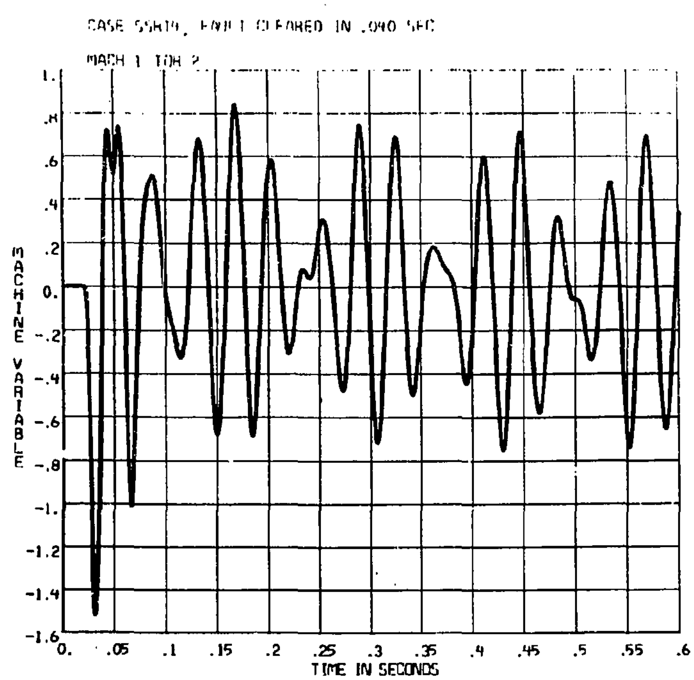


c) series capacitor phase A voltage

FIGURE 10.5. (Cont'd). Torque Amplification with Fault Cleared in 17 Milliseconds

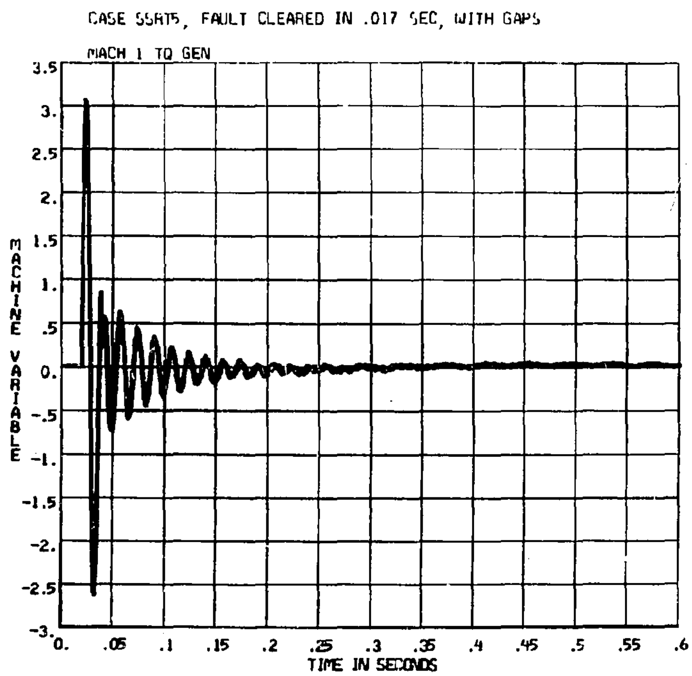


a) air gap torque

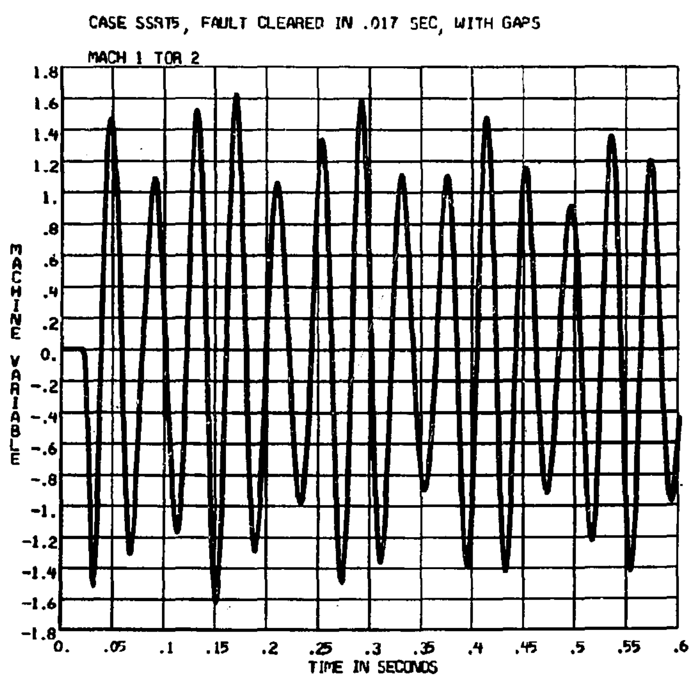


b) GEN-LP torque

FIGURE 10.6. Torque Amplification with Fault Cleared in 40 Milliseconds



a) air gap torque



b) GEN-LP torque

FIGURE 10.7. Torque Amplification with Bypass Gaps, Fault Cleared in 17 Milliseconds

Suggested investigations:

1. Run self-excitation cases with blocking filters of R = 125 ohms and R = 50 ohms.

2. Run a case at 30% compensation. Design a second mode blocking filter and cascade it with the first mode blocking filter, and then run cases at 30% and at 55% compensation.

3. Allow the series capacitors to "reinsert" in the last torque amplification case. This can be done by setting an opening delay time in columns 25-34 of the switch cards. The delay time should be set at four cycles or .067 seconds. The gaps will then open four cycles after they spark over, by which time the fault should be cleared. Since the capacitors may be needed for transient stability, the reinsertion transient voltage across the capacitors should not exceed 360 kV.

4. Run the self-excitation case with the machine at full load.

5. High-speed reclosing in non-compensated systems can also cause high transient torques. Remove the capacitors from the torque amplification case and vary fault clearing times to obtain high torques. Reclose within 10 cycles, with the fault cleared and with the fault still present.

6. Determine the effect of blocking filters on torque amplification.

Section 11

CASE 11: TACS STUDIES

This sample study will illustrate use of the EMTP to simulate thyristor-controlled systems such as HVDC terminals and Static VAR Compensators (SVC). The EMTP is a good tool for investigating harmonics, control performance, and electrical transients on these systems. A single-phase full-wave voltage controller will be used to illustrate thyristor switch models and the TACS feature of the EMTP.

Figure 11.1 shows the input format of a thyristor switch card. These cards are included with other switch cards in the EMTP input file. The special parameters are:

- GRID - TACS variable which supplies a gate pulse to the thyristor. The thyristor can begin conduction only when GRID is greater than zero.
- Open/Close - TACS variable which controls opening and closing of a switch.
- Closed - The switch is open in the steady state unless the word "CLOSED" appears in this field.
- V_{ig} - Minimum ignition voltage of the switch, usually zero.
- I_{hold} - Minimum conduction current of the switch, usually zero.
- t_{deion} - Time required after current extinction for reverse voltage blocking to become effective, usually zero.

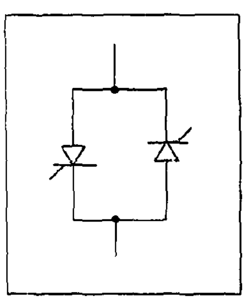
A "1" punched in column 79 will cause the thyristor switch operations to be included in the printout similar to regular switches. This feature should not normally be used.

