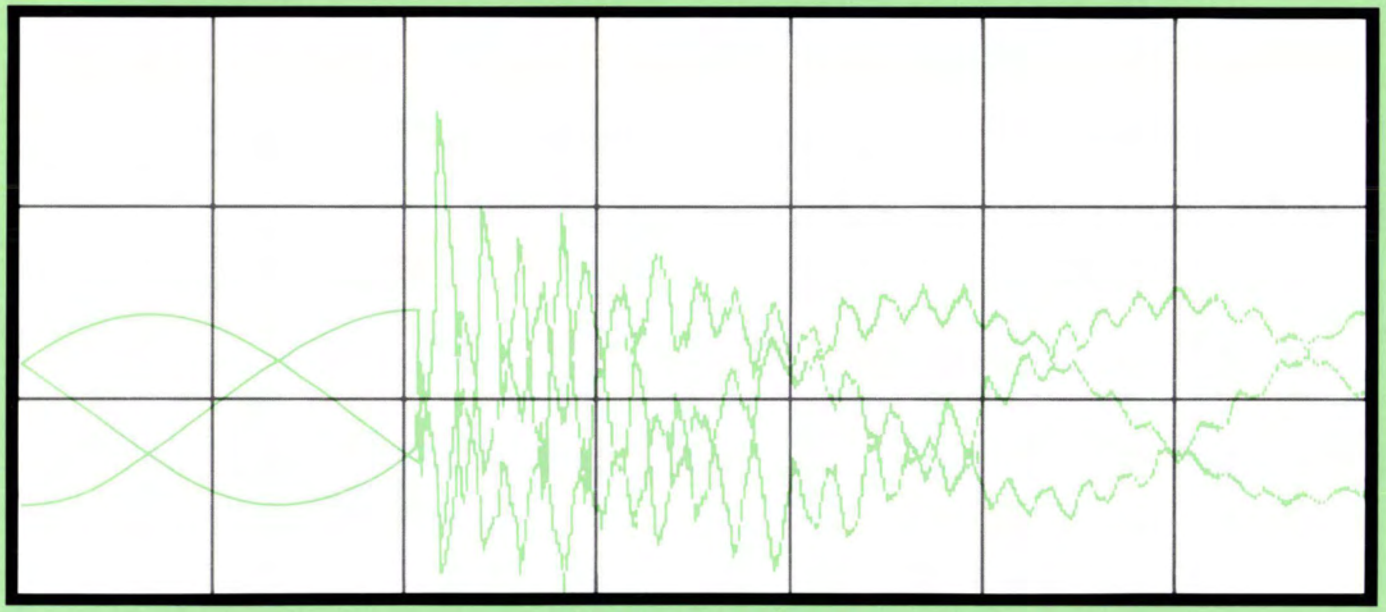
EPRI EL-4651, Volume 2

Electromagnetic Transients Program (EMTP)

WORKBOOK II



ELECTRIC POWER RESEARCH INSTITUTE

EMTP DEVELOPMENT COORDINATION GROUP

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REPORT SUMMARY

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

Electromagnetic Transients Program (EMTP)

Volumes 2–4

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

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

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

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

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

EPRI PERSPECTIVE

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

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

PROJECT

RP2149-6
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Electromagnetic Transients Program (EMTP)
Volume 2: Workbook II

EL-4651, Volume 2
Research Project 2149-6

Final Report, June 1989

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ABSTRACT

This workbook is the second in a series of books intended to introduce the EMTP to users. It assumes that the user is familiar with elementary uses of the EMTP and presents more advanced modeling techniques. The workbook uses a case-study approach, where gradually more sophisticated models of the same system are introduced. The book starts with a description of cable modeling and electromagnetic induction. As in Workbook I, the idea is not only to show how to create models using the EMTP, but also how to obtain reasonable values for necessary parameters, and what and how to simulate it. Detailed templates to facilitate the creation of data for the EMTP are also provided. The book then introduces frequency dependent line models. Other topics covered include: statistical studies using EMTP, circuit breaker models and frequency dependent source representation. A final chapter discusses insulation coordination. This last chapter is largely stand-alone, and can be used as an introduction to the material rather than a recapitulation of the book, if so desired.

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SECTION 1

INTRODUCTION

This Workbook is designed to be used as a mean of learning the use of many of the more advanced features of the EMTP. This Workbook deals with the representation of cables, frequency dependent lines and more comprehensive system studies. The user is assumed to be familiar with the basic capabilities of the EMTP. The user should know how to prepare data and run simple cases, how to represent lumped RLC components, mutually coupled branches, simple nonlinearities, sources, simple distributed lines and switches. The user is also assumed to be familiar with plotting and printing results. Finally, the user should be aware of some of the auxiliary programs associated with the EMTP: the `LINE CONSTANTS` routine and the `SATURATION` routine. All these materials are covered in detail in Workbook I.

Workbook I was based on successive refinements on the study of a single sample 13 bus system from different points of view. To a large extent, Workbook II continues that philosophy, even though in some cases departures from the idea will take place. Figure 1.1 illustrates the one line diagram for the 13 bus system of interest.

Throughout this Workbook there are a number of ***problems***. These problems are an integral part of the book and should be solved or at least attempted. Also provided are a number of *templates*. These templates provide an effective and concise means for explaining what data is required, as well as being useful for data entry if desired. Often both a short and a long version of each template are provided. The short version usually fits in one page and is quite useful for data entry. The longer version of the template is more detailed and explains most parameters available. Along with this book you should also have received a *diskette* formatted for use with an IBM-PC running under MS-DOS or a compatible system. This diskette contains a copy of all the templates as well as data for several examples and problems.

The first part of the book (sections 2 to 9) describes the use of more detailed models than Workbook I. It introduces cables and frequency dependent line models. Sections 8 to10 describe important new features of the EMTP, some now implemented (frequency dependent models), some to be implemented in the near future (breakers and corona). Of necessity, the coverage in these sections is quite sketchy.

The last section of this book, section 11, puts the entire issue of uses of the EMTP within the perspective of insulation coordination. This section can be considered a summary and overview of all others, or can be treated as introductory material that should precede any specific studies. No specific EMTP models are presented in this section, but the section sets the stage for a user to learn to ask appropriate questions.

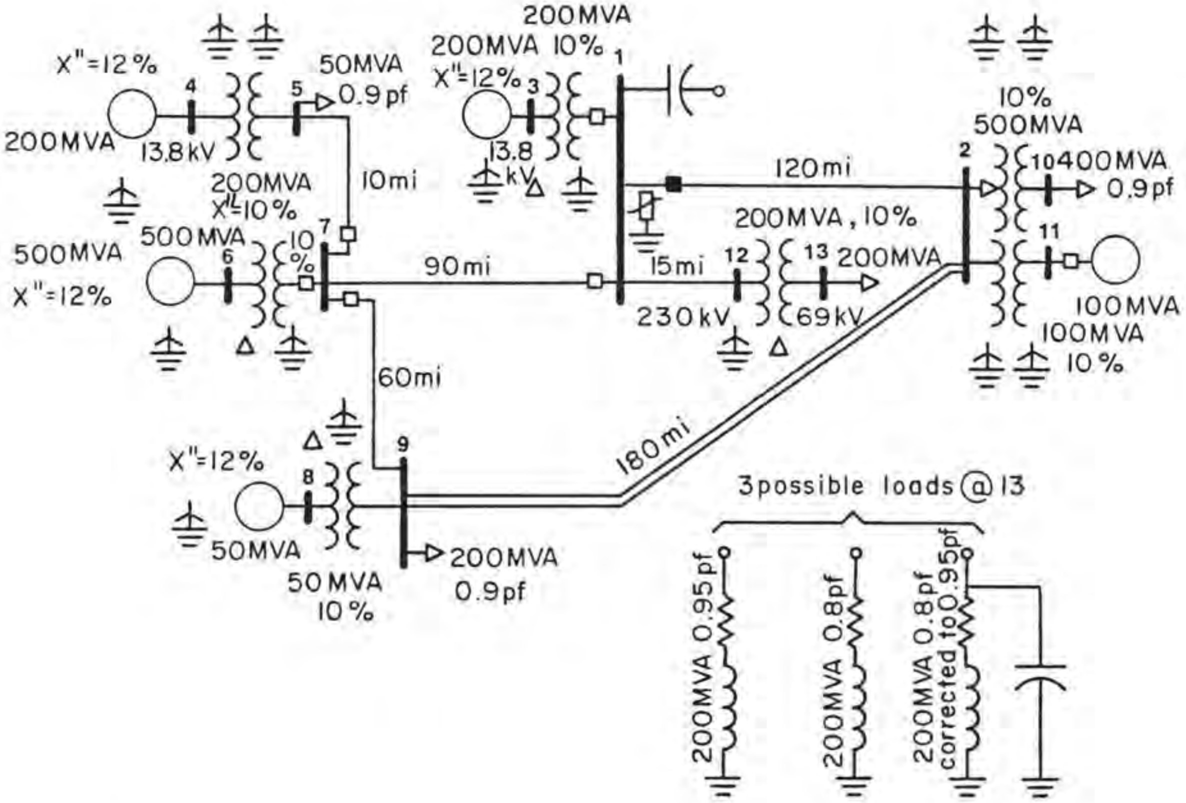


Figure 1.1: The sample 13 bus system.

SECTION 2

CABLE PARAMETER CALCULATIONS

The EMTP has the capability of representing high voltage cables as well as overhead lines. The reader is assumed to be familiar with the LINE CONSTANTS model of the EMTP, as well as the representation of transposed and untransposed distributed parameter lines within the EMTP. This section includes an overview of the most important features of cables, as well as examples and problems involving cable parameter calculations.

2.1. Types of Cables

A cable usually consists of one or more concentric conductors, each of them surrounded by a solid, liquid or gas insulating material. Most cables are designed to operate underground. The construction of a cable may vary, but typically a cable is constructed with either a solid or hollow center conductor (the *core*), a surrounding insulator and an electrically conductive *sheath*. The sheath may be designed to be in direct contact with ground, or may be surrounded by further insulation. This insulation may, in turn, be protected further by additional layers of conducting and insulating materials. In the case of multi-phase cables, all phases may in turn be surrounded by a metallic enclosure, often referred to as a *pipe*. Figure 2.1 illustrates several typical cable construction arrangements.

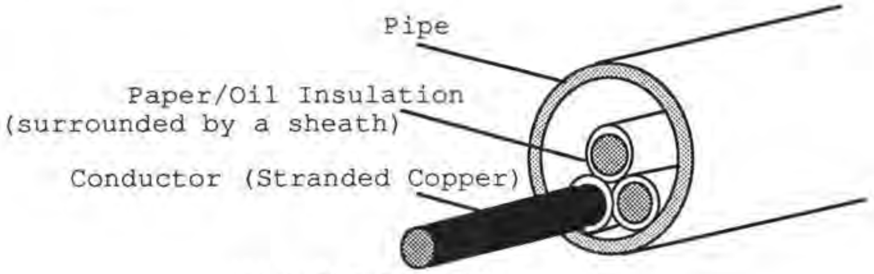
Note that lower voltage cables are often constructed in non-cylindrical conductor arrangements. The present EMTP cannot accurately deal with these cables. The parameters of these lower voltage cables are best obtained directly from the manufacturer rather than using the CABLE CONSTANTS routine within the EMTP.

The characteristics of cables depend on the materials and dimensions of the cable. Typical cable parameters are such that propagation velocities for most cable modes are much slower than the corresponding propagation velocities for comparable overhead lines. The concept of *mode* is described later on.

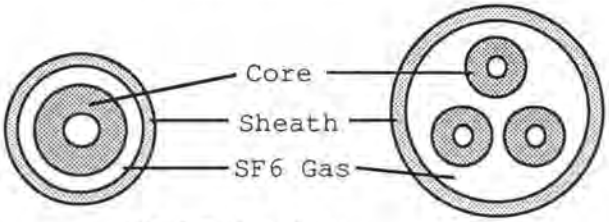
2.2. Getting Data for Cables

The data for a study involving cables is normally obtained from the cable manufacturer. If the manufacturer's data is not available or if the user wants to do a very coarse preliminary study, the following rough estimates may be used to evaluate approximate parameters for a cable. As a minimum, the user must know the intended voltage class and the intended cable capacity, along with the type of insulating material and the probable existence of sheath and armor conductors.

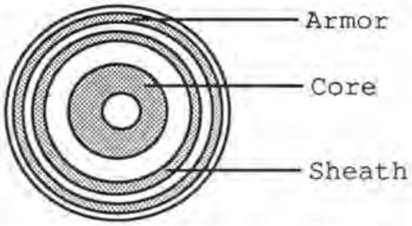
(a) Low voltage sectored cable. (b) Low voltage three phase cable.



(c) A pipe type cable.



(d) SF_6 bus ducts.



(e) A single core coaxial cable with core, sheath and armor conductors.

Figure 2.1: Sample cable configurations.

Table 2.1: Typical Cable Parameters

Resistivity of Cu Conductors	1.724x10-8 Ω-m
Resistivity of Al Conductors	2.828x10-8 Ω-m
Resistivity of Steel (low)	≈12x10-8 Ω-m
Resistivity of Steel (typical)	≈18x10-8 Ω-m
Resistivity of Steel (high)	≈88x10-8 Ω-m
Resistivity of Lead (20 °C)	≈22x10-8 Ω-m
Soil Resistivity (typical)	100 Ω-m
Soil Resistivity (rocky)	1000 Ω-m
Resistivity of Seawater (submarine cables)	≈ 0.25 Ω-m
Relative Permeability of Pipe Steel	400
Relative Permeability of Silicon Steel (4% Si)	7000*
Relative Permeability of Steel (Grain oriented, used in transformers, not in cables)	35000*
Relative Permittivity of Rubber Insulation	3.5
Relative Permittivity of PolyEthylene	2.4
Relative Permittivity of Oil Insulation	2.5
Relative Permittivity of Oil Impregnated Paper	3.8
Relative Permittivity of SF_6 Insulation	1

Table 2.2: Typical Cable Conductor Sizes**

Current	Material	Size	Radius(m)
200 amps	Cu	#00	0.0044
500 amps	Cu	500 MCM	0.0180

Table 2.3: Typical Insulation Requirements**

Voltage	Insulation	Thickness(m)
69 kV	paper	0.0080
230 kV	paper	0.0235

* For reference only. Not normally used in cables.

** These values are order of magnitude estimates only.

Problem 2.1: You are told that a substation is supplied by a 200 MVA 230 kV SF_6 bus duct. Determine reasonable parameters to use in a CABLE CONSTANTS study.

Problem 2.2: You are told that a substation is supplied by an oil-filled cable. Determine reasonable parameters to use for a 69 kV oil impregnated 20 MVA cable.

2.3. Preparing Data for the EMTP CABLE CONSTANTS Routine

The EMTP CABLE CONSTANTS routine requires that you supply the following information as a minimum. Do not proceed further until you have gathered all the required information:

- The type of cable system: One or more coaxial underground cables directly buried, overhead coaxial cables, overhead ordinary lines, or coaxial cables surrounded by a conducting metallic enclosure (a pipe), either directly buried or overhead.

- The earth characteristics. You need the resistivity (somewhere between 1 Ω-m and 10,000 Ω-m, with 100 Ω-m considered typical) and the relative permeability of the earth (usually 1). Three uniform resistivity earth layers are permitted for underground cables.

- The construction of each cable in the cable system: The electrical characteristics of materials (resistivity and relative permittivity) and thickness of each conducting and insulating layer.
- The grounding pattern of the cable sheath and armor within the length of cable of interest. *Important:* The sheath or armor of a cable grounded only at its terminals is not generally internally grounded. The cable is internally grounded only if either layer is grounded at regular intervals and you do not want to model the detailed cable behavior between grounding points by representing the entire length of the cable by many short cables.
- The number of cables that make up the cable system and their relative positions: How far apart are they? How deep under the surface of ground are they buried?

The preparation of data for the EMTP requires you to prepare data organized as follows:

- A BEGIN NEW DATA CASE line.
- A CABLE CONSTANTS request line.
- A line describing the type of cable system, the type of ground, the number of coaxial cables, the desired output, and the grounding pattern.

The remainder of the data depends on the type of cable used, but typically you must specify the following:

- The number of conductors in each coaxial cable.
- The electrical characteristics of every conducting and insulating layer in every coaxial cable.
- If a pipe exists: the characteristics of the pipe.
- The relative position of each conductor.
- The frequency or frequencies at which the parameters are desired and the earth resistivity ρ in Ω-m at which the parameters are to be calculated.

As the best means of describing the data preparation in detail, we enclose three very detailed templates. These templates are also available in the accompanying diskette, and may be used directly to enter data. For each sheet we enclose a long detailed version and an abbreviated version. The enclosed templates are:

- Template for regular overhead or underground coaxial cable systems.
- Template for pipe enclosed coaxial cable systems.
- Template for automatic generation of crossbonded Π sections.

No template for the overhead line parameter calculations has been prepared. We recommend the use of the LINE CONSTANTS routine for the calculation of overhead line parameters.

2.4. Interpreting Modes

Under ideal (frequency independent lossless) conditions, voltages and currents in a multiphase transmission line travel only at certain discrete speeds. In general, a portion of the signal applied at one end of the line travels at one speed, while another portion of the same signal travels at a different speed. The number of possible discrete propagation speeds for a given multiphase line usually is equal to the number of conductors in the line. These speeds can be calculated based entirely on the parameters and configuration of the line. Each of these propagation velocities corresponds to a propagation mode.

When specific voltage or current combinations applied to all phases travel at a single speed, we say that those combinations have excited a single mode of the line. An example is when an identical voltage is applied to the three phase conductors of an overhead line. This usually excites a single mode, normally called the ***ground*** mode. Most signals (particularly transient signals) will excite all modes of a multiphase line. The best way to study signals in multiphase lines is by decomposing each signal into its *modal components*.

Modes are characterized by their propagation velocity. Modes are also characterized by a number of *modal transformation matrices*. These modal transformation matrices specify the meaning of each mode in terms of phase quantities (that is, how to go from modal voltages and currents to phase voltages and currents) and how each particular combination of phase voltages and currents are converted to modal quantities. In general, the modal transformation matrices for modal quantities are different for voltages and currents, but are not unrelated.

The fundamental equations that describe the modal behavior of distributed parameter lines are:

$$V_p = [T_v]\,V_m \qquad V_m = [T_v]^{-1}\,V_p$$

$$I_p = [T_i]\,I_m \qquad I_m = [T_i]^{-1}\,I_p$$

The subscript p denotes phase quantities. The subscript m denotes modal quantities. The matrices $[T_v]$ and $[T_i]$ are the modal transformation matrices. These matrices are not unique inasmuch as each column can be multiplied with a nonzero factor, but they are related to each other. The usual (but not necessarily the only) relationship among these modal transformation matrices is:

$$[T_i]^t = [T_v]^{-1}$$

These modal transformation matrices can be interpreted in terms of actual voltages and currents. The following observations hold:

- The *columns* of $[T_v]^{-1}$ indicate which modal voltages are excited by each of the phase conductor (or, in the case of a cable, the actual physical conductor) voltages with respect to local ground.
- The *rows* of $[T_v]^{-1}$ (which are equal to or proportional to the *columns* of $[T_i]$) can be interpreted in terms of modal currents. They denote the physical conductors through which a given modal current will flow. A zero sum *row* denotes a current that flows entirely within the conductors themselves. A nonzero sum *row* means that part of the modal current flows through ground.

- The *columns* of $[T_i]^{-1}$ denote which current modes are excited by a given conductor current. They also allow you to infer when a particular combination of phase currents will or will not excite a given mode. For example, if the values of the phase currents add up to zero after scaling them by the elements in a *row* of $[T_i]^{-1}$, then that particular combination of currents does not excite the mode represented by that *row*.

Modal transformation matrices found can be complex as a result of considering resistances. When using modal transformation matrices in the time domain simulations, the EMTP approximates complex modal transformation matrices as real constant matrices.

2.5. Typical Cable Modes

It is difficult to generalize results specific to a few cables as valid to all cables. This section should be considered only a coarse approximation to the behavior of cables. The results tend to be reasonably good approximations for fairly high frequencies (above 1 kHz). At lower frequencies, current penetrates significantly into the earth in many cable system configurations, making the cable modes significantly different from those shown in this section. The grounding pattern of sheaths and armors also affects the true modes seen by a cable system.

Sections 2.5.1 to 2.5.6 illustrate a number of possible modal transformation matrix $[T_i]$ which can also be assumed to be equal to $([T_v]^{-1})^t$, and the matrix $[T_i]^{-1}$, which can also be assumed to be equal to $[T_v]^t$. The columns of either $[T]$ matrix can be scaled arbitrarily and the matrix remains a valid (albeit different) modal transformation matrix. The effect of scaling is to change the definition of the modal impedances and admittances, but does not affect the modal propagation velocities. Modal impedances are meaningless unless there is an explicit or implied modal transformation matrix specified.

2.5.1. Single Phase Core Cable

Consider a cable with a core, sheath and armor, all insulated from each other, as illustrated in Figure 2.1(c). An approximation of typical modal transformation matrices are:

$$[T_i] = \begin{array}{c c} \begin{array}{ccc} \text{Mode \#1 (usually ground)} & \text{Mode \#2} & \text{Mode \#3} \\ \downarrow & \downarrow & \downarrow \end{array} & \\ \left[\begin{array}{ccc} 0 & 0 & 1 \\ 0 & 1 & -1 \\ 1 & -1 & 0 \end{array}\right] & \begin{array}{l} \leftarrow \text{Core conductor} \\ \leftarrow \text{Sheath conductor} \\ \leftarrow \text{Armor conductor} \end{array} \end{array}$$

$$[T_i]^{-1} = \begin{array}{cccl} \text{Core conductor} & \text{Sheath conductor} & \text{Armor conductor} & \\ \downarrow & \downarrow & \downarrow & \\ 1 & 1 & 1 & \leftarrow \text{Mode \#1} \\ 1 & 1 & 0 & \leftarrow \text{Mode \#2} \\ 1 & 0 & 0 & \leftarrow \text{Mode \#3} \end{array}$$

By studying the columns of $[T_i]$, current mode #1 can be interpreted as a current flowing through the armor and returning through ground, mode #2 as a current flowing through the sheath and returning through the armor, and mode #3 as a current flowing through the core conductor and returning through the sheath.

Similarly, we can interpret the rows of $[T_i]$. Under the assumption $[T_i]^t$ equals $[T_v]^{-1}$, the rows of $[T_i]$ are equivalent to the columns of $[T_v]^{-1}$. Therefore, row one of $[T_i]$ has an interpretation of a voltage applied to the core conductor alone results in excitation of mode #3. A voltage applied to the sheath conductor alone will excite modes #2 and #3 as shown in row two of the matrix. Row three represents a phase voltage at the armor alone excites modes #1 and #2.

Applying a combination of voltages to different conductors at the same time can cause a mode cancellation. For example, if two voltages with equal magnitude but opposite in polarity are applied to the sheath and armor conductors, mode #2 will not be excited. This can be seen from column two of matrix $[T_i]$.

By studying the columns of $[T_i]^{-1}$ we can determine that a current in the core conductor alone (returning through ground) will excite all three modes, a current in the sheath alone will excite modes #1 and #2, and a current through the armor will excite only mode #1. However, a current through the core returning through the sheath will excite only mode #3, since mode #1 and #2 are cancelled out.

This ideal model for the three conductor concentric cable can be reduced if the armor is in continuous contact with ground. Under this condition, the modal transformation matrices reduce to:

$$[T_i] = \begin{array}{ccl} \text{Mode \#1} & \text{Mode \#2} & \\ \downarrow & \downarrow & \\ 0 & 1 & \leftarrow \text{Core conductor} \\ 1 & -1 & \leftarrow \text{Sheath conductor} \end{array}$$

$$[T_i]^{-1} = \frac{1}{2} \begin{array}{ccl} \text{Core conductor} & \text{Sheath conductor} & \\ \downarrow & \downarrow & \\ 1 & 1 & \leftarrow \text{Mode \#1} \\ 1 & 1 & \leftarrow \text{Mode \#2} \end{array}$$

Finally, if both the armor and the sheath are grounded at frequent intervals, the model for the cable can be reduced to a single mode. In this case modal currents become identical to the actual core conductor currents:

$$[T_i] = \begin{array}{cc} \text{Mode \#1} & \\ \downarrow & \\ \left[\;1\;\right] & \leftarrow \text{Core conductor} \end{array}$$

$$[T_i]^{-1} = \begin{array}{cc} \text{Core conductor} & \\ \downarrow & \\ \left[\;1\;\right] & \leftarrow \text{Mode \#1} \end{array}$$

Submarine cables often have their sheath bonded to the armor, which is in electric contact with the sea water. Also, submarine cables are usually layed far apart to limit damage from dropping anchors, etc., to a single phase. For these reasons, it is often possible to represent submarine cables as simple uncoupled single phase distributed parameter lines.

2.5.2. Three Phase Core Cable, No Armor

If the three cables that comprise a three phase cable system are in close proximity to each other, it becomes sometimes necessary to represent the coupling between the phases rather than representing each phase individually. A representative modal transformation matrix for the cable system illustrated in Figure 2.2 has the following form:

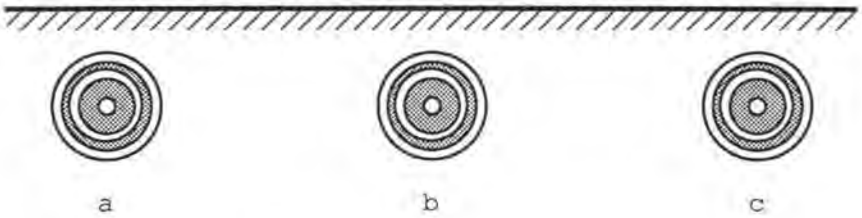


Figure 2.2: Three phase cable system comprised of three single core coaxial cables. Each cable consists of a core and sheath conductor.

$$[T_i] = \begin{array}{cccccccc} 1 & 2 & 3 & 4 & 5 & 6 & \leftarrow \text{Mode} \\ \left[\begin{matrix} 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \end{matrix}\right. & \begin{matrix} 0 \\ 0 \\ 0 \\ -1 \\ 0 \\ 1 \end{matrix} & \begin{matrix} 0 \\ 0 \\ 0 \\ -1 \\ 2 \\ -1 \end{matrix} & \begin{matrix} 1 \\ 0 \\ 0 \\ -1 \\ 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 1 \\ 0 \\ 0 \\ -1 \\ 0 \end{matrix} & \left.\begin{matrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ -1 \end{matrix}\right] & \begin{matrix} \text{ca} \\ \text{cb} \\ \text{cc} \\ \text{sa} \\ \text{sb} \\ \text{sc} \end{matrix} \\ & & & & & & \uparrow \\ & & & & & & \text{Conductor} \end{array}$$

$$[T_i]^{-1} = \frac{1}{6}\begin{array}{c|cccccc|l} & ca & cb & cc & sa & sb & sc & \leftarrow \text{Conductor} \\ \hline & 2 & 2 & 2 & 2 & 2 & 2 & 1 \\ & -3 & 0 & 3 & -3 & 0 & 3 & 2 \\ & -1 & 2 & -1 & -1 & 2 & -1 & 3 \\ & 6 & 0 & 0 & 0 & 0 & 0 & 4 \\ & 0 & 6 & 0 & 0 & 0 & 0 & 5 \\ & 0 & 0 & 6 & 0 & 0 & 0 & 6 \\ & & & & & & & \uparrow \\ & & & & & & & \text{Mode} \end{array}$$

The first mode can be interpreted as a current flowing through all three sheaths and returning through ground, i.e. ground return mode; the second mode as a current flowing in the two outer sheaths, and the third mode as a current flowing in the center sheath conductor and returning through the sheath conductors of the two outer phases (sheath to sheath mode). The last three modes are the same as in the single phase core cable: currents flowing through the cores and returning through the sheath conductors (core to sheath mode).

From the columns of $[T_i]^{-1}$ we can observe that a current in the core of a single conductor would tend to excite the core to sheath mode of that conductor plus the sheath to sheath modes and the ground return mode. However, if a zero sum current is applied to all three core conductors, the sheath modes will not be excited.

2.5.3. Three Phase Core Cable with Armor

In this cable system we assume three identical single phase cables buried in a flat configuration, as illustrated in Figure 2.3 The approximate high frequency modal transformation matrix for this cable is:

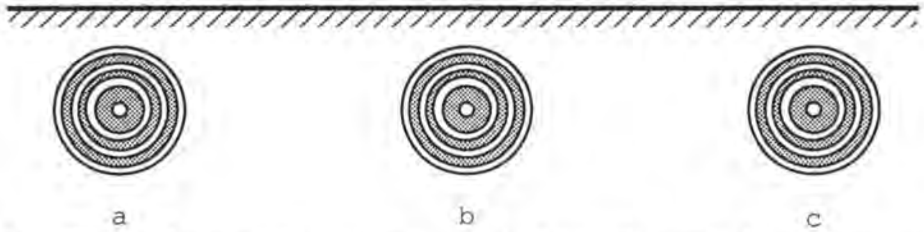


Figure 2.3: Three phase cable system comprised of three single core coaxial cables. Each cable consists of a core, sheath and armor conductor.

$$
\left[T_i\right]^{-1} = \begin{array}{|ccccccccc|c}
 & \text{core} & & & \text{sheath} & & & \text{armor} & & \\
a & b & c & a & b & c & a & b & c & \\
\hline
0 & 0 & 0 & 0 & 0 & 0 & .333 & .333 & .333 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & -.500 & 0 & .500 & 2 \\
0 & 0 & 0 & 0 & 0 & 0 & -.333 & .667 & -.333 & 3 \\
\hline
0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 4 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 5 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 6 \\
\hline
1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 7 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 8 \\
0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 9 \\
\hline
 & & & & & & & & & \uparrow \\
 & & & & & & & & & \text{Mode}
\end{array}
$$

The approximate interpretation of these modes is as follows:

- Mode #1 is the earth return mode. Its attenuation tends to be quite high and its propagation velocity is low, often ranging from 10 m/μs to 20 m/μs for frequencies above 10 Hz.
- Modes #2 and #3 are propagation modes between the armors of the three cables. These modes correspond roughly to the two aerial modes of an overhead line, although the propagation velocity of these modes is quite low. Furthermore, it is likely that the armors will be grounded either continuously or at least at periodic intervals, so these modes may not manifest themselves.
- Modes #4 to #6 are coaxial modes between the sheath and armor. At high frequencies, these modes are independent to each phase of the cable system, although at low frequencies these modes do couple the phases as well.
- Modes #7 to #9 are coaxial modes between the core and sheath. As before, these modes are independent modes of each phase at high frequencies, but couple all three phases at low frequencies.