Figure 11.2 shows common applications of thyristors or diodes. Figure 11.2a illustrates an anti-parallel connection of thyristors, as might be used in one leg of an SVC. Figure 11.2b illustrates a bridge connection of thyristors, as might be used in a three-phase controlled rectifier. A similar connection of thyristors would be used in an HVDC terminal. Figure 11.3 shows a single thyristor with associated RC snubber and current-limiting reactor. These extra components have a physical purpose in protecting the thyristor from excessive dv/dt and di/dt. They are also useful in EMTP models from the standpoint of numerical stability.

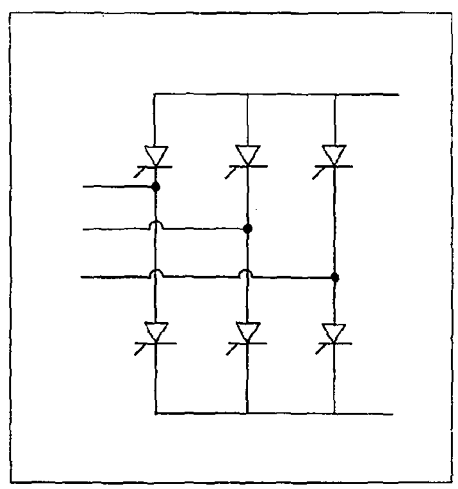
Type	BUS K	BUS M	V_{ig}	I_{hold}	t_{deion}
I2	A6	A6	E10.0	E10.0	E10.0
(set = 11)			(usually set = 0.0)		

	CLOSED		GRID	OPEN/CLOSE		OUTPUT
10X	A6	4X	A6	A6	3X	I1

FIGURE 11.1. EMTP Thyristor Switch Input Format



a) Anti-parallel



b) Three-phase bridge

FIGURE 11.2. Typical Thyristor and Diode Connections

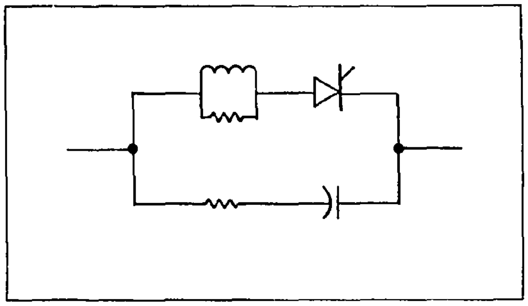


FIGURE 11.3. Thyristor with Snubber and Current-Limiting Reactor

The TACS input structure is shown in Table 11.1. The TACS cards come after the miscellaneous data cards and special requests, and before the EMTP electrical network input.

TABLE 11.1

TACS Input Structure

TACS HYBRID

Functions (simultaneous)
    BLANK CARD

Sources
    BLANK CARD

Devices/Variables (sequential)
    BLANK CARD

Output Requests
    BLANK CARD

Initial Conditions
    BLANK CARD

EMTP network cards

At each time step, TACS updates the source values and solves the control system. It then passes outputs to the electrical network. This process is not truly simultaneous; there is a one-time-step lag between TACS and the electrical network. At each time step, the electrical network is solved first, using TACS outputs from the preceding time step. Then TACS is solved using current electrical network outputs, in preparation for the next time step.

Within TACS, the simultaneous solution may be broken up by the supplemental variables and devices in the third group of Table 11.1. These variables should be placed either before or after the rest of the control system, in a logical sense. If these variables must be placed "inside" the control system, the simultaneous TACS solution will be broken, and additional time step lags will result.

A listing of components available in TACS follows. The elements used in the sample case are flagged with an asterisk (*).

TABLE 11.2

TACS Components

Sources

*Electrical network node voltages
EMTP switch currents
EMTP switch status (open or closed)
Synchronous machine internal variables
*Level signal
Cosine function
Pulse train
Sawtooth wave
Simulation time
Current time step number
Time step size
Power frequency (Hertz)
*Power frequency (radians per second)
Zero
*+1
-1
"Infinity"
*Pi

Simultaneous Functions

Laplace transfer functions with limits
Linear gains with limits

Supplemental Functions

*Mathematical and logical operations
Frequency sensor
Relay-operated switch
*Level-triggered switch
Transport delay
Pulse transport delay
Digitizer
Nonlinear gain
Time-sequenced switch
*Controlled integrator
Differentiator

TABLE 11.2 (Cont'd)

TACS Components

Input variable "If" tester
Signal selector
Sample and track
Maximum/minimum selector
Maximum/minimum tracker
Accumulator and counter

The mathematical and logical operations mentioned in Table 11.2 can be input in the same format as FORTRAN statements.

TACS variables can be requested for printing and plotting in a manner similar to the electrical network node voltage output specification.

TACS calculates initial conditions based on the source inputs, all of which are available at time zero because the electrical network was initialized first. TACS will calculate a d.c. or a.c. steady-state solution based on this information. However, in some cases, the user must supply past-history initial conditions for s-blocks, integrators, transport delays, and certain other components. The user can specify initial conditions for TACS variables to obtain a proper startup. In some cases, this will be a long and involved manual calculation.

The TACS example presented is a single-phase full-wave voltage controller depicted in Figure 11.4. Reference (20) contains more details about this circuit and other power electronic circuits. The peak source voltage magnitude is 150 volts, and the series RL load impedance will be 2 ohms at 60 Hertz. The antiparallel thyristors are controlled by TACS variables GRID1 and GRID2. A high resistance is placed in parallel with the load to avoid numerical problems associated with repetitive current chopping in the load inductance. An alternative would be to connect series RC snubber circuits across the thyristors. The time constant of this RC circuit should be greater than the EMTP time step.

Thyristor firing pulses are timed by integrating the voltage across each thyristor to obtain flux linkages. For a sinusoidal source voltage and no current in the load, the flux linkages are:

$$\lambda = \int_0^t E \sin \omega t \, dt = \frac{E}{\omega} (1 - \cos \omega t) \tag{11-1}$$

If we only integrate the positive half cycles of thyristor voltage, the flux linkage builds up as soon as the voltage wave crosses zero in the positive direction. We would like to know what the flux linkages will be at the desired firing angle.

The firing angle in degrees is related to the time beyond voltage zero crossing by

$$\omega t_c = \frac{\alpha\pi}{180} \tag{11-2}$$

where ω is the angular power frequency, t_c is the time past zero crossing, and $\alpha\pi/180$ is the desired firing angle in radians. This expression is substituted into the flux linkage equation to obtain the reference flux linkage level.

$$\lambda_R = \frac{E}{\omega} (1 - \cos(\frac{\alpha\pi}{180})) \tag{11-3}$$

Whenever the integrated flux linkages across a thyristor reach λ_R, the desired firing angle has been reached, and it is time to generate a firing pulse.

Figure 11.5 depicts the above process for one thyristor in Figure 11.4, which serves a 2-ohm resistive load. The top voltage waveforms are the positive half cycles of voltage across the thyristor. The second waveform is the integrated flux linkage, which is reset to zero whenever the thyristor voltage goes negative. Also shown on the second waveform is the calculated reference flux linkage for firing angles of 60^o and 120^o. As soon as λ exceeds λ_R, a firing pulse is generated. The third waveform is the source voltage (positive half cycles only), where the shaded portion of the waveform is actually applied to the load after the thyristor fires. I_R in the fourth waveform is the load current. It is extinguished as soon as it crosses zero, and the thyristor turns off to await the next firing pulse. The same process is repeated for the other anti-parallel thyristor, which will supply half cycles of negative source voltage to the load.