2.5.4. Simplified Symmetrically Arranged Pipe Type Cable

We consider now a system of insulated conductors within a pipe. For simplicity, we stucy cables *without sheaths* symmetrically arranged inside an insulated conducting pipe, as illustrated in Figure 2.4. In reality, most cables except possibly quite low voltage cables would be normally surrounded by some form of sheath. As before, the modes portrayed here are at best a coarse approximation. Your specific configuration will determine the true modes at any given frequency.

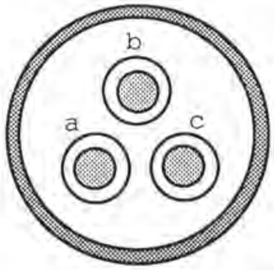


Figure 2.4: Three phase cable system with metallic pipe enclosure (symmetrical arrangement).

$$
[T_i] = \begin{array}{cl} \begin{array}{cccc} 1 & 2 & 3 & 4 \leftarrow \text{Mode} \end{array} & \\ \left[\begin{array}{cccc} 0 & 1 & -1 & -1 \\ 0 & 1 & 0 & 2 \\ 0 & 1 & 1 & -1 \\ 1 & -3 & 0 & 0 \end{array}\right] & \begin{array}{l} \text{ca} \\ \text{cb} \\ \text{cc} \\ \text{p} \end{array} \\ & \begin{array}{l} \uparrow \\ \text{Conductor} \end{array} \end{array}
$$

$$
[T_i]^{-1} = \frac{1}{6} \begin{array}{cl} \begin{array}{cccc} \text{ca} & \text{cb} & \text{cc} & \text{p} \leftarrow \text{Conductor} \end{array} & \\ \left[\begin{array}{cccc} 6 & 6 & 6 & 6 \\ 2 & 2 & 2 & 0 \\ -3 & 0 & 3 & 0 \\ -1 & 2 & -1 & 0 \end{array}\right] & \begin{array}{l} 1 \\ 2 \\ 3 \\ 4 \end{array} \\ & \begin{array}{l} \uparrow \\ \text{Mode} \end{array} \end{array}
$$

The modes of the pipe type cable can be interpreted as: the first mode corresponds to a current flowing in the pipe and returning through ground. The second mode corresponds to a current flowing through the three conductors and returning through the pipe. The next two modes are currents flowing through the core conductors, and, because of symmetry, any combination of two modes involving only the core conductors is valid. Here we show a current flowing through one conductor and returning through the other one, and a current flowing through one conductor and returning through the other two.

The reader is cautioned that pipes are often magnetic. The effect of magnetic saturation is accounted for in the formulas commonly employed in the calculation of cable parameters, including those in the EMTP. However, the effect of magnetic saturation is not. For most pipe type cables, the characteristics of the cable are largely independent of the thickness of the pipe and of the characteristics of the surrounding ground.

2.5.5. Unsymmetrically Arranged Pipe Type Cable

The final case considered here is an unsymmetrically arranged pipe type cable as illustrated in Figure 2.5. More than in any other previous case, the results shown here are very coarse approximations to the true modes, which can only be obtained from detailed EMTP calculations. Once again, for simplicity we have elected to ignore sheaths, although sheaths would normally be present in most cable systems.

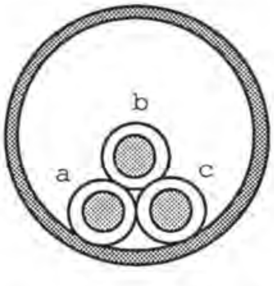


Figure 2.5: Three phase cable system with metallic pipe enclosure (unsymmetrical arrangement).

$$[T_i] = \begin{array}{ccccc} 1 & 2 & 3 & 4 & \leftarrow \text{Mode} \\ \hline 0 & 1 & 1 & -1 & \text{ca} \\ 0 & 0 & 0 & 4 & \text{cb} \\ 0 & 1 & -1 & -1 & \text{cc} \\ 1 & -2 & 0 & -2 & \text{p} \\ & & & & \uparrow \\ & & & & \text{Conductor} \end{array}$$

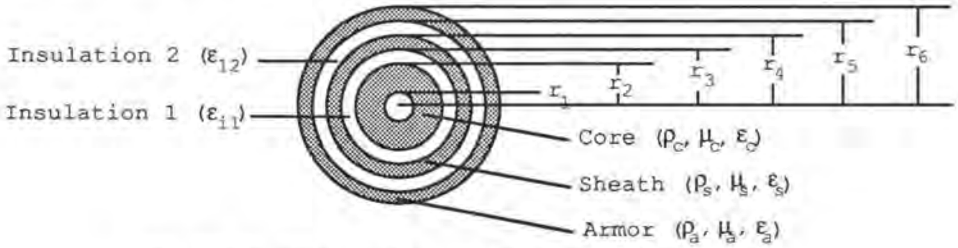
$$[T_i]^{-1} = \frac{1}{4} \begin{array}{ccccc} \text{ca} & \text{cb} & \text{cc} & \text{p} & \leftarrow \text{Conductor} \\ \hline 4 & 4 & 4 & 4 & 1 \\ 2 & 1 & 2 & 0 & 2 \\ 2 & 0 & -2 & 0 & 3 \\ 0 & 1 & 0 & 0 & 4 \\ & & & & \uparrow \\ & & & & \text{Mode} \end{array}$$

The interpretation of the modes is almost the same as before, with the exception that there is only one unique pure core mode. The second core mode involves a partial current return through the pipe.

For unsymmetrically arranged pipe type cables the best way to obtain the parameters of the cable is not by calculation but by measurement. If measurements are not available, the EMTP CABLE CONSTANTS program can be used.

2.6. Sample 230 kV Cables

Consider now a number of specific problems concerning the use of the EMTP to calculate cable parameters. The first objective is to produce a table of modal parameters for a number of specific cable configurations. Consider first the single core coaxial cable illustrated in Figure 2.6. Using this cable as a model, solve the following problems. The specific formats to be used for the preparation of the data can be easily inferred from the enclosed templates.



(a) Single core coaxial cable cross section.

$r_1 = 1.0000$ cm $r_2 = 2.5250$ cm $r_3 = 5.1800$ cm
$r_4 = 5.5525$ cm $r_5 = 6.7500$ cm $r_6 = 7.3500$ cm
$\rho_c = 1.78\times10^{-8}\ \Omega$-m $\rho_s = 2.8\times10^{-7}\ \Omega$-m $\rho_a = 7.54\times10^{-8}\ \Omega$-m
$\mu_c = \mu_s = \mu_a = 1.0$
$\varepsilon_{i1} = \varepsilon_{i2} = 3.5$
earth resistivity $\rho_e = 20\ \Omega$-m
depth of cable from earth surface 60 cm

(b) Cable data.

Figure 2.6: A single core coaxial cable consisting of a core, sheath and armor.

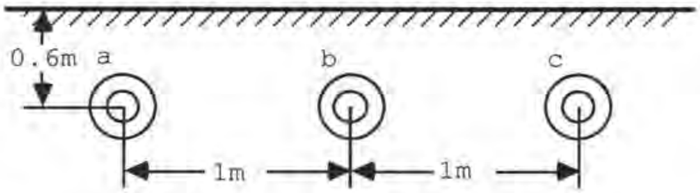


Figure 2.7: Three phase cable system consisting of three single core coaxial cables buried underground.

Problem 2.3: Prepare input data for calculating cable parameters at 1 Hz, 10 Hz, 60 Hz, 100 Hz, 1 kHz and 10 kHz. Cable data and configuration are given in Figure 2.6 and Figure 2.7 respectively. Assume no conductor is grounded.

Problem 2.4: Repeat Problem 2.3 with the armor in continuous contact with ground. Assume no insulation around the armour.

When the sheath and/or armor of the cable are grounded internally, that is, they are either continuously grounded or they are grounded at intervals shorter than the assumed length of the cable to be represented as a unit, some of the modes of propagation do not manifest themselves. The problem is identical in nature to the problem of elimination of ground conductors in overhead lines.

Obtaining parameters for cables when the sheath and/or armor are grounded can be done by specifying an appropriate parameter in the miscellaneous data line of the `CABLE CONSTANTS` input using parameter `NGRND`. It is useful, however, to understand how to obtain the same result *by hand* from the ungrounded parameters. This will help us understand the results of the `CABLE CONSTANTS` model and verify the reasonableness of the results obtained.

A simple procedure for grounding the armor is to recognize that there will be one fewer distinct mode when the voltage at the armor is set to zero. If there is a pure ground return mode excited only by the armor, then both references to the armor and to the corresponding mode can be simply deleted.

$$[T_i] = \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \leftarrow \text{Mode} \end{array} \\ \left[\begin{array}{ccc} 0 & 0 & 1 \\ 0 & 1 & -1 \\ 1 & -1 & 0 \end{array}\right] \begin{array}{l} c \\ s \\ a \leftarrow \text{Eliminate this conductor} \end{array} \\ \begin{array}{l} \uparrow \\ \text{Eliminate this mode} \end{array} \end{array}$$

If the mode is not purely due to armor currents, then one must resort to reduction of the phase (or actual conductor) `[Z]` and `[Y]` matrices, and to a re-computation of the modal transformation matrices and modal impedances. The phase matrix `[Y]` is reduced by simply deleting all rows and columns that correspond to the grounded component. The `[Z]` matrix can be easily reduced by first inverting it, then deleting all rows and columns of the grounded components, then re-inverting it. New modal transformation matrices and modal impedances can then be determined.

When two conductors are simply connected to each other but not grounded, the reduction process is a two step process:

- First, the rows and columns in the series impedance matrix that correspond to one of the conductors must be subtracted from all other rows and columns to which the conductor is connected. This process effectively adds all conductor currents and converts the conductor voltages to differential voltages.
- Second, since the differential voltages are zero, the rows and columns that correspond to these connected conductors can be eliminated by inversion, deletion of the rows and columns and re-inversion (as in the case of grounding a conductor). The admittance matrix is reduced by simply adding rows and columns.

Once this is done, new modal transformation matrices and modal impedances must be determined.

2.6.1. Examples of Bundling and Reduction

We now consider three examples of this reduction process. We first consider an example using an overhead line case and then two examples using an underground cable case. The overhead line case may be unrealistic and somewhat academic, but has been selected because it illustrates the computations needed in a very general case.

Consider the overhead lines illustrated in Figure 2.8, using the input data shown in Figure 2.9, the EMTP `LINE CONSTANTS` program generates the following per phase series impedance matrix for all three conductors:

```
0.14071+j0.84878     0.05922+j0.38729     0.05922+j0.33502
0.05922+j0.38729     0.14071+j0.84878     0.05922+j0.38729
0.05922+j0.33502     0.05922+j0.38729     0.14071+j0.84878
```

To bundle the last two conductors, we first subtract column 2 from column 3:

```
0.14071+j0.84878     0.05922+j0.38729     0.00000-j0.05227
0.05922+j0.38729     0.14071+j0.84878    -0.08149-j0.46149
0.05922+j0.33502     0.05922+j0.38729     0.08149+j0.46149
```

We now subtract row 2 from row 3:

```
0.14071+j0.84878     0.05922+j0.38729     0.00000-j0.05227
0.05922+j0.38729     0.14071+j0.84878    -0.08149-j0.46149
0.00000-j0.05227    -0.08149-j0.46149     0.16298+j0.92298
```

To eliminate row 3 and column 3, invert the matrix:

```
 0.25619-j1.53230    -0.14782+j0.89606    -0.04498+j0.36636
-0.14782+j0.89606     0.34031-j2.10077     0.15335-j1.00261
-0.04498+j0.36636     0.15335-j1.00261     0.25619-j1.53230
```

Then simply erase row 3 and column 3 from the inverse matrix:

```
 0.25619-j1.53230    -0.14782+j0.89606
-0.14782+j0.89606     0.34031-j2.10077
```

Finally, re-invert this 2 by 2 matrix:

```
0.14122+j0.84591     0.05922+j0.36116
0.05922+j0.36116     0.09996+j0.61804
```

This matrix is the series impedance matrix assuming that conductors 2 and 3 are connected together at regular intervals over their entire length. This result agrees exactly with the EMTP results obtained with the `LINE CONSTANTS` program if we request that conductors 2 and 3 be bundled into a single conductor by giving them the same phase number. If we do this, we obtain the following result:

```
1    0.14122E+00+j0.84591E+00
2    0.59218E-01+j0.36115E+00    0.99964E-01+j0.61803E+00
```

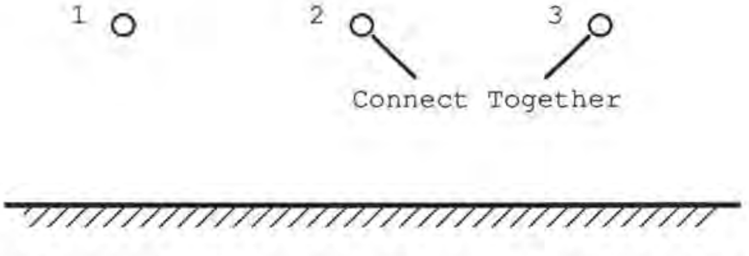


Figure 2.8: An example of the methodology of bundling and interconnecting conductors.

We now consider two examples based on cable data. The following impedance matrix for a cable was obtained using the CABLE CONSTANTS routine for a cable:

```
0.10606E-02+j0.16515E-05
0.10041E-02+j0.14923E-05   0.12263E-02+j0.14900E-05
0.98765E-03+j0.14386E-05   0.98765E-03+j0.14386E-05   0.10092E-02+j0.14362E-05
```

Its complete inverse is:

```
 0.11275E+05-j0.25075E+02
-0.16292E+04+j0.16765E+01   0.40843E+04-j0.69776E+00
-0.94393E+04+j0.22581E+02  -0.24026E+04-j0.10384E+01   0.12579E+05-j0.22103E+02
```

In order to ground just the armor, we simply eliminate the third row and column of this matrix and re-invert, to obtain:

```
0.9412E-04+j0.2112E-06
0.3754E-04+j0.5205E-07    0.2598E-03+j0.4974E-07
```

This result compares well with a similar result obtained using the EMTP and requiring that the armor be grounded:

```
0.9465E-04+j0.2105E-06
0.3807E-04+j0.5129E-07    0.2603E-03+j0.4898E-07
```

The last example illustrates how to perform a calculation that is not easily done directly from the EMTP itself. Assume that we want to consider that the armor and sheath are connected together *but not grounded.* This can be done by combining the 2nd and 3rd rows and columns above, and then re-inverting the resulting 2 by 2 matrix:

```
0.1060E-02+j0.1645E-05
0.9890E-03+j0.1443E-05    0.1007E-02+j0.1437E-05
```

```
C LINE CONSTANTS input (illustrate bundling by matrix reduction).
BEGIN NEW DATA CASE
LINE CONSTANTS
METRIC
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  1   .5 .080033 4      1. 2.81432     -5.    10.
  2   .5 .080033 4      1. 2.81432      0.    10.
  2   .5 .080033 4      1. 2.81432      5.    10.
BLANK card terminates conductor cards
C Frequency cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f
    100.       60.        1.        110110                           1
BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

Figure 2.9: LINE CONSTANTS input data for generating per phase impedance matrix for conductor bundling example.

An equivalent procedure is used by the CABLE CONSTANTS program and can be used to, for example, connect armor to sheath on a cable, or to connect sheaths together at regular intervals.

We may add that an alternative procedure for performing this computation that does not require matrix inversion but rather only a partial LDU factorization of the impedance matrix is possible, and is actually used within the EMTP [1].

When a conductor such as the armor or sheath of a cable or the ground overhead conductors of an overhead line are grounded at frequent intervals, the procedure is to calculate the series parameters of the conductor without grounding, then invert the corresponding series impedance matrix, eliminate the rows and columns that correspond to the grounded conductors, and reinvert the resultant smaller matrix. Again, in reality the EMTP uses an equivalent but numerically more efficient partial LDU matrix factorization procedure. In most cases, all this is done automatically for you as you select the appropriate options within the CABLE CONSTANTS or LINE CONSTANTS programs.

Problem 2.5: Take the results of Problem 2.1 and use them to calculate by hand when the armor is grounded at very frequent intervals. Prepare input data to obtain result directly from the EMTP. Compare the results.

Problem 2.6: Repeat Problem 2.5 assuming the armor does not exist and compare the results.

2.7. Interpreting the Results of the CABLE CONSTANTS Routine

Once the CABLE CONSTANTS routine has been run, the problem is to interpret and use its results in the simulation of transients involving cable systems. You have a choice between Π sections models, distributed parameter models and frequency dependent distributed parameter models. Since we have not described frequency dependent models yet, this section illustrates how to use the CABLE CONSTANTS results in both Π section simulations and in distributed parameter representations of the system. The use of this information in the EMTP is exactly the same as in the case of the untransposed overhead line.

Problem 2.7: Figure 2.10(b) illustrates a portion of the typical EMTP output that you will be facing when you run the CABLE CONSTANTS model on a single phase cable. Using this data, prepare the necessary EMTP data lines to represent a 15 mile length of cable as a set of 5 Π sections. Assume all three phases are decoupled.

Problem 2.8: Using the same data, prepare the necessary EMTP data to represent the cable as a distributed parameter multi-modal line.

Problem 2.9: Figure 2.11(b) illustrates the CABLE CONSTANTS output for a symmetrically arranged pipe type cable. Using this output prepare the EMTP data lines necessary to simulate the cable both as Π sections and also distributed parameter lines.

Problem 2.10: Figure 2.12 illustrates two types of unsymmetrically arranged pipe type cables. For each of these cables, prepare the appropriate input data to calculate the parameters of the cable.

```
C CABLE CONSTANTS input for a single phase cable (armor grounded).
BEGIN NEW DATA CASE
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS                                                1
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2   -1    1    0    1    0    0         2
C Number of conductors in each SC cable          N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    3
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
       .01    .02525     .0518   .055525     .0675     .0735
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
C ----rhoA<------muA<-----muI3<epsilonI3
   7.54E-8        1.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4
        .6        0.
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
            20.          1000.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) CABLE CONSTANTS input data for a single phase cable (grounded armor).

```
********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ      **********
         RESISTANCE AND INDUCTANCE
ROW   0.9464740E-04   0.3807165E-04
      0.2105003E-06   0.5129401E-07
 1
ROW   0.3807165E-04   0.2603444E-03
      0.5129401E-07   0.4898482E-07
 2
          CONDUCTANCE AND CAPACITANCE
ROW   0.0000000E+00   0.0000000E+00
      0.2709761E-09  -0.2709761E-09
 1
ROW   0.0000000E+00   0.0000000E+00
     -0.2709761E-09   0.1268004E-08
 2
         VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
              ACTUAL MODES* TO NATURAL MODES:  AI
ROW      -0.2060779         1.0221491
         -6.2936482         1.7461846
 1
 ROW       1.0221491       -0.1882133
          1.7461839       63.2066574
 2
              NATURAL MODES TO ACTUAL MODES*:  A
ROW        0.1841349        1.0000000
          61.4604530        0.0000000
 1
ROW        0.9999999        0.2016123
           0.0000000       -8.0398197
 2
         CHARACTERISTIC IMPEDANCES, ACTUAL MODES*
ROW       31.4319077        7.1800327
          -1.1172684       -0.3227623
 1
ROW        7.1800327        7.6075511
          -0.3227623       -2.6951706
 2
                             TABLE OF MODAL QUANTITIES.
         MODAL     PROPAGATION        MODAL IMPEDANCE              MODAL
MODE   ATTENUATION   VELOCITY        REAL         IMAGINARY     SUSCEPTANCE**
         (DB/KM)      (M/S)             Z(OHM/M)                  IMY(MHO/M)
   1     0.17967E+00 0.13181E+09   0.241321E-03  0.257404E-03  0.763616E-05
   2     0.13813E-01 0.14957E+09   0.106420E-03  0.132049E-02  0.133399E-05
        CHARAC. IMP., NATURAL MODE    CHARAC. ADM., NATURAL MODE
         REAL          IMAGINARY          REAL          IMAGINARY
             SQRT(Z/Y)  (OHM)                SQRT(Y/Z)  (MHO)
        0.639295E+01 -0.228832E+01   0.138657E+00  0.496314E-01
        0.314846E+02 -0.134139E+01   0.317040E-01  0.135074E-02
```

(b) Output of part (a).

* "ACTUAL MODES" really means actual phase conductors. Notation will be changed in version 2.0 of the DCG/EPRI EMTP.

** There is also a nonzero shunt conductance not shown in the output, which is usually very small.

```
********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ    **********
          RESISTANCE AND INDUCTANCE
ROW   0.1061502E-02   0.1004926E-02   0.9885071E-03
 1    0.1651523E-05   0.1492316E-05   0.1438623E-05
ROW   0.1004926E-02   0.1227199E-02   0.9885071E-03
 2    0.1492316E-05   0.1490007E-05   0.1438623E-05
ROW   0.9885071E-03   0.9885071E-03   0.1010091E-02
 3    0.1438623E-05   0.1438623E-05   0.1436219E-05

           CONDUCTANCE AND CAPACITANCE
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00
 1    0.2709761E-09  -0.2709761E-09   0.0000000E+00
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00
 2   -0.2709761E-09   0.1268004E-08  -0.9970273E-09
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00
 3    0.0000000E+00  -0.9970273E-09   0.4090013E-05

           VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
               ACTUAL MODES TO NATURAL MODES:  AI
ROW       0.0000000         0.0000007         0.9999996
 1        0.0000000        61.3922005        -0.0000357
ROW      -0.2060778         1.0221484        -0.8178255
 2       -6.2935286         1.7461048         3.6884520
ROW       1.0221486        -0.1882090        -0.9242665
 3        1.7461326        63.2061806        -8.5777769

               NATURAL MODES TO ACTUAL MODES:  A
ROW       1.0013922         0.1841301         1.0000000
 1        0.1457481        61.4600716         0.0000000
ROW       1.0013922         1.0000000         0.2016123
 2        0.1457481        -0.0000001        -8.0396748
ROW       1.0000000        -0.0000007        -0.0000001
 3        0.0000000        60.4006577        52.6476593

          CHARACTERISTIC IMPEDANCES, ACTUAL MODES
ROW      32.0272865         7.7754068         0.5944844
 1       -1.1474603        -0.3529606        -0.0316554
ROW       7.7754068         8.2029200         0.5944828
 2       -0.3529606        -2.7253680        -0.0316549
ROW       0.5944844         0.5944828         0.5935782
 3       -0.0316554        -0.0316549        -0.0331172

                              TABLE OF MODAL QUANTITIES.
          MODAL     PROPAGATION        MODAL IMPEDANCE               MODAL
MODE   ATTENUATION   VELOCITY        REAL         IMAGINARY      SUSCEPTANCE
         (DB/KM)       (M/S)            Z(OHM/M)                 IMY(MHO/M)
  1    0.73904E+01 0.41201E+06   0.101009E-02  0.902403E-02  0.256920E-01
  2    0.17967E+00 0.13181E+09   0.241322E-03  0.257402E-03  0.763617E-05
  3    0.13813E-01 0.14957E+09   0.106420E-03  0.132049E-02  0.133399E-05

       CHARAC. IMP., NATURAL MODE   CHARAC. ADM., NATURAL MODE
           REAL         IMAGINARY        REAL         IMAGINARY
              SQRT(Z/Y)  (OHM)              SQRT(Y/Z)  (MHO)
       0.593578E+00 -0.331172E-01   0.167947E+01  0.937019E-01
       0.639292E+01 -0.228834E+01   0.138657E+00  0.496322E-01
       0.314846E+02 -0.134139E+01   0.317040E-01  0.135074E-02
```

(c) Output of a case similar to (a) except the armor is not grounded.

```
*********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ    **********
         RESISTANCE AND INDUCTANCE
      0.1061502E-02  0.9738354E-03  0.9731062E-03  0.1004926E-02  0.9738354E-03
      0.1651523E-05  0.9091257E-06  0.7705189E-06  0.1492316E-05  0.9091257E-06
ROW   0.9731062E-03  0.9885071E-03  0.9738354E-03  0.9731062E-03
      0.7705189E-06  0.1438623E-05  0.9091257E-06  0.7705189E-06
 1
      0.9738354E-03  0.1061502E-02  0.9738354E-03  0.9738354E-03  0.1004926E-02
      0.9091257E-06  0.1651523E-05  0.9091257E-06  0.9091257E-06  0.1492316E-05
ROW   0.9738354E-03  0.9738354E-03  0.9885071E-03  0.9738354E-03
      0.9091257E-06  0.9091257E-06  0.1438623E-05  0.9091257E-06
 2
      0.9731062E-03  0.9738354E-03  0.1061502E-02  0.9731062E-03  0.9738354E-03
      0.7705189E-06  0.9091257E-06  0.1651523E-05  0.7705189E-06  0.9091257E-06
ROW   0.1004926E-02  0.9731062E-03  0.9738354E-03  0.9885071E-03
      0.1492316E-05  0.7705189E-06  0.9091257E-06  0.1438623E-05
 3
      0.1004926E-02  0.9738354E-03  0.9731062E-03  0.1227199E-02  0.9738354E-03
      0.1492316E-05  0.9091257E-06  0.7705189E-06  0.1490007E-05  0.9091257E-06
ROW   0.9731062E-03  0.9885071E-03  0.9738354E-03  0.9731062E-03
      0.7705189E-06  0.1438623E-05  0.9091257E-06  0.7705189E-06
 4
      0.9738354E-03  0.1004926E-02  0.9738354E-03  0.9738354E-03  0.1227199E-02
      0.9091257E-06  0.1492316E-05  0.9091257E-06  0.9091257E-06  0.1490007E-05
ROW   0.9738354E-03  0.9738354E-03  0.9885071E-03  0.9738354E-03
      0.9091257E-06  0.9091257E-06  0.1438623E-05  0.9091257E-06
 5
      0.9731062E-03  0.9738354E-03  0.1004926E-02  0.9731062E-03  0.9738354E-03
      0.7705189E-06  0.9091257E-06  0.1492316E-05  0.7705189E-06  0.9091257E-06
ROW   0.1227199E-02  0.9731062E-03  0.9738354E-03  0.9885071E-03
      0.1490007E-05  0.7705189E-06  0.9091257E-06  0.1438623E-05
 6
      0.9885071E-03  0.9738354E-03  0.9731062E-03  0.9885071E-03  0.9738354E-03
      0.1438623E-05  0.9091257E-06  0.7705189E-06  0.1438623E-05  0.9091257E-06
ROW   0.9731062E-03  0.1010091E-02  0.9738354E-03  0.9731062E-03
      0.7705189E-06  0.1436219E-05  0.9091257E-06  0.7705189E-06
 7
      0.9738354E-03  0.9885071E-03  0.9738354E-03  0.9738354E-03  0.9885071E-03
      0.9091257E-06  0.1438623E-05  0.9091257E-06  0.9091257E-06  0.1438623E-05
ROW   0.9738354E-03  0.9738354E-03  0.1010091E-02  0.9738354E-03
      0.9091257E-06  0.9091257E-06  0.1436219E-05  0.9091257E-06
 8
      0.9731062E-03  0.9738354E-03  0.9885071E-03  0.9731062E-03  0.9738354E-03
      0.7705189E-06  0.9091257E-06  0.1438623E-05  0.7705189E-06  0.9091257E-06
ROW   0.9885071E-03  0.9731062E-03  0.9738354E-03  0.1010091E-02
      0.1438623E-05  0.7705189E-06  0.9091257E-06  0.1436219E-05
 9
          VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
              ACTUAL MODES TO NATURAL MODES:  AI
          0.0000000      0.0000000      0.0000000      0.0000001      0.0000001
          0.0000000      0.0000000      0.0000000     63.5968246     64.0829849
ROW       0.0000001      0.3385442      0.3558214      0.3385442
         63.5968208      0.1405777      0.6280946      0.1405768
 1
          0.0000000      0.0000000      0.0000000     -0.0000008      0.0000000
          0.0000000      0.0000000      0.0000000     55.5138321      0.0000000
ROW       0.0000008     -0.4999993      0.0000000      0.4999997
         55.5138397     -0.0000737    -21.2029209     -0.0000697
 2
          0.0000000      0.0000000      0.0000000     -0.0000007      0.0000014
          0.0000000    -37.6394196      0.0000000     55.8676300     55.3787575
ROW      -0.0000007     -0.3385439      0.6442107     -0.3385440
         55.8676300      0.1404894     -0.3470227      0.1404897
 3
```