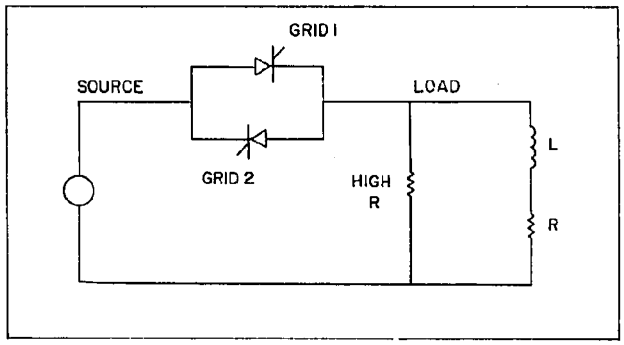


FIGURE 11.4. Single-Phase Full-Wave Controlled Rectifier

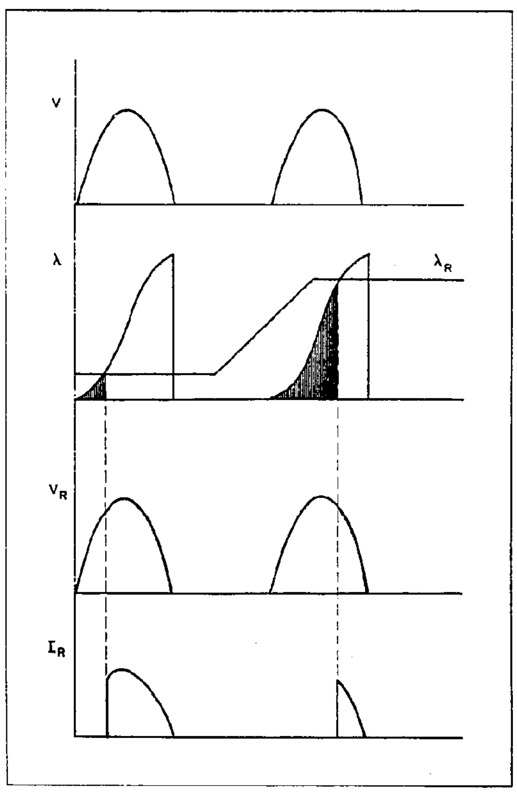


FIGURE 11.5. Flux Linkage Firing Control for a Resistive Load

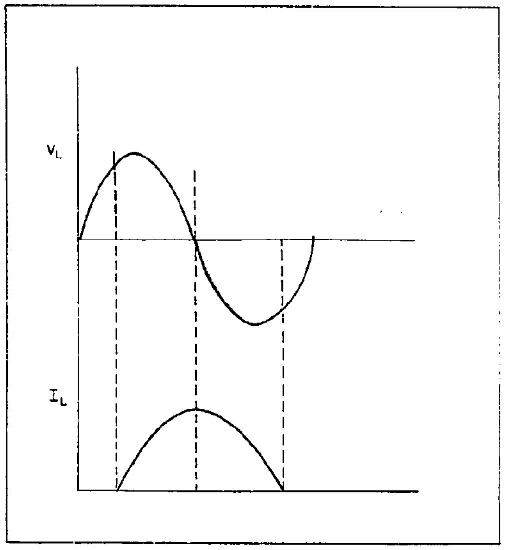


FIGURE 11.6. Inductive Load Current

The firing pulse generation for an inductive load, or a combination RL load, is the same. However, the load current waveforms will be different. As shown in Figure 11.6, the current in the inductor increases as long as the applied voltage is positive. The current decreases while the voltage is negative and finally extinguishes at a current zero. The current pulses through a thyristor-controlled inductor are symmetrical around the voltage zero crossings, unlike the resistive load currents. For the pure inductance example shown in Figure 11.6, current induction lasts longer than 180^{o} due to the inductance's electrical inertia. When another thyristor is connected in antiparallel to fire based on negative half cycles of voltage, conduction will be continuous for firing angles up to 90 degrees.

Four different load impedances were simulated to cover the range of lagging power factors shown in Table 11.3. Reference (20) gives equations and curves for calculating the rms load current as a function of the firing angle and the load impedance angle defined by $\emptyset = \tan^{-1} (\omega L/R)$. The normalized rms currents in Table 11.3 may be used to calculate the actual rms load current according to $I_R = (2V/Z)\ I_{RN}$. In these sample cases, the load impedance Z is 2 ohms, and the rms source voltage V is $150/\sqrt{2} = 106.07$ volts. Therefore, the rms load currents should be 106.07 times I_{RN} from Table 11.3.

TABLE 11.3

Load Impedance Parameters

Power Factor	Ø [deg.]	R [Ω]	L [mH]	I_{RN} α=30°	α=90°
.00 lag	90	0.00	5.31	.500	.500
.26 lag	75	0.52	5.12	.500	.380
.71 lag	45	1.41	3.75	.500	.315
1.00	0	2.00	0.00	.485	.355

The EMTP input file for the simulation of a .71 power factor load with α=90^0 is presented in Table 11.4. The time step chosen was 50 microseconds, which is approximately 1 degree at 60 Hz. Due to the time step delay inherent in TACS, there will be at least a one degree error (delay) in the generated firing pulses. The TACS data comes immediately after the miscellaneous data cards. Figure 11.7 provides a block diagram of the functions simulated by this TACS input.

The two TACS simultaneous functions calculate differential voltages across the thyristors for input to the two flux linkage integrators. Two of the four TACS sources are node voltages passed in from the EMTP network so that the thyristor voltages can be calculated. These are type 90 sources in TACS. The other two sources are d.c. values which are active in the steady state, and their purpose is to provide the user with a convenient place to change parameters of the simulation. The first of these, ALPHA, is the desired firing angle in degrees, while E is the peak source voltage magnitude. The angular power frequency, OMEGA, is automatically provided in TACS.

All of the supplemental functions are type 98, or "Output" type variables. Therefore, in each time step, the following sequence of events occurs:

1) EMTP network solution uses existing thyristor states and grid signals.
2) Updated SOURCE and LOAD voltages are passed to TACS.
3) Simultaneous functions calculate new thyristor voltages.
4) Output functions generate grid signals if appropriate.

The first output function is a FORTRAN-type expression to calculate the reference flux linkage, LAMDAR. In this simulation, it could have been made a type 99 "Input" variable, in which case its evaluation would be inserted between steps 2 and 3 above. In fact, if the firing angle remains constant as it does in the sample cases, the user could manually calculate LAMDAR and use it as a TACS source. However, it is usually more convenient to set up general TACS input files which can be used for a variety of cases, even at a small cost in computational efficiency.

The second and fourth output functions are type 58 integrators. For example, the first of these has input VTHY1, integrated output LAMDA1, and a gain of 1.0. The control signal specified in columns 69-74, namely VTHY1, is used to reset the integrator. This means that the integrator output is zero whenever the input voltage is negative, thereby producing the half-wave rectified integrals shown in Figure 11.5. The numerical parameters in columns 57-62 and 63-68 indicate that the integral is calculated as 1/(0.0 + 1.0 s).

The third and fifth output functions are type 52 switches or level detectors which generate firing pulses for the two thyristors. For example, whenever LAMDA1 exceeds the threshold level LAMDAR, the output signal GRID1 is set equal to PLUS1 (an internally-defined TACS source equal to 1.0). This provides a firing pulse to thyristor number 1, which will begin conduction if the voltage across it is currently positive. Whenever LAMDA1 is less than LAMDAR, the output GRID1 is set equal to 0.0.