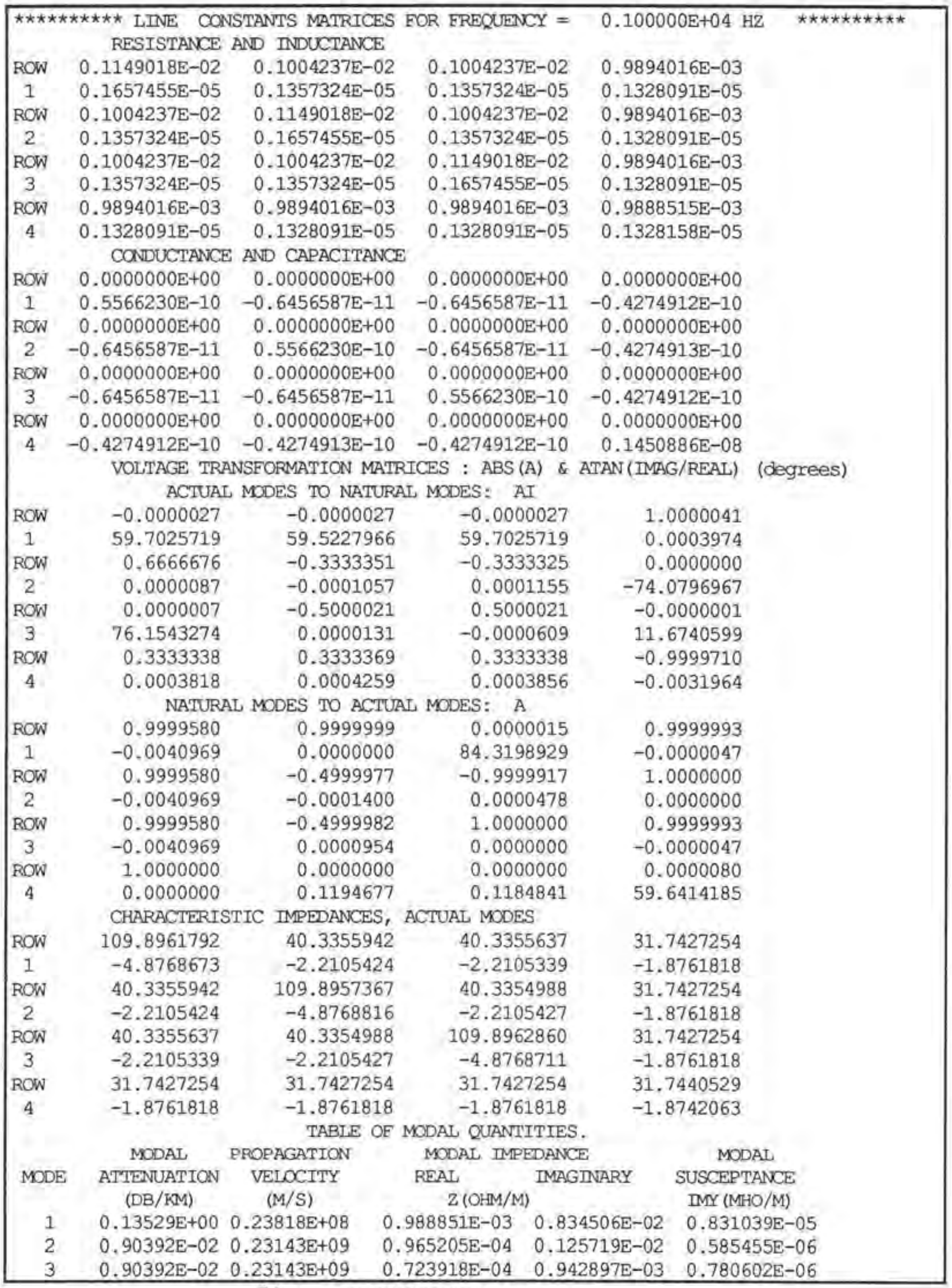
```
         0.0697355     -0.1327002      0.0697594     -0.3460283      0.6584599
        -6.1650772     -6.6539512     -6.1500068      1.8817780      1.3928976
ROW     -0.3461467      0.2761623     -0.5309490      0.2755536
         1.8968431      4.0355625      3.7474437      3.8929930
 4
        -0.1030234      0.0000227      0.1030218      0.5111189     -0.0001124
        -6.2935028     50.4457932     -6.2969837      1.7497885     58.5196266
ROW     -0.5111114     -0.4079484      0.0049863      0.4108010
         1.7463121      3.3398407     68.0097046      4.2655296
 5
        -0.0697781     -0.0733494     -0.0697706      0.3460645      0.3637762
        -6.1464295     -5.6533699     -6.1465707      1.8905296      2.3835878
ROW      0.3460269     -0.2768716     -0.2904187     -0.2758459
         1.8903886      3.7091069      4.0316663      3.4474473
 6
        -0.0001409      1.0222017     -0.0001409      0.0002397     -0.1883643
       -62.5762939      1.7455038    -62.5795898      7.5982490     63.1351433
ROW      0.0002397      0.0057329     -0.9393929      0.0069459
         7.5912609     28.8926010     -8.1659803     23.6497383
 7
         1.0221856      0.0000611     -0.0000658     -0.1883138      0.0002041
         1.7456465    -79.3168869    -65.4335556     63.1558228     10.0675993
ROW      0.0001119     -0.9254428      0.0230424      0.0177868
         4.7542491     -8.2516060      4.2481208      1.4274994
 8
         0.0000285      0.0000611      1.0221856      0.0000953      0.0002041
       -82.1237793    -79.3117142      1.7456462      7.2632494     10.0637197
ROW     -0.1883138      0.0307042      0.0301842     -0.9195346
        63.1558228     -2.4481704     -1.6407950     -8.0569172
 9
                         TABLE OF MODAL QUANTITIES.
         MODAL     PROPAGATION        MODAL IMPEDANCE              MODAL
MODE  ATTENUATION    VELOCITY        REAL         IMAGINARY     SUSCEPTANCE
        (DB/KM)       (M/S)              Z(OHM/M)                IMY(MHO/M)
 1    0.14553E+02 0.27727E+06   0.974071E-03  0.708396E-02  0.722005E-01
 2    0.39808E+00 0.60610E+06   0.184923E-04  0.209136E-02  0.513841E-01
 3    0.47791E+00 0.71426E+06   0.360201E-04  0.194007E-02  0.398806E-01
 4    0.17972E+00 0.13180E+09   0.156547E-03  0.164903E-03  0.118573E-04
 5    0.17970E+00 0.13180E+09   0.120698E-03  0.128745E-03  0.152697E-04
 6    0.17966E+00 0.13182E+09   0.848451E-04  0.925503E-04  0.214403E-04
 7    0.13824E-01 0.14957E+09   0.106518E-03  0.132048E-02  0.133400E-05
 8    0.13821E-01 0.14957E+09   0.106488E-03  0.132048E-02  0.133399E-05
 9    0.13821E-01 0.14957E+09   0.106488E-03  0.132048E-02  0.133399E-05
```

(d) Partial output of a three phase cable system (3 single phase single core coaxial cables in a flat layout) with ungrounded armor.

Figure 2.10: CABLE CONSTANTS input data and output for single phase coaxial cables.

```
C CABLE CONSTANTS input for a single phase pipe type cable (symmetrical
C arrangement)
BEGIN NEW DATA CASE
C Cable constants card------------------------------------><N<-------------->
CABLE CONSTANTS                                              0
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    3   -1    3    0    1    0    0    1    0
C Parameters of the conducting pipe
C -----RP1<------RP2<------RP3<------rho<-------mu<-epsilon1<-epsilon2
     .1061     .1261     .1461   7.54E-8        1.        1.       3.5
C Location of each SC cable within the conducting pipe
C ---Dist1<---Theta1<----Dist2<---Theta2<----Dist3<---Theta3<----Dist4<---Theta4
     .0666       90.     .0666      210.     .0666      -30.
C Number of conductors for each SC cable         N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    1    1    1
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
         0     .0140    .02794
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
   1.78E-8        1.        1.       3.5
C Second and third cable
         0     .0140    .02794
   1.78E-8        1.        1.       3.5
         0     .0140    .02794
   1.78E-8        1.        1.       3.5
C Vertical distance between center of the conducting pipe and the earth surface
C --center
       1.0
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
           20.           1000.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

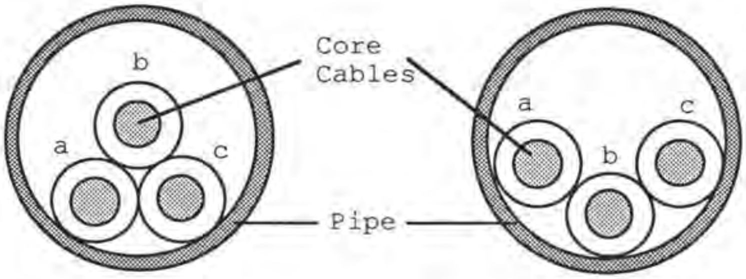
(a) CABLE CONSTANTS input data.



```
********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ    **********
          RESISTANCE AND INDUCTANCE
ROW   0.1149018E-02   0.1004237E-02   0.1004237E-02   0.9894016E-03
 1    0.1657455E-05   0.1357324E-05   0.1357324E-05   0.1328091E-05
ROW   0.1004237E-02   0.1149018E-02   0.1004237E-02   0.9894016E-03
 2    0.1357324E-05   0.1657455E-05   0.1357324E-05   0.1328091E-05
ROW   0.1004237E-02   0.1004237E-02   0.1149018E-02   0.9894016E-03
 3    0.1357324E-05   0.1357324E-05   0.1657455E-05   0.1328091E-05
ROW   0.9894016E-03   0.9894016E-03   0.9894016E-03   0.9888515E-03
 4    0.1328091E-05   0.1328091E-05   0.1328091E-05   0.1328158E-05
          CONDUCTANCE AND CAPACITANCE
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
 1    0.5566230E-10  -0.6456587E-11  -0.6456587E-11  -0.4274912E-10
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
 2   -0.6456587E-11   0.5566230E-10  -0.6456587E-11  -0.4274913E-10
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
 3   -0.6456587E-11  -0.6456587E-11   0.5566230E-10  -0.4274912E-10
ROW   0.0000000E+00   0.0000000E+00   0.0000000E+00   0.0000000E+00
 4   -0.4274912E-10  -0.4274913E-10  -0.4274912E-10   0.1450886E-08
          VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)  (degrees)
               ACTUAL MODES TO NATURAL MODES:  AI
ROW      -0.0000027      -0.0000027      -0.0000027       1.0000041
 1       59.7025719      59.5227966      59.7025719       0.0003974
ROW       0.6666676      -0.3333351      -0.3333325       0.0000000
 2        0.0000087      -0.0001057       0.0001155     -74.0796967
ROW       0.0000007      -0.5000021       0.5000021      -0.0000001
 3       76.1543274       0.0000131      -0.0000609      11.6740599
ROW       0.3333338       0.3333369       0.3333338      -0.9999710
 4        0.0003818       0.0004259       0.0003856      -0.0031964
               NATURAL MODES TO ACTUAL MODES:  A
ROW       0.9999580       0.9999999       0.0000015       0.9999993
 1       -0.0040969       0.0000000      84.3198929      -0.0000047
ROW       0.9999580      -0.4999977      -0.9999917       1.0000000
 2       -0.0040969      -0.0001400       0.0000478       0.0000000
ROW       0.9999580      -0.4999982       1.0000000       0.9999993
 3       -0.0040969       0.0000954       0.0000000      -0.0000047
ROW       1.0000000       0.0000000       0.0000000       0.0000080
 4        0.0000000       0.1194677       0.1184841      59.6414185
          CHARACTERISTIC IMPEDANCES, ACTUAL MODES
ROW     109.8961792      40.3355942      40.3355637      31.7427254
 1       -4.8768673      -2.2105424      -2.2105339      -1.8761818
ROW      40.3355942     109.8957367      40.3354988      31.7427254
 2       -2.2105424      -4.8768816      -2.2105427      -1.8761818
ROW      40.3355637      40.3354988     109.8962860      31.7427254
 3       -2.2105339      -2.2105427      -4.8768711      -1.8761818
ROW      31.7427254      31.7427254      31.7427254      31.7440529
 4       -1.8761818      -1.8761818      -1.8761818      -1.8742063
                             TABLE OF MODAL QUANTITIES.
          MODAL     PROPAGATION        MODAL IMPEDANCE              MODAL
 MODE   ATTENUATION   VELOCITY       REAL         IMAGINARY     SUSCEPTANCE
          (DB/KM)       (M/S)              Z(OHM/M)              IMY(MHO/M)
   1    0.13529E+00 0.23818E+08   0.988851E-03  0.834506E-02  0.831039E-05
   2    0.90392E-02 0.23143E+09   0.965205E-04  0.125719E-02  0.585455E-06
   3    0.90392E-02 0.23143E+09   0.723918E-04  0.942897E-03  0.780602E-06
```

(b) CABLE CONSTANTS output.

Figure 2.11: CABLE CONSTANTS input data and output for a symmetric pipe type cable system.



(a) Trefoil arrangement. (b) Flat arrangement.

Figure 2.12: Unsymmetrically arranged pipe type cables.

2.8. The effect of Frequency and Ground Resistivity on Cables

The modal parameters of most cable systems are dependent to a greater or lesser degree on the frequency at which they are measured. Voltage and current modal transformation matrices also tend to be significantly frequency dependent, except for symmetric arrangements of the phase cables. The dependence of modal transformation matrices on frequency only occurs up to a frequency of 1 to 2 kHz, after which the modal parameters of the cable continue to be frequency dependent, but the modal transformation matrices are no longer significantly frequency dependent. We illustrate here the modal parameters for a three phase cable system and comparable results are obtained using the CABLE CONSTANTS program as shown in Figure 2.13.

Voltage transformation matrix $[T_v]^{-1}$ for the system at f = 10 Hz:

$$\begin{array}{c|ccccccccc|c}
 & & \text{core} & & & \text{sheath} & & & \text{armor} & & \\
 & a & b & c & a & b & c & a & b & c & \\
\hline
 & 0 & 0 & 0 & .006 & .006 & .006 & .337 & .348 & .337 & 1 \\
 & .002 & 0 & -.002 & -.078 & 0 & .078 & -.466 & 0 & .466 & 2 \\
 & .004 & -.007 & .004 & -.073 & .141 & -.073 & -.287 & .555 & -.287 & 3 \\
 & -.019 & -.020 & -.019 & .343 & .354 & .343 & -.325 & -.336 & -.325 & 4 \\
[T_v]^{-1}= & -.026 & 0 & .026 & .473 & 0 & -.473 & .482 & 0 & .482 & 5 \\
 & .015 & -.030 & .015 & -.290 & -.562 & -.290 & .314 & -.607 & .314 & 6 \\
 & .343 & .354 & .343 & -.115 & -.119 & -.115 & -.267 & -.276 & -.267 & 7 \\
 & -.508 & 0 & .508 & .183 & 0 & -.183 & .396 & 0 & -.396 & 8 \\
 & -.343 & .663 & -.343 & .129 & -.249 & .129 & .268 & -.517 & .268 & 9 \\
\hline
 & & & & & & & & & & \uparrow \\
 & & & & & & & & & & \text{Mode}
\end{array}$$

Voltage transformation matrix $[T_v]^{-1}$ at f > 10 kHz:

$$[T_v]^{-1} = \begin{array}{ccccccccc|c}
 & \text{core} & & & \text{sheath} & & & \text{armor} & & \\
a & b & c & a & b & c & a & b & c & \\
0 & 0 & 0 & 0 & 0 & 0 & .340 & .363 & .340 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & -.500 & 0 & .500 & 2 \\
0 & 0 & 0 & 0 & 0 & 0 & -.340 & .637 & -.340 & 3 \\
0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 4 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 5 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 6 \\
1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 7 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 8 \\
0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 9 \\
 & & & & & & & & & \uparrow \\
 & & & & & & & & & \text{Mode}
\end{array}$$

Notice that the effect of frequency on the cable parameters is significant in this case. The most notable effects are in modes #4 to #6 and in modes #7 to #9. Modes #4 to #6 at low frequency are combined sheath-armor modes involving all three phases. At high frequencies these modes continue to be sheath-armor modes, but each phase behaves independent of the others. Modes #7 to #9 at low frequencies are core-sheath-armor modes involving all three phases. At high frequencies these modes become purely core-sheath modes and each phase becomes independent of the others.

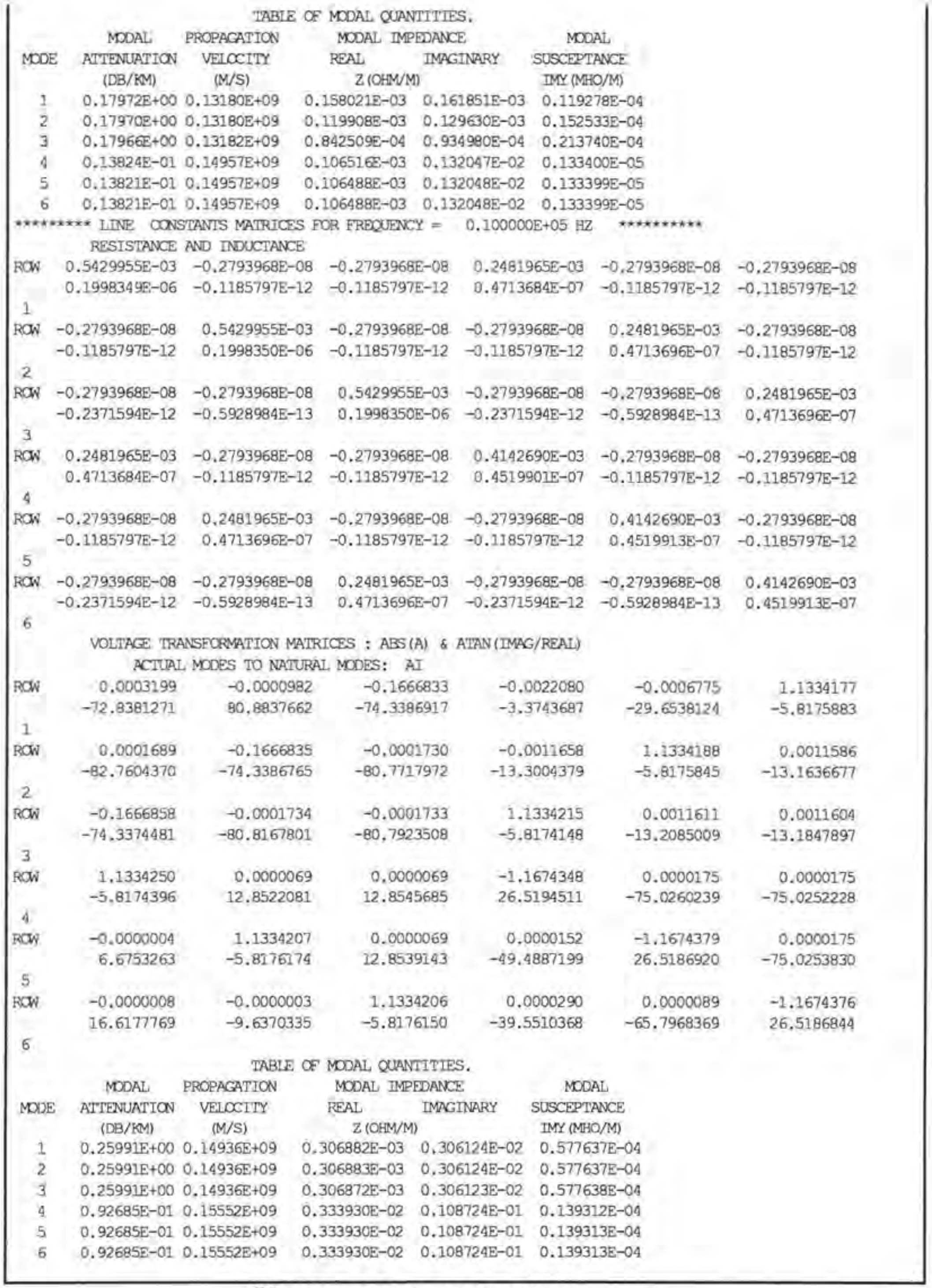
We add in passing that if the armor had been continuously grounded, the effect would have been much less noticeable.