TACS output variables are requested by name in a format similar to the node voltage output requests. They are identified for printout and plotting purposes as branch currents with the first node name being TACS, and the second node name being the actual variable. For example, the second CALCOMP PLOT card in Table 11.4 plots the TACS variables LAMDA1 and LAMDAR on the same graph.

No non-zero initial conditions are specified for TACS in this case. In practice, this means that the integrators will not be preset to their proper values which correspond to the actual thyristor voltages at time zero. This will result in firing angle errors early in the simulation. For highly inductive loads, this will produce a decaying d.c. offset current. These startup transients are typical of EMTP simulations involving thyristor circuits.

TABLE 11.4

EMTP Input for Single-Phase Full-Wave Rectifier

```
C FILE NAME: FWAVE
C     SIMULATES A SINGLE-PHASE FULL-WAVE CONTROLLED RECTIFIER
C     USING THE EMTP'S TACS FEATURE.
BEGIN NEW DATA CASE
C FIRST MISCELLANEOUS DATA CARD:
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C     1-8     9-16    17-24   25-32
C T-STEP   T-MAX   X-OPT   C-OPT
C SECNDS SECONDS    O=MH    O=UF
C          .       F(HZ)   F(HZ)
  50.E-6      .1
C
C SECOND MISCELLANEOUS DATA CARD
C     1-8     9-16    17-24   25-32   33-40   41-48   49-56   57-64   65-72   73-80
C   PRINT    PLOT NETWORK   PR.SS  PR.MAX   I PUN   PUNCH    DUMP   MULT.  DIAGNOS
C O=EACH  O=EACH    O= NO   O= NO   O= NO   O= NO   O= NO    INTO  ENERG.    PRINT
C K=K-TH  K=K-TH   1=YES   1=YES   1=YES   1=YES   1=YES    DISK STUDIES    O=NO
    2001       1       1       1       1                          1
C THE NEXT CARD SIGNALS THE INPUT OF TACS DATA
TACS HYBRID
C TACS SIMULTANEOUS FUNCTION BLOCKS
C N NAME        INPUT SIGNAL NAMES            GAIN          LIMITS
C   (3-8)    (20-25,28-33,36-41,44-49)       (51-56)  (57-62,63-68,69-74,75-80)
C CALCULATED THYRISTOR VOLTAGES
  VTHY1     +SOURCE -LOAD
  VTHY2     -SOURCE +LOAD
BLANK CARD ENDING TACS FUNCTIONS
C TACS SOURCES
C TYPE NAME      AMPLITUDE  FREQ. OR T  ANGLE OR WIDTH            T-START  T-STOP
C       (3-8)      (11-20)     (21-30)       (31-40)              (61-70)  (71-80)
C EMTP VOLTAGES AT NODES "SOURCE" AND "LOAD"
90SOURCE
90LOAD
C FIRING ANGLE
01ALPHA        90.0                                                   -1.0
C SOURCE VOLTAGE MAGNITUDE
01E           150.0                                                   -1.0
BLANK CARD ENDING TACS SOURCES
C TACS SEQUENTIAL FUNCTIONS AND DEVICES
C TYPES: 98=OUTPUT GROUP
C        99=INPUT GROUP
C        88=INSIDE GROUP
C TYPE NAME CODE   INPUT SIGNAL NAMES              NUMERICAL PARAMETERS   .
C (1-2) (3-8) (9-10)  (20-25,28-33,26-41,44-49) (51-56,57-62,63-68,69-74,75-80)
C
C OR, A FREE-FORMAT FORTRAN MATHEMATICAL EXPRESSION
C TYPE NAME          EXPRESSION
C (1-2) (3-8)          (12-80)
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C REFERENCE FLUX LINKAGES CALCULATED FROM FIRING ANGLE AND
C SOURCE VOLTAGE MAGNITUDE
98LAMDAR   = E/OMEGA * ( 1.0 - COS (ALPHA * PI / 180.) )
C INTEGRATES THYRISTOR NUMBER 1 VOLTAGE
98LAMDA158+VTHY1                                  1.0    0.0    1.0VTHY1
C COMPARES THYRISTOR NUMBER 1 FLUX LINKAGE TO REFERENCE LEVEL AND
C GENERATES FIRING PULSE
98GRID1 52+PLUS1                                  1.0    0.0    0.0LAMDARLAMDA1
C INTEGRATES THYRISTOR NUMBER 2 VOLTAGE
98LAMDA258+VTHY2                                  1.0    0.0    1.0VTHY2
C COMPARES THYRISTOR NUMBER 2 FLUX LINKAGE TO REFERENCE LEVEL AND
C GENERATES FIRING PULSE
98GRID2 52+PLUS1                                  1.0    0.0    0.0LAMDARLAMDA2
BLANK CARD ENDING TACS DEVICES
```

TABLE 11.4 (Cont'd)

EMTP Input for Single-Phase Full-Wave Rectifier

```
C TACS OUTPUT VARIABLE REQUESTS
C     NAMES
C  (3-8,9-14,...,75-80)
C
  VTHY1 VTHY2 ALPHA LAMDARLAMDA1LAMDA2GRID1 GRID2
BLANK CARD ENDING TACS OUTPUTS
C SINCE NO INITIAL CONDITIONS ARE SPECIFIED, ALL TACS VARIABLES
C EXCEPT THE EMTP NODE VOLTAGES WILL AUTOMATICALLY START AT ZERO.
BLANK CARD ENDING TACS INITIAL CONDITIONS
C
C BRANCHES
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8   9-14  15-20 21-26 27-32 33-38 39-44
C   NODE NAMES    REFERENCE  RES.   IND.  CAP.                 (OUTPUT IN COLUMN 80)
C                   BRANCH           MH     UF                                 I=   1
C   BUS1   BUS2   BUS3  BUS4    OHM   OHM   UMHO                               V=   2
C                                                                             I,V  3
C                                                                             P,E  4
  LOAD                          1.41   3.75                                         1
  LOAD                          200.
BLANK CARD ENDING BRANCHES
C SWITCH CARDS FOR THYRISTORS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C 1-2 3-8 9-14        15-24       25-34       35-44           55-60    65-70  71-76
C TYPE BUS1 BUS2      V-IG        I-HOLD      T-DEION         INITIAL         TACS
C (11=THYRISTOR)                                              STATE     GRID CONTROL
C (12=CONTROLLED SWITCH)
C                                                        (OUTPUT OPTION IN COLUMN 80)
11SOURCELOAD                                                           GRID1        1
11LOAD  SOURCE                                                         GRID2        1
BLANK CARD ENDING SWITCHES
C SOURCE CARDS
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C COLUMN 1,2: TYPE OF SOURCE 1 - 17.(E.G. 11-13 ARE RAMP FUNCTIONS, 14 = COSINE)
C COLUMN 9,10: 0=VOLTAGE SOURCE, -1=CURRENT SOURCE
C     3-8        11-20       21-30       31-40       41-50      51-60      61-70      71-80
C    NODE    AMPLITUDE FREQUENCY TO IN SEC     AMPL-A1    TIME-T1    T-START     T-STOP
C    NAME                 IN HZ        DEGR                 SECONDS    SECONDS    SECONDS
14SOURCE          150.        60.          0.                                 -1.
BLANK CARD ENDING SOURCES
C NODE VOLTAGE OUTPUT
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C    3-8   9-14  15-20 21-26 27-32 33-38 39-44 45-50 51-56 57-62 63-68 69-74 75-80
C   BUS1  BUS2  BUS3  BUS4  BUS5  BUS6  BUS7  BUS8  BUS9 BUS10 BUS11 BUS12 BUS13
  SOUR
BLANK CARD ENDING NODE VOLTAGE OUTPUTS
```