```
C CABLE CONSTANTS input for a three phase SC coaxial cable system (illustrate
C the dependency of modal impedence on frequency).
BEGIN NEW DATA CASE
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS                                                1
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2   -1    3    0    1    0    0         2
C Number of conductors in each SC cable          N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    3    3    3
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
       .01    .02525     .0518   .055525     .0675     .0735
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
C ----rhoA<------muA<-----muI3<epsilonI3
   7.54E-8        1.
C Second and third cable
       .01    .02525     .0518   .055525     .0675     .0735
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
   7.54E-8        1.
       .01    .02525     .0518   .055525     .0675     .0735
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
   7.54E-8        1.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4
        .6       -1.        .6        0.        .6        1.
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
            20.             .1
            20.            60.
            20.          1000.
            20.         10000.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) CABLE CONSTANTS input data.

```
********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+00 HZ    **********
         RESISTANCE AND INDUCTANCE
ROW    0.1079376E-04   0.2529685E-06   0.2475441E-06   0.2537708E-06   0.2529685E-06   0.2475441E-06
       0.2529748E-05   0.1754960E-05   0.1617671E-05   0.2341125E-05   0.1754960E-05   0.1617671E-05
 1
ROW    0.2529685E-06   0.1080025E-04   0.2529685E-06   0.2529685E-06   0.2602583E-06   0.2529685E-06
       0.1754960E-05   0.2527181E-05   0.1754960E-05   0.1754960E-05   0.2338558E-05   0.1754960E-05
 2
ROW    0.2475441E-06   0.2529685E-06   0.1079376E-04   0.2475441E-06   0.2529685E-06   0.2537708E-06
       0.1617671E-05   0.1754960E-05   0.2529748E-05   0.1617671E-05   0.1754960E-05   0.2341125E-05
 3
ROW    0.2537708E-06   0.2529685E-06   0.2475441E-06   0.2231907E-03   0.2529685E-06   0.2475441E-06
       0.2341125E-05   0.1754960E-05   0.1617671E-05   0.2338614E-05   0.1754960E-05   0.1617671E-05
 4
ROW    0.2529685E-06   0.2602583E-06   0.2529685E-06   0.2529685E-06   0.2231971E-03   0.2529685E-06
       0.1754960E-05   0.2338558E-05   0.1754960E-05   0.1754960E-05   0.2336048E-05   0.1754960E-05
 5
ROW    0.2475441E-06   0.2529685E-06   0.2537708E-06   0.2475441E-06   0.2529685E-06   0.2231907E-03
       0.1617671E-05   0.1754960E-05   0.2341125E-05   0.1617671E-05   0.1754960E-05   0.2338614E-05
 6
         VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
             ACTUAL MODES TO NATURAL MODES:  AI
ROW       -0.0721225      -0.0739627      -0.0721224       0.3355283       0.3440895       0.3355281
          -0.3744761      -0.2496518      -0.3743011       0.1969323       0.3217511       0.1971086
 1
ROW        0.1074684      -0.0000104      -0.1074577      -0.4989086       0.0000484       0.4988596
          -0.0490576       0.4938415      -0.0492965       0.0182859       0.5170498       0.0180504
 2
ROW        0.0722196      -0.1408653       0.0722401      -0.3352679       0.6539448      -0.3353630
           0.0020018      -0.1211292       0.0052017       0.0507573      -0.0723706       0.0539625
 3
ROW        0.3355283       0.3440899       0.3355282       0.0049510       0.0050773       0.0049510
           0.1969598       0.3215064       0.1969638     -59.9491539     -59.8242073     -59.9483986
 4
ROW       -0.4989078      -0.0000007       0.4989085      -0.0051251      -0.0000001       0.0051250
           0.0189326      24.4689198       0.0189517      -8.4532661       2.1301367      -8.4531384
 5
ROW       -0.3353153       0.6539445      -0.3353157      -0.0034303       0.0066902      -0.0034302
           0.0527612      -0.0722369       0.0518362      -6.0959039      -6.2202559      -6.0981331
 6
                        TABLE OF MODAL QUANTITIES.
          MODAL    PROPAGATION      MODAL IMPEDANCE          MODAL
MODE   ATTENUATION  VELOCITY       REAL       IMAGINARY   SUSCEPTANCE
         (DB/KM)     (M/S)            Z(OHM/M)             IMY(MHO/M)
  1     0.25810E-02 0.20935E+07   0.769057E-04  0.140944E-05  0.231898E-08
  2     0.25896E-02 0.21048E+07   0.111217E-03  0.211210E-06  0.160053E-08
  3     0.25901E-02 0.21051E+07   0.145790E-03 -0.117579E-07  0.122096E-08
  4     0.20296E-03 0.19372E+08   0.389816E-05  0.131366E-05  0.388455E-09
  5     0.22427E-03 0.23030E+08   0.526187E-05  0.289965E-06  0.267753E-09
  6     0.22550E-03 0.23163E+08   0.689536E-05  0.292080E-06  0.204274E-09
*********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.600000E+02 HZ    **********
         RESISTANCE AND INDUCTANCE
ROW    0.4299919E-04   0.1106928E-06  -0.1735680E-07   0.2827655E-04   0.1106928E-06  -0.1735680E-07
       0.2411756E-06  -0.3444446E-08  -0.1730676E-08   0.5847136E-07  -0.3444446E-08  -0.1730676E-08
 1
ROW    0.1106891E-06   0.4290342E-04   0.1106891E-06   0.1106891E-06   0.2818078E-04   0.1106891E-06
      -0.3444292E-08   0.2424991E-06  -0.3444601E-08  -0.3444292E-08   0.5979488E-07  -0.3444601E-08
 2
ROW   -0.1735680E-07   0.1106964E-06   0.4299919E-04  -0.1735680E-07   0.1106964E-06   0.2827655E-04
      -0.1730445E-08  -0.3444523E-08   0.2411753E-06  -0.1730445E-08  -0.3444523E-08   0.5847105E-07
 3
ROW    0.2827655E-04   0.1106928E-06  -0.1735680E-07   0.2511935E-03   0.1106928E-06  -0.1735680E-07
       0.5847136E-07  -0.3444446E-08  -0.1730676E-08   0.5615041E-07  -0.3444446E-08  -0.1730676E-08
 4
ROW    0.1106891E-06   0.2818078E-04   0.1106891E-06   0.1106891E-06   0.2510978E-03   0.1106891E-06
      -0.3444292E-08   0.5979488E-07  -0.3444601E-08  -0.3444292E-08   0.5747393E-07  -0.3444601E-08
 5
ROW   -0.1735680E-07   0.1106964E-06   0.2827655E-04  -0.1735680E-07   0.1106964E-06   0.2511935E-03
      -0.1730445E-08  -0.3444523E-08   0.5847105E-07  -0.1730445E-08  -0.3444523E-08   0.5615010E-07
 6
```

```
         VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL) (degrees)
              ACTUAL MODES TO NATURAL MODES:  AI
ROW     -0.1016374    -0.0000004     0.1016352     0.5081981     0.0000019    -0.5081871
        -0.4900489    36.5097580    -0.4901102     0.1359794    36.7135048     0.1359234
 1
ROW     -0.0685636    -0.0712544    -0.0685721     0.3429057     0.3563633     0.3429484
        -0.0834467     0.2086402    -0.0835124     0.1345400     0.4266247     0.1344670
 2
ROW      0.0686182    -0.1320643     0.0686189    -0.3428855     0.6599256    -0.3428890
        -0.5461574    -0.8383576    -0.5466788     0.2638361    -0.0283639     0.2633152
 3
ROW     -0.3428869     0.6599269    -0.3428873     0.0278697    -0.0536382     0.0278696
         0.2636501    -0.0282418     0.2633928    11.8090982    11.5173798    11.8090658
 4
ROW      0.5081967     0.0000032    -0.5081871    -0.0412947    -0.0000003     0.0412939
         0.1360810    14.5442619     0.1359293     9.0292368    32.6430893     9.0290422
 5
ROW      0.3429051     0.3563621     0.3429486    -0.0276305    -0.0287148    -0.0276340
         0.1344610     0.4263717     0.1344178     3.2450445     3.5370977     3.2451832
 6
                          TABLE OF MODAL QUANTITIES.
        MODAL     PROPAGATION      MODAL IMPEDANCE             MODAL
 MODE  ATTENUATION  VELOCITY      REAL       IMAGINARY     SUSCEPTANCE
         (DB/KM)     (M/S)            Z(OHM/M)              IMY(MHO/M)
   1   0.63768E-01 0.47982E+08  0.124747E-03  0.911004E-05  0.924454E-06
   2   0.64001E-01 0.48144E+08  0.874823E-04  0.606136E-05  0.131830E-05
   3   0.63646E-01 0.47920E+08  0.161881E-03  0.120060E-04  0.712040E-06
   4   0.51760E-02 0.13538E+09  0.270439E-04  0.596503E-04  0.123823E-06
   5   0.52247E-02 0.13606E+09  0.207442E-04  0.454815E-04  0.160811E-06
   6   0.52914E-02 0.13766E+09  0.143464E-04  0.311761E-04  0.229342E-06
********** LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ    **********
         RESISTANCE AND INDUCTANCE
ROW   0.9470456E-04  -0.6280607E-07  -0.2980232E-07   0.3812881E-04  -0.6280607E-07  -0.2980232E-07
      0.2105028E-06  -0.3631502E-11  -0.1408134E-11   0.5129653E-07  -0.3631502E-11  -0.1408134E-11
 1
ROW  -0.6280607E-07   0.9472872E-04  -0.6268965E-07  -0.6280607E-07   0.3815297E-04  -0.6268965E-07
     -0.3483278E-11   0.2105037E-06  -0.3557390E-11  -0.3483278E-11   0.5129742E-07  -0.3557390E-11
 2
ROW  -0.2997695E-07  -0.6286427E-07   0.9470468E-04  -0.2997695E-07  -0.6286427E-07   0.3812893E-04
     -0.1408134E-11  -0.3705615E-11   0.2105026E-06  -0.1408134E-11  -0.3705615E-11   0.5129638E-07
 3
ROW   0.3812881E-04  -0.6280607E-07  -0.2980232E-07   0.2604015E-03  -0.6280607E-07  -0.2980232E-07
      0.5129653E-07  -0.3631502E-11  -0.1408134E-11   0.4898734E-07  -0.3631502E-11  -0.1408134E-11
 4
ROW  -0.6280607E-07   0.3815297E-04  -0.6268965E-07  -0.6280607E-07   0.2604257E-03  -0.6268965E-07
     -0.3483278E-11   0.5129742E-07  -0.3557390E-11  -0.3483278E-11   0.4898823E-07  -0.3557390E-11
 5
ROW  -0.2997695E-07  -0.6286427E-07   0.3812893E-04  -0.2997695E-07  -0.6286427E-07   0.2604016E-03
     -0.1408134E-11  -0.3705615E-11   0.5129638E-07  -0.1408134E-11  -0.3705615E-11   0.4898719E-07
 6
         VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
              ACTUAL MODES TO NATURAL MODES:  AI
ROW      0.0696312    -0.1322748     0.0696662    -0.3455106     0.6563490    -0.3456843
        -6.2794833    -7.1916699    -6.3453779     1.7674314     0.8552367     1.7015294
 1
ROW     -0.1032207    -0.0004236     0.1028902     0.5120984     0.0021015    -0.5104587
        -5.9348826    63.7491760    -6.2742071     2.1086090    71.7941437     1.7692863
 2
ROW     -0.0696600    -0.0738144    -0.0696957     0.3454785     0.3660820     0.3456554
        -6.6231689    -4.6956639    -5.9809923     1.4137905     3.3412938     2.0559592
 3
ROW     -0.0001410     1.0222017    -0.0001411     0.0002400    -0.1883612     0.0002401
       -62.8373985     1.7454897   -62.4241676     7.2862849    63.1350670     7.7006450
 4
ROW      1.0221860     0.0000614    -0.0000660    -0.1883196     0.0002052     0.0001122
         1.7457199   -78.8707123   -65.5231094    63.1565399    10.5123634     4.5965633
 5
ROW      0.0000287     0.0000616     1.0221860     0.0000960     0.0002060    -0.1883170
       -82.3919373   -78.5149689     1.7456913     6.9989591    10.8573742    63.1561737
 6
```



```
                         TABLE OF MODAL QUANTITIES.
       MODAL    PROPAGATION     MODAL IMPEDANCE          MODAL
MODE  ATTENUATION  VELOCITY     REAL      IMAGINARY   SUSCEPTANCE
       (DB/KM)      (M/S)         Z(OHM/M)             IMY(MHO/M)
  1    0.17972E+00 0.13180E+09  0.158021E-03  0.161851E-03  0.119278E-04
  2    0.17970E+00 0.13180E+09  0.119908E-03  0.129630E-03  0.152533E-04
  3    0.17966E+00 0.13182E+09  0.842509E-04  0.934980E-04  0.213740E-04
  4    0.13824E-01 0.14957E+09  0.106516E-03  0.132047E-02  0.133400E-05
  5    0.13821E-01 0.14957E+09  0.106488E-03  0.132048E-02  0.133399E-05
  6    0.13821E-01 0.14957E+09  0.106488E-03  0.132048E-02  0.133399E-05
********* LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+05 HZ   **********
        RESISTANCE AND INDUCTANCE
ROW   0.5429955E-03  -0.2793968E-08  -0.2793968E-08   0.2481965E-03  -0.2793968E-08  -0.2793968E-08
      0.1998349E-06  -0.1185797E-12  -0.1185797E-12   0.4713684E-07  -0.1185797E-12  -0.1185797E-12
 1
ROW  -0.2793968E-08   0.5429955E-03  -0.2793968E-08  -0.2793968E-08   0.2481965E-03  -0.2793968E-08
     -0.1185797E-12   0.1998350E-06  -0.1185797E-12  -0.1185797E-12   0.4713696E-07  -0.1185797E-12
 2
ROW  -0.2793968E-08  -0.2793968E-08   0.5429955E-03  -0.2793968E-08  -0.2793968E-08   0.2481965E-03
     -0.2371594E-12  -0.5928984E-13   0.1998350E-06  -0.2371594E-12  -0.5928984E-13   0.4713696E-07
 3
ROW   0.2481965E-03  -0.2793968E-08  -0.2793968E-08   0.4142690E-03  -0.2793968E-08  -0.2793968E-08
      0.4713684E-07  -0.1185797E-12  -0.1185797E-12   0.4519901E-07  -0.1185797E-12  -0.1185797E-12
 4
ROW  -0.2793968E-08   0.2481965E-03  -0.2793968E-08  -0.2793968E-08   0.4142690E-03  -0.2793968E-08
     -0.1185797E-12   0.4713696E-07  -0.1185797E-12  -0.1185797E-12   0.4519913E-07  -0.1185797E-12
 5
ROW  -0.2793968E-08  -0.2793968E-08   0.2481965E-03  -0.2793968E-08  -0.2793968E-08   0.4142690E-03
     -0.2371594E-12  -0.5928984E-13   0.4713696E-07  -0.2371594E-12  -0.5928984E-13   0.4519913E-07
 6
        VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
            ACTUAL MODES TO NATURAL MODES:  AI
ROW        0.0003199      -0.0000982      -0.1666833      -0.0022080      -0.0006775       1.1334177
         -72.8381271      80.8837662     -74.3386917      -3.3743687     -29.6538124      -5.8175883
 1
ROW        0.0001689      -0.1666835      -0.0001730      -0.0011658       1.1334188       0.0011586
         -82.7604370     -74.3386765     -80.7717972     -13.3004379      -5.8175845     -13.1636677
 2
ROW       -0.1666858      -0.0001734      -0.0001733       1.1334215       0.0011611       0.0011604
         -74.3374481     -80.8167801     -80.7923508      -5.8174148     -13.2085009     -13.1847897
 3
ROW        1.1334250       0.0000069       0.0000069      -1.1674348       0.0000175       0.0000175
          -5.8174396      12.8522081      12.8545685      26.5194511     -75.0260239     -75.0252228
 4
ROW       -0.0000004       1.1334207       0.0000069       0.0000152      -1.1674379       0.0000175
           6.6753263      -5.8176174      12.8539143     -49.4887199      26.5186920     -75.0253830
 5
ROW       -0.0000008      -0.0000003       1.1334206       0.0000290       0.0000089      -1.1674376
          16.6177769      -9.6370335      -5.8176150     -39.5510368     -65.7968369      26.5186844
 6
                         TABLE OF MODAL QUANTITIES.
       MODAL    PROPAGATION     MODAL IMPEDANCE          MODAL
MODE  ATTENUATION  VELOCITY     REAL      IMAGINARY   SUSCEPTANCE
       (DB/KM)      (M/S)         Z(OHM/M)             IMY(MHO/M)
  1    0.25991E+00 0.14936E+09  0.306882E-03  0.306124E-02  0.577637E-04
  2    0.25991E+00 0.14936E+09  0.306883E-03  0.306124E-02  0.577637E-04
  3    0.25991E+00 0.14936E+09  0.306872E-03  0.306123E-02  0.577638E-04
  4    0.92685E-01 0.15552E+09  0.333930E-02  0.108724E-01  0.139312E-04
  5    0.92685E-01 0.15552E+09  0.333930E-02  0.108724E-01  0.139313E-04
  6    0.92685E-01 0.15552E+09  0.333930E-02  0.108724E-01  0.139313E-04
```

(b) CABLE CONSTANTS output.

Figure 2.13: Illustration of frequency dependency of modal impedance and transformation matrices using CABLE CONSTANTS. The matrices are calculated at frequencies 0.1 Hz, 60 Hz, 1 kHz and 10 kHz.

2.9. References

[1] Hermann W. Dommel et al, "Electromagnetic Transients Program Reference Book (EMTP Manual Theory)," Prepared for the Bonneville Power Administration, P. O. Box 3621, Portland, Oregon, 97208, August 1986.

SECTION 3

USING CABLE MODELS

This section illustrates several practical uses of cable models. Several simple examples from Workbook I are repeated here, with a cable replacing the corresponding overhead line. Many of the same effects seen on overhead lines also occur in cables. There are, however, several effects of unique interest in cable systems, such as the calculation of sheath voltages. This section studies primarily effects unique to cables. Also, in most cases only reasonably high frequency effects will be considered. The implication of this will be that the cable parameters will be calculated typically at about 1 kHz rather than 60 Hz. The consequences of using parameters calculated at a frequency other than 60 Hz are:

- There will be slight to noticeable discrepancies at fundamental frequency between the conditions calculated as initial conditions by the EMTP and the true initial conditions of the system. Items such as steady-state sheath circulating currents will not necessarily be accurately evaluated, unless the studies are repeated using different frequency parameter values.
- There will not be time domain initialization transients due to the cable. A smooth transition from the phasor steady-state solution at the higher frequency (e.g., 1 kHz) to the transient solution can be expected unless nonlinear elements are present. This means that you do not have to run a simulation for very long before applying the transient.
- The ultimate steady-state results will not be accurate if the simulation is continued for a very long time.

3.1. Typical Cable Problems

The electrical characteristics that make cables unique are their slower propagation velocity for all modes (particularly the ground return mode), the greater degree to which the cable parameters and modal transformation matrices depend on frequency, and the presence of coaxial propagation modes as the main modes by which cable voltages and currents are transmitted. Cable systems are subject to the same kinds of overvoltage due to faults, switching and lightning as overhead lines, only the problems become evident at much shorter lengths than that of overhead lines. Also, the greater shunt capacitance of cables makes cable switching operations prone to the same kinds of problems as some capacitor switching problems. In addition, one must worry about overvoltages induced not only in the conductor, but possibly overvoltages across the sheath insulation and possibly the armor insulation.

For cables with both sheath and armor, the sheath forms a coupling between the core conductor and the outer armor. As a result it may be necessary to, for example, ground the sheath of a cable at regular intervals to prevent excessive induced voltage buildup. This can result in undesirable circulating currents in the sheath. Crossbonding is used for heavy current ac cables because it results in significant economies in the cable system by reducing circulating sheath currents. Crossbonding means that the sheath of one phase in one cable section is connected to the sheath of a different phase in the next cable section. By cross-connecting the cable sheaths among the phases at regular intervals, the induced sheath voltages can be kept low under normal conditions without the need for grounding. The crossbonding points may or may not be grounded. Problems may occur in crossbonded cable systems during lightning or switching transients, and it is often of interest to study these overvoltages.

The information used to represent a cable model using the distributed parameter line is the modal information available from the CABLE CONSTANTS program, along with the modal transformation matrix $[T_i]^{-1}$. For most studies parameters evaluated at about 1 kHz will produce reasonable results, but this is not necessarily correct in all cases and judgment must be exercised.

Problem 3.1: Consider a cable system represented as nine sections of distributed parameter single phase coaxial cable, each consisting of a core and an ungrounded sheath. Obtain the parameters for the cable from the appropriate figure in the previous section. You may assume that all three phases are uncoupled, and that you wish to model the crossbonding in detail. The cable is crossbonded, and the crossbonding points are grounded by means of 20 Ω resistances. Illustrate how you would arrange the EMTP data case to model the crossbonding in detail.

Except for very fast transients, the combination of three crossbonded sections of cable exhibits a behavior in which the voltage of the sheaths in all three phases can be assumed to be the same. If we make the assumption that the voltage at all three sheaths is truly the same, then the three phase cables can be modeled as a single four mode line rather than a six mode line (there is only one sheath mode). Using this approach to model the crossbonded cable not only reduces the number of modes, but also reduces the number of nodes that must be considered. Instead of dealing with *n* minor sections we now deal with only *n/3* major cable sections.

To obtain the parameters used in this model, one must reduce by hand the information available from the CABLE CONSTANTS routine. The procedure involves nothing more than assuming that all three sheaths are connected to each other over their entire length. The reduction process was outlined in the previous section. We illustrate the procedure in conjunction with the solution to the following problem.

Problem 3.2: Consider that in the previous problem we are willing to represent only the major crossbonded sections of the cable. Provide a suitable representation of the cable system with only four modes and three major sections.

Exact Π circuit representations of cables are not suitable for transient analysis. Exact Π circuits are valid at single steady-state frequencies. Nominal Π circuits, however, can sometimes be used to represent cable systems. These Π circuit models have several limitations, such as they cannot represent frequency dependence and they are not suitable for fast transients. However, for short cable sections and slow transients represented with relatively large time steps, they may provide a better alternative for the representation of the cables besides the distributed parameter models. These are cases where the simple cable capacitances are much more important than the complicated series impedances.

The representation of cable systems using Π circuits is quite straightforward. To represent the cable as a nominal Π we must use the per phase rather than the modal information from the CABLE CONSTANTS routine.

Problem 3.3: Represent the six mode and four mode cables above by means of nominal Π circuit models. Obtain the data for the Π circuit from printouts in the previous section.

Problem 3.4: It is possible to have the EMTP automatically generate the Π sections for you, either with or without crossbonding. Prepare CABLE CONSTANTS data to have the EMTP generate the Π circuits for each section automatically.

3.2. Examples of Energization of a Grounded Sheath Cable System

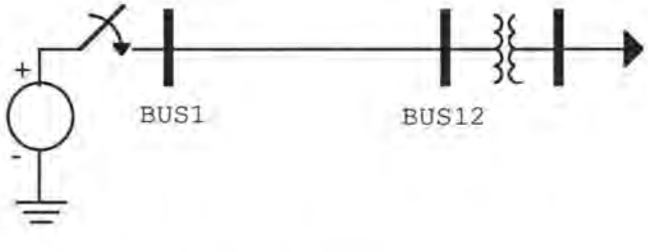
This section provides several examples of the use of cable models. All examples deal with the energization of a 15 mile cable from bus 1 to bus 12. The source representation at bus 1 is kept deliberately simple. At bus 12 we model a transformer connected to a secondary side load.

Figure 3.1(e) illustrates the receiving end voltages on the sheaths of the cables. The cables are represented using Π sections model considering nine Π sections. The sheath is assumed grounded at the sending end and at each Π section. Because the armor has been assumed grounded and the frequency of interest is high enough, each one of the three phases is represented as a separate cable. This is only an approximation. Notice that a significant voltage develops at the receiving end of the sheath.

Figure 3.2 illustrates the energization of the same cable under the same conditions, but using a distributed line model. Notice that the results are very similar to those of the Π sections model.