TABLE 11.4 (Cont'd)

EMTP Input for Single-Phase Full-Wave Rectifier

```
C PLOTTING OF THE RESULTS
  CALCOMP PLOT
C (CASE TITLE UP TO 78 CHARACTERS)
 2 2-OHM LOAD, ALPHA=90, PF=.71 LAG
C COLUMN 2,    "1"
C COLUMN 3, 4=NODE VOLTAGE, 8=BRANCH VOLTAGE, 9=CURRENT
C COLUMN 4, UNITS OF HORIZONTAL SCALE, 1=DEGR, 2=CYCLES, 3=SEC, 4=MSEC, 5=USEC
C COLUMN 5-7, HORIZONTAL SCALE (UNITS PER INCH)
C COLUMN 11-15, TIME WHERE PLOT ENDS (UNITS OF COLUMN 4)
C COLUMN 16-20, VALUE OF BOTTOM VERTICAL SCALE
C COLUMN 21-24, VALUE AT TOP OF VERTICAL SCALE
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C                      UP TO  4 NODE NAMES FOR             49-64          65-80
C                            NODE VOLTAGE PLOTS
C                      UP TO  2  PAIRS OF , NODE           GRAPH    VERTICAL AXIS
C                      NAMES  FOR   BRANCH   OR          HEADING          HEADING
C                                  SWITCH PLOTS            LABEL            LABEL
C                      1ST  ELEMENT 2ND ELEMENT
C                       25-30 31-36 37-42 43-48
C                        BUS1  BUS2  BUS3  BUS4
 14410.     100.       SOURCELOAD
 19410.     100.       TACS  LAMDA1TACS  LAMDAR
 19410.     100.       TACS  LAMDA2TACS  LAMDAR
 19410.     100.       TACS  VTHY1 TACS  VTHY2
 19410.     100.       LOAD
BLANK CARD ENDING PLOTS
BLANK CARD ENDING THE CASE
```

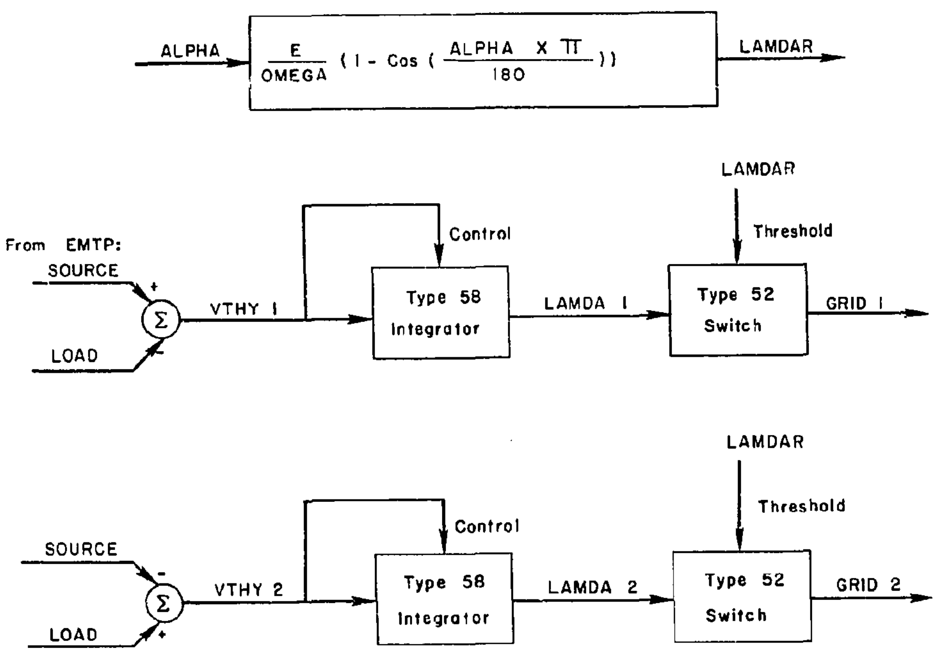


FIGURE 11.7. TACS Implementation of Flux Linkage Firing Control

The EMTP network input in Table 11.4 is relatively simple. A 200-ohm parallel resistor was added to provide a current path when the inductor current is switched off by the thyristors. Care must be taken with the type 11 thyristor switches to ensure that TACS grid signals are sent to thyristors with the proper polarity connection.

Figures 11.8 through 11.11 illustrate the simulation parameters for a resistive load at $\alpha=90^{0}$. Only quarter-cycle portions of the source voltage are actually applied to the load. The integrated flux linkages reach the reference level and generate firing pulses, except that no firing pulse is generated in the first half cycle for thyristor 1, as shown in Figure 11.9. This occurs because no attempt was made to initialize the integrators--they should not truly start at zero. When firing pulses are generated and the thyristors conduct, the integrator inputs collapse and the integrators reset to zero.

Figures 11.12 and 11.13 illustrate the case of $\alpha=30^{\circ}$ for a resistive load. None of the initial firing pulses are missed because the reference flux level is very low, and firing occurs early in each half cycle.

Figures 11.14 through 11.17 show the load currents for the four different load impedances at $\alpha=30^{\circ}$ and $\alpha=90^{\circ}$. The load current waveforms appear consistent with the rms magnitudes predicted in Table 11.3 for most cases. Conduction is not continuous for all of the cases predicted in Table 11.3 primarily because of time step delays in TACS. The d.c. offsets during startup become larger and take longer to decay as α increases and as the load becomes more inductive. In fact, the purely inductive load presents a problem. For $\alpha=30^{\circ}$ a persistent negative d.c. offset appears, and for $\alpha=90^{\circ}$ the d.c. offset decays very slowly. With a pure inductive load in the circuit of Figure 11.4, sustained d.c. currents can be "trapped" in the inductor during switching conditions such as faults or startup. This phenomenon is a real concern in actual SVC control system designs. Means of addressing this problem will be discussed under the suggested investigations.

The TACS sample cases ran in 1 second on a Cray 1S computer.

Suggested investigations:

1. Use an RC snubber instead of the parallel load resistance.

2. Attempt to improve the results in Figure 11.17 by:

   a) specifying TACS initial conditions.
   b) adjusting the source voltage phase angle to reduce the initial startup error.
   c) use a Type 4 TACS source to ramp up the firing angle from 0° to 90°.
   d) changing the series load resistance to 0.01 ohms, which simulates a reactor Q of 200.

3. Add a supplemental TACS function to vary the firing angle during the simulation.

4. Add EMTP sources and switches to experiment with harmonic distortion and switching transients. Integral timing methods handle these effects better than simply timing from voltage zero crossings.

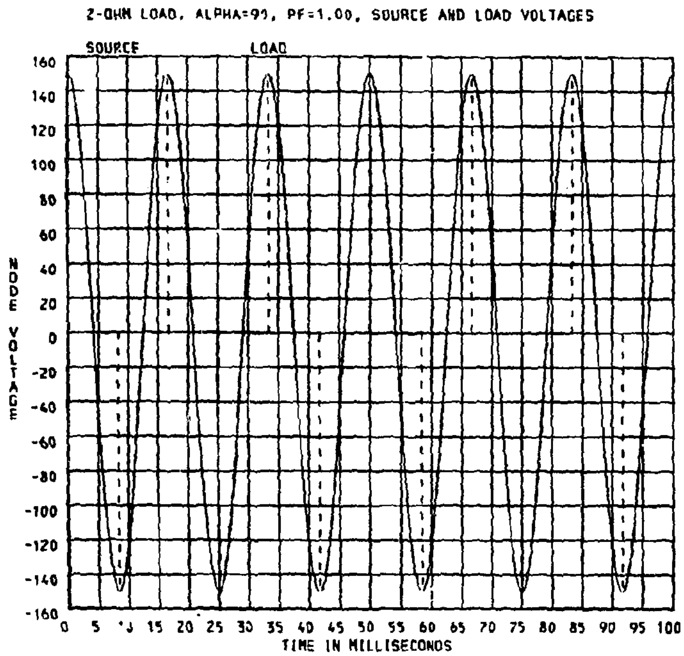


FIGURE 11.8. Source and Load Voltages, $\alpha=90^0$, p.f.=1.00

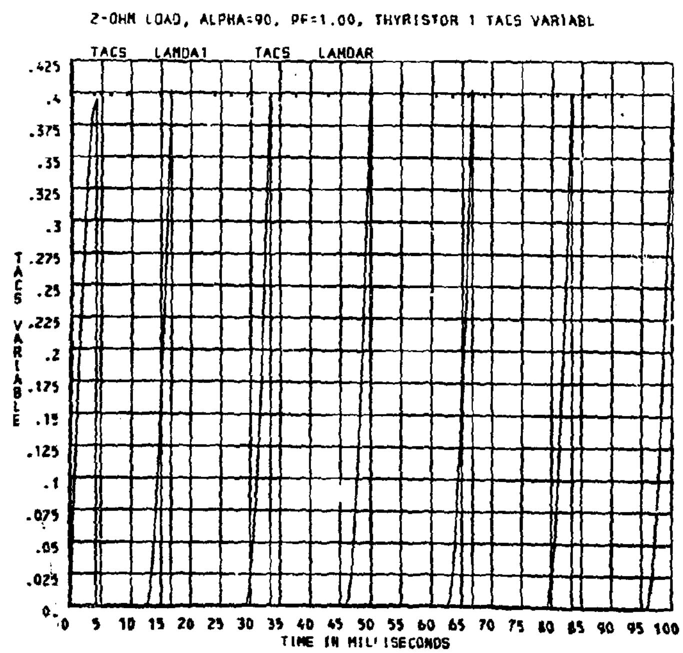


FIGURE 11.9. Thyristor 1 Flux Linkages, $\alpha=90^0$, p.f.=1.00

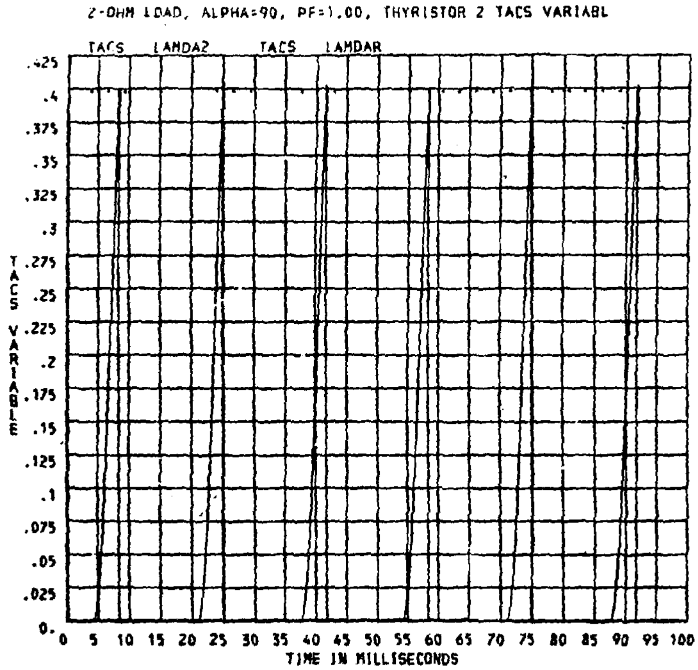


FIGURE 11.10. Thyristor 2 Flux Linkages, α=90°, p.f.=1.00

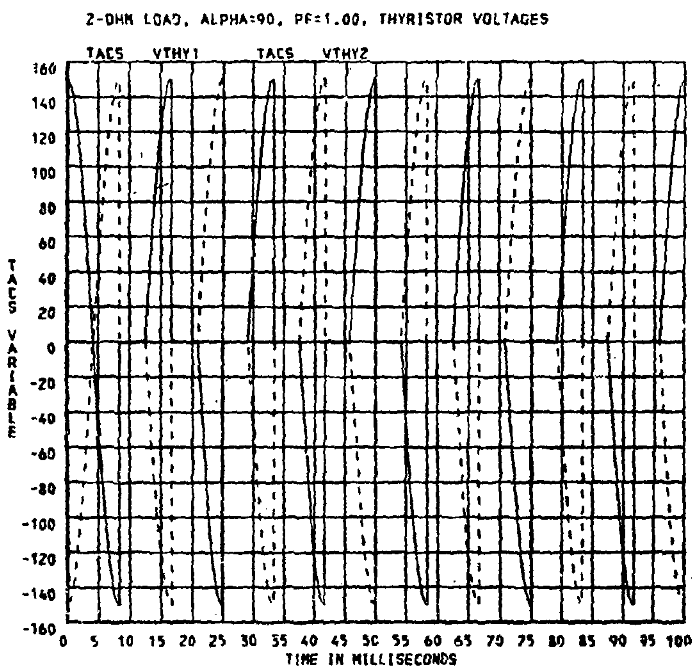


FIGURE 11.11. Thyristor Voltages, α=90°, p.f.=1.00

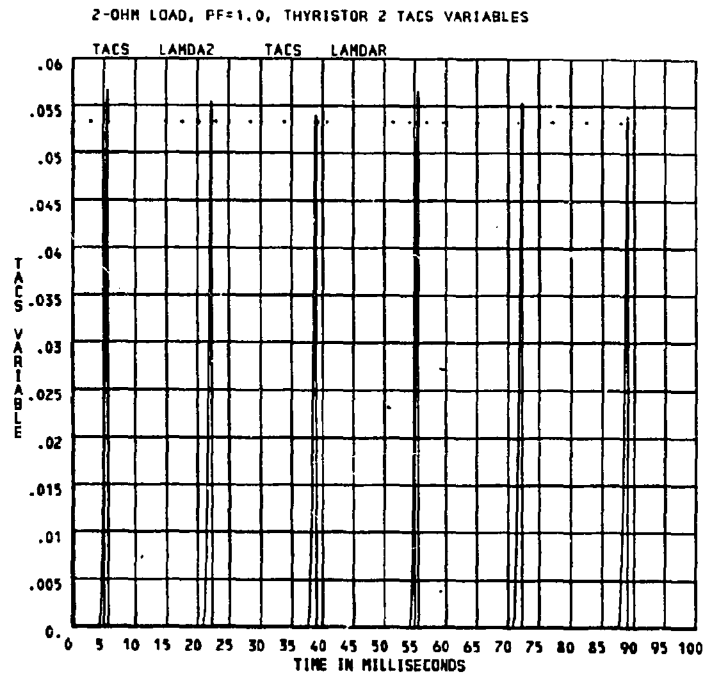


FIGURE 11.12. Thyristor 2 Flux Linkages, $\alpha=30^{0}$, p.f.=1.00

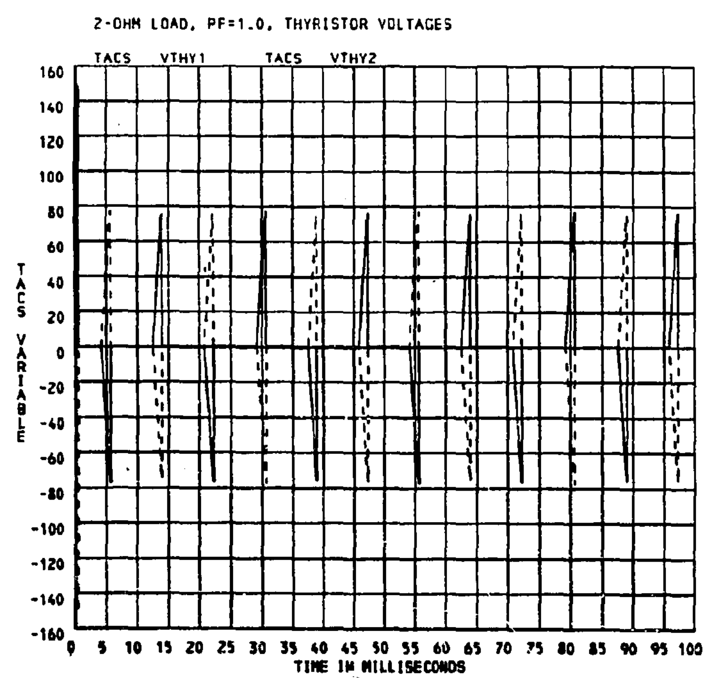
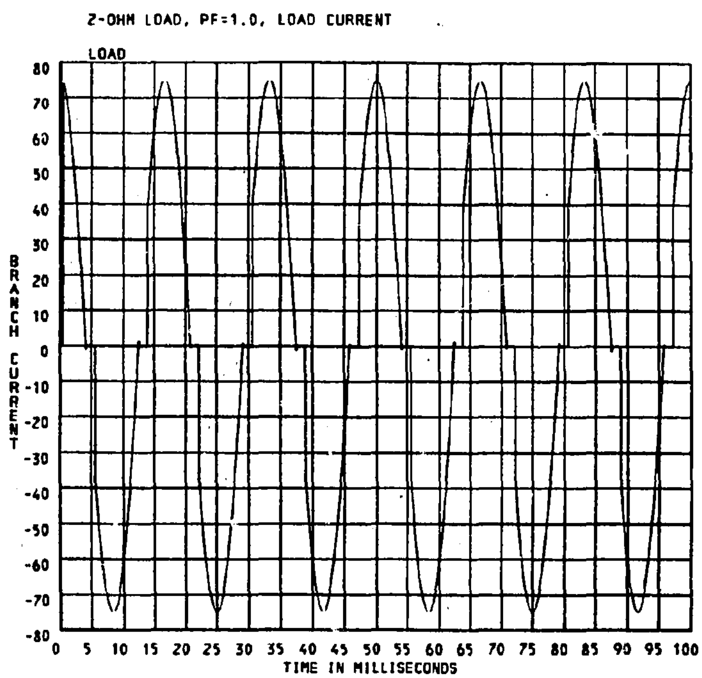
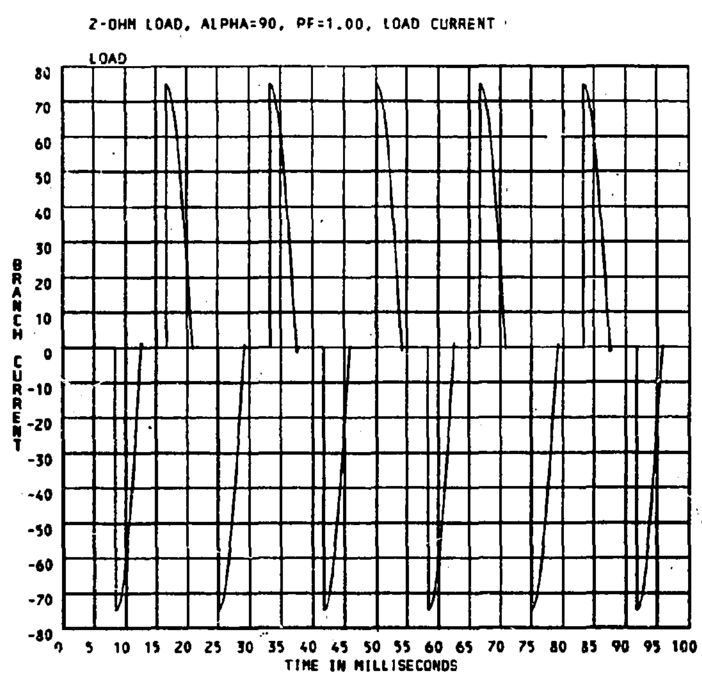


FIGURE 11.13. Thyristor Voltages, $\alpha=30^{0}$, p.f.=1.00

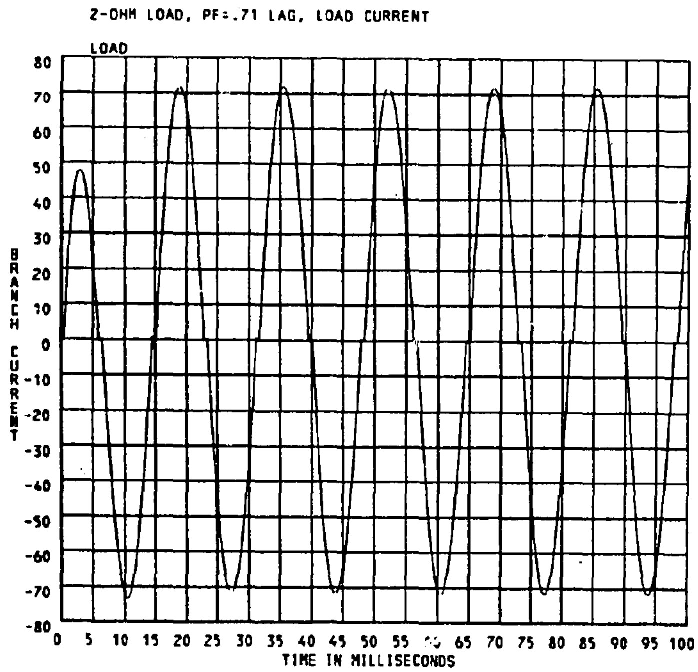


a) $\alpha=30^0$

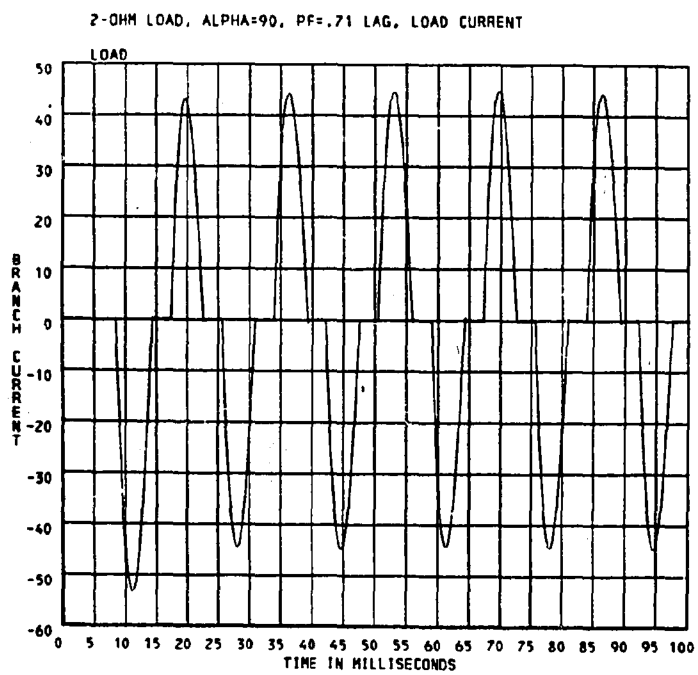


b) $\alpha=90^0$

FIGURE 11.14. Load Currents for p.f. = 1.00

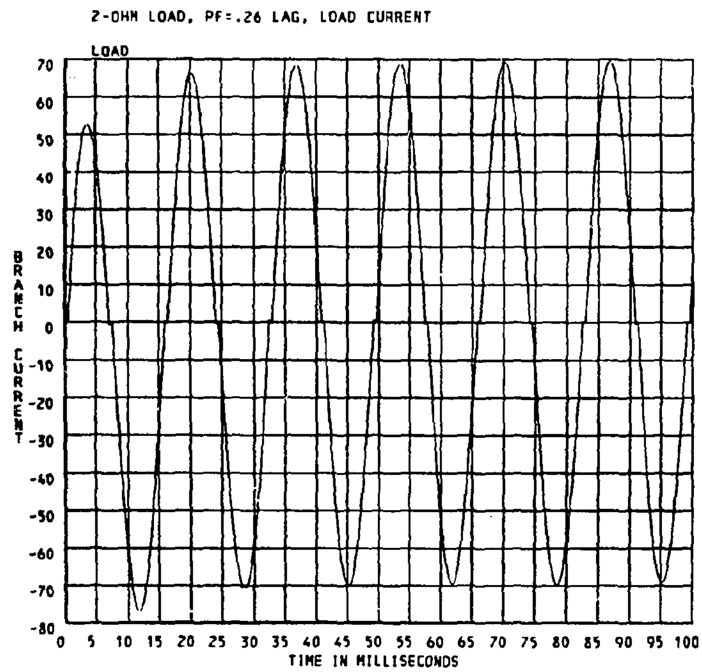


a) $\alpha=30^{0}$

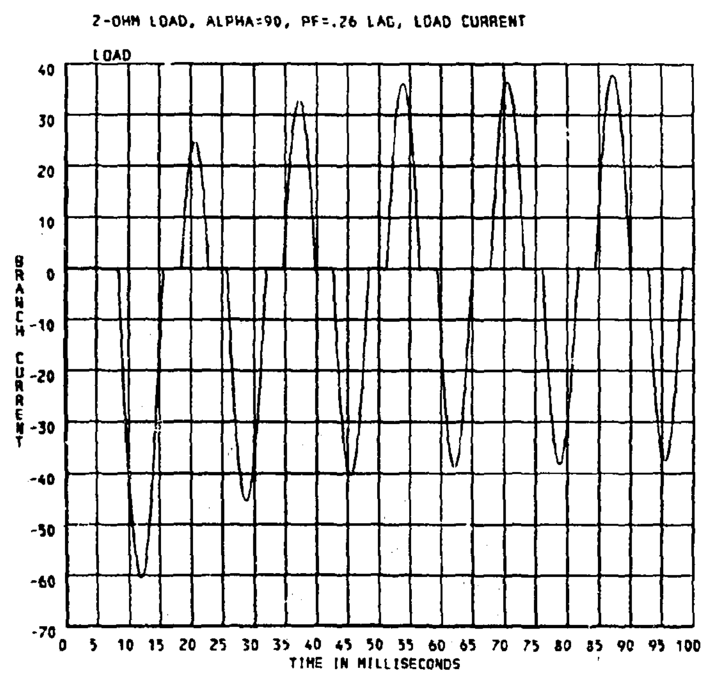


b) $\alpha=90^{0}$

FIGURE 11.15. Load Currents for p.f. = .71

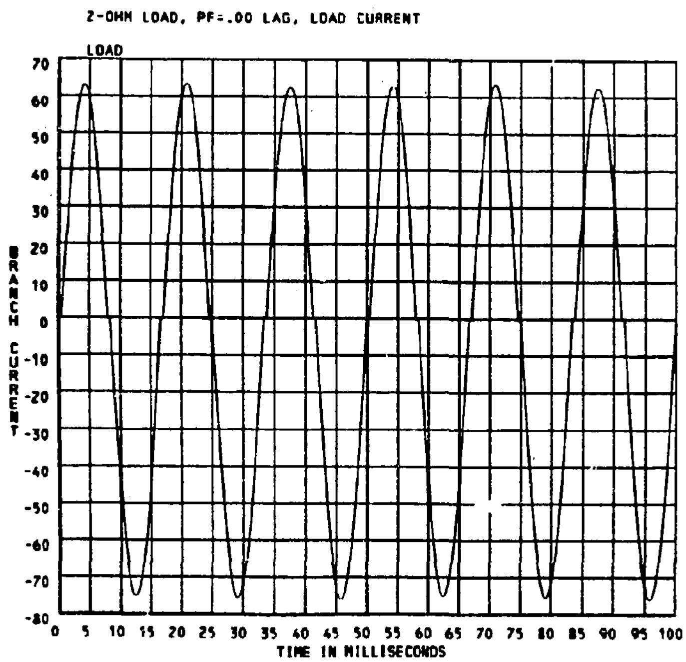


a) $\alpha=30^0$

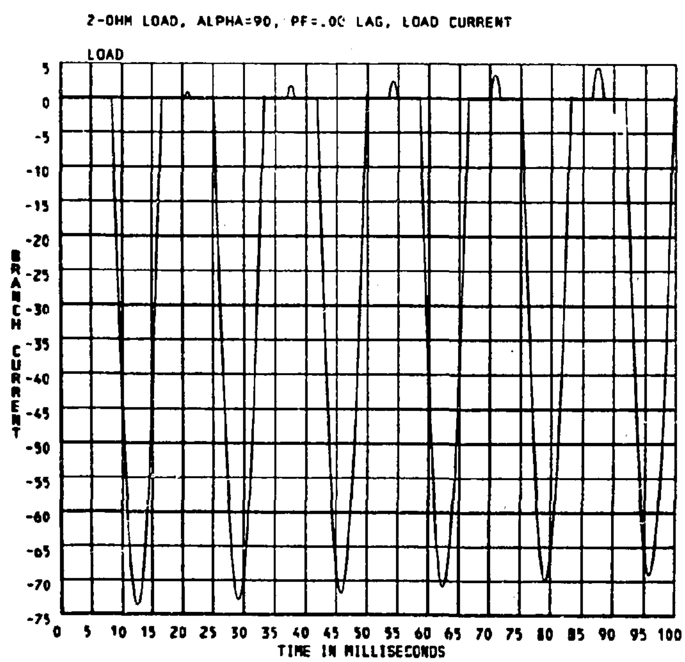


b) $\alpha=90^0$

FIGURE 11.16. Load Currents for p.f. = .26



a) α=30°



b) α=90°

FIGURE 11.17. Load Currents for p.f. = 0.0

Section 12

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