In both of these examples all three phases are virtually uncoupled. Also, the armor is grounded, which means that a good portion of the ground mode current (if any) will return through the armor. Because of this, the modeling problem is greatly simplified. Each cable phase can be represented independently, and furthermore, there are almost no frequency dependent effects on the transformation matrix to worry about. The frequency dependence of the modal impedances could change the results significantly, however.

Figure 3.3 illustrates the same example but with the cable crossbonded. Crossbonding virtually eliminates the voltages that develop on the sheath when a balanced energization takes place. You can crossbond a cable by manually interconnecting the intermediate sheath points to each other, or by having the EMTP CABLE CONSTANTS generate the data automatically. When a cable is crossbonded, even though we assume no coupling between phases within a cable section we cannot completely ignore the effect of coupling between the phases. If we energize all three phases the sheath voltages are greatly reduced. However, if a single phase is energized, we will have significant sheath voltages induced.



(a) Circuit diagram.

```
C CABLE CONSTANTS input for a single three conductors cable (represents each of
C the three seperated 3-phase cables.)
BEGIN NEW DATA CASE
C Cable constants card---------------------------------------><N<--------------->
CABLE CONSTANTS                                                1
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2   -1    1    0    1    0    0         2
C Number of conductors in each SC cable          N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    3
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
       .01    .02525     .0518   .055525     .0675     .0735
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
C ----rhoA<------muA<-----muI3<epsilonI3
   7.54E-8        1.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4
        .6        0.
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
            20.          1000.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(b) CABLE CONSTANTS input data.

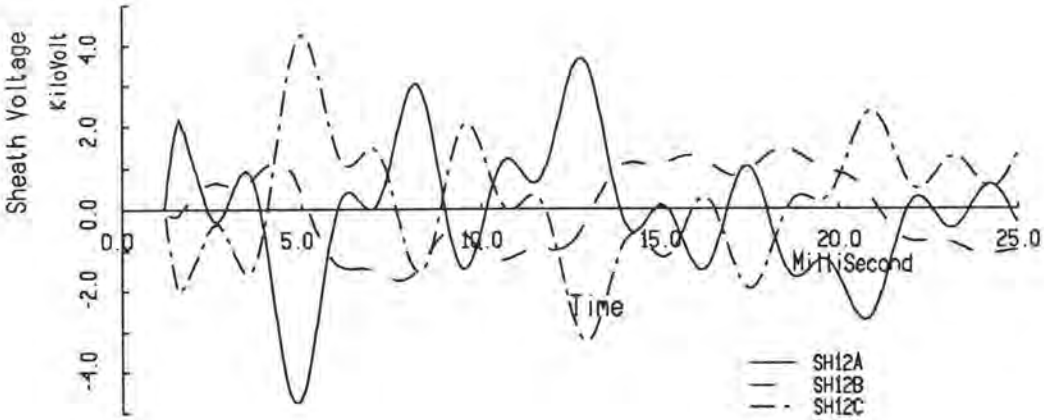
```
********* LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ    **********
         RESISTANCE AND INDUCTANCE
ROW   0.9464740E-04   0.3807165E-04
      0.2105003E-06   0.5129401E-07
 1
ROW   0.3807165E-04   0.2603444E-03
      0.5129401E-07   0.4898482E-07
 2
         CONDUCTANCE AND CAPACITANCE
ROW   0.0000000E+00   0.0000000E+00
      0.2709761E-09  -0.2709761E-09
 1
ROW   0.0000000E+00   0.0000000E+00
     -0.2709761E-09   0.1268004E-08
 2
         VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
              ACTUAL MODES TO NATURAL MODES:  AI
ROW        -0.2060779        1.0221491
           -6.2936482        1.7461846
 1
ROW         1.0221491       -0.1882133
            1.7461839       63.2066574
 2
              NATURAL MODES TO ACTUAL MODES:  A
ROW         0.1841349        1.0000000
           61.4604530        0.0000000
 1
ROW         0.9999999        0.2016123
            0.0000000       -8.0398197
 2
         CHARACTERISTIC IMPEDANCES, ACTUAL MODES
ROW        31.4319077        7.1800327
           -1.1172684       -0.3227623
 1
ROW         7.1800327        7.6075511
           -0.3227623       -2.6951706
 2
                              TABLE OF MODAL QUANTITIES.
           MODAL    PROPAGATION       MODAL IMPEDANCE             MODAL
 MODE   ATTENUATION   VELOCITY       REAL        IMAGINARY     SUSCEPTANCE
          (DB/KM)      (M/S)             Z(OHM/M)               IMY(MHO/M)
   1    0.17967E+00 0.13181E+09   0.241321E-03  0.257404E-03  0.763616E-05
   2    0.13813E-01 0.14957E+09   0.106420E-03  0.132049E-02  0.133399E-05
        CHARAC. IMP., NATURAL MODE    CHARAC. ADM., NATURAL MODE
          REAL        IMAGINARY          REAL        IMAGINARY
            SQRT(Z/Y)  (OHM)               SQRT(Y/Z)  (MHO)
        0.639295E+01 -0.228832E+01   0.138657E+00  0.496314E-01
        0.314846E+02 -0.134139E+01   0.317040E-01  0.135074E-02
```

(c) CABLE CONSTANTS output.

```
C Energization of a three phase 15 mile 230 kV cable (BUS 1 - BUS 12) connected
C to xfmr and RLC load.  Cable is represented as 9 pi-sections.  Circuit data
C is obtained from the "LINE CONSTANTS matrices" in the CABLE CONSTANTS output.
C
C             RESISTANCE AND INDUCTANCE              CONDUCTANCE AND CAPACITANCE
C  ROW    0.9464740E-04   0.3807165E-04    ROW   0.0000000E+00   0.0000000E+00
C   1     0.2105003E-06   0.5129401E-07     1    0.2709761E-09  -0.2709761E-09
C  ROW    0.3807165E-04   0.2603444E-03    ROW   0.0000000E+00   0.0000000E+00
C   2     0.5129401E-07   0.4898482E-07     2   -0.2709761E-09   0.1268004E-08
C
C Notice that the CABLE CONSTANTS output quantities for R, L and C are in ohm/m,
C H/m and F/m.  The EMTP requires the branch data in ohm, mH and uF.
BEGIN NEW DATA CASE
C ----dt<---tmax<---xopt<---copt------------------------------------------------>
  20.E-6  25.E-3      0.      0.
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                 <---Icat
      15       1                                                1
C
C ...........................  Circuit data  ..................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   O
  BUS12ABUS13A                  70.16                                          0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                   211.6 421.0                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
        BUS13A                        3.353                                    0
        BUS13B      BUS13A                                                     0
        BUS13C      BUS13A                                                     0
  THEVA SRC1A              0.714 70.68                                         0
  THEVB SRC1B THEVA SRC1A                                                      0
  THEVC SRC1C THEVA SRC1A                                                      0
C Bus-->Bus--><----------><----R<----L<----C<----R<----L<----C
 1BUS1A PI1AC             .25387.56461 .7268
 2      PI1AS             .10212.13758-.7268.69831.131393.4012
 1PI1AC PI2AC BUS1A PI1AC
 2PI1AS PI2AS
 1PI2AC PI3AC BUS1A PI1AC
 2PI2AS PI3AS
 1PI3AC PI4AC BUS1A PI1AC
 2PI3AS PI4AS
 1PI4AC PI5AC BUS1A PI1AC
 2PI4AS PI5AS
 1PI5AC PI6AC BUS1A PI1AC
 2PI5AS PI6AS
 1PI6AC PI7AC BUS1A PI1AC
 2PI6AS PI7AS
 1PI7AC PI8AC BUS1A PI1AC
 2PI7AS PI8AS
 1PI8AC BUS12ABUS1A PI1AC
 2PI8AS SH12A
C Bus-->Bus-->Bus-->Bus-->
 1BUS1B PI1BC BUS1A PI1AC
 2      PI1BS
 1PI1BC PI2BC BUS1B PI1BC
 2PI1BS PI2BS
 1PI2BC PI3BC BUS1B PI1BC
 2PI2BS PI3BS
 1PI3BC PI4BC BUS1B PI1BC
 2PI3BS PI4BS
 1PI4BC PI5BC BUS1B PI1BC
 2PI4BS PI5BS
 1PI5BC PI6BC BUS1B PI1BC
 2PI5BS PI6BS
```

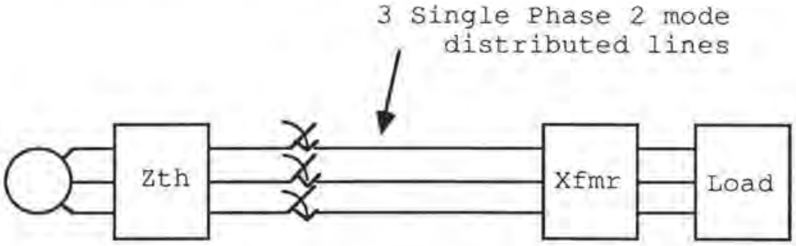
```
 1PI6BC PI7BC BUS1B PI1BC
 2PI6BS PI7BS
 1PI7BC PI8BC BUS1B PI1BC
 2PI7BS PI8BS
 1PI8BC BUS12BBUS1B PI1BC
 2PI8BS SH12B
C Bus-->Bus-->Bus-->Bus-->
 1BUS1C PI1CC BUS1A PI1AC
 2      PI1CS
 1PI1CC PI2CC BUS1C PI1CC
 2PI1CS PI2CS
 1PI2CC PI3CC BUS1C PI1CC
 2PI2CS PI3CS
 1PI3CC PI4CC BUS1C PI1CC
 2PI3CS PI4CS
 1PI4CC PI5CC BUS1C PI1CC
 2PI4CS PI5CS
 1PI5CC PI6CC BUS1C PI1CC
 2PI5CS PI6CS
 1PI6CC PI7CC BUS1C PI1CC
 2PI6CS PI7CS
 1PI7CC PI8CC BUS1C PI1CC
 2PI7CS PI8CS
 1PI8CC BUS12CBUS1C PI1CC
 2PI8CS SH12C
BLANK card terminates circuit data
C
C ............................  Switch data  .................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  SRC1A BUS1A      1.E-3     9999.         0                                   0
  SRC1B BUS1B      1.E-3     9999.         0                                   0
  SRC1C BUS1C      1.E-3     9999.         0                                   0
BLANK card terminates switch data
C
C ............................  Source data  .................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA       187.79       60.        0.        0.                 -1.     9999.
14THEVB       187.79       60.     -120.        0.                 -1.     9999.
14THEVC       187.79       60.      120.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................  Output requests ..............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  SH12A SH12B SH12C
BLANK card treminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(d) EMTP data case.



(e) Bus 12 sheath voltages.

Figure 3.1: Energization of a 15 mile cable system connecting bus 1 and bus 12 of the sample 13 bus system. A single phase cable model is used to represent each of the three phases in an uncoupled three phase cable system (armors are grounded).

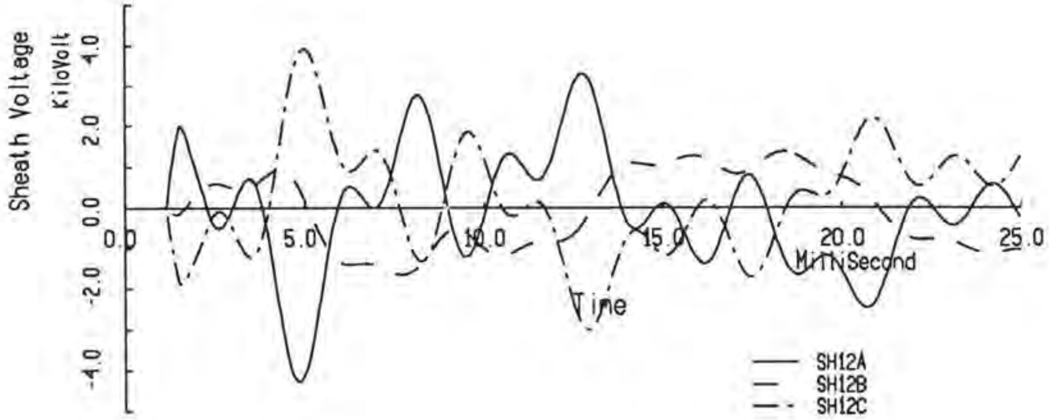


(a) Circuit diagram.

```
C Energization of a three phase 15 mile 230 kV cable (BUS 1 - BUS 12) connected
C to xfmr and RLC load.  Cable is modelled as three distributed-parameter lines,
C one for each cable.  Circuit data is obtained from the "Table of modal
C quantities" in the CABLE CONSTANTS output.
C
C LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ
C
C          VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
C               ACTUAL MODES TO NATURAL MODES:  AI
C ROW      -0.2060779         1.0221491
C  1       -6.2936482         1.7461846
C ROW        1.0221491       -0.1882133
C  2         1.7461839       63.2066574
C
C           MODAL    PROPAGATION       MODAL IMPEDANCE            MODAL
C MODE   ATTENUATION  VELOCITY        REAL        IMAGINARY    SUSCEPTANCE
C           (DB/KM)       (M/S)             Z(OHM/M)             IMY(MHO/M)
C   1    0.17967E+00 0.13181E+09   0.241321E-03  0.257404E-03  0.763616E-05
C   2    0.13813E-01 0.14957E+09   0.106420E-03  0.132049E-02  0.133399E-05
C
C Notice that the modal impedance and the modal susceptance are in ohm/m and
C mho/m.  EMTP input with xopt = copt = 0 and ILine = 0 in the distribute-
C parameter line requires R' in ohm/unit length,  in A in mH/unit length, B in
C uF/unit length.  The unit length used here is kilometer.  Remember the modal
C quantities are calculated at 1000 Hz in this example.  Note also that the
C voltage transformation matrices are provided in the CABLE CONSTANTS output
C instead of current transformation matrices.  If we assume Transpose([Ti]) =
C Inverse([Tv]), then an approximate, real (the matrix [AI], i.e. Inverse([Tv]),
C is in polar coordinate) transformation matrix can be used.
BEGIN NEW DATA CASE
C ----dt<---tmax<---xopt<---copt--------------------------------------------->
  20.E-6  25.E-3        0       0
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                  <---Icat
      15       1                                                1
C
C ........................... Circuit data ..................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   O
  BUS12ABUS13A                      70.16                                      0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                   211.6 421.0                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
        BUS13A                          3.353                                  0
        BUS13B      BUS13A                                                     0
        BUS13C      BUS13A                                                     0
  THEVA SRC1A              0.714 70.68                                         0
  THEVB SRC1B THEVA SRC1A                                                      0
  THEVC SRC1C THEVA SRC1A                                                      0
C Distributed parameter line data
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<--------------------->O
-1BUS1A BUS12A            .24132.040971.2153 24.14 0 0 2                       0
-2      SH12A             .10642.21016.21231 24.14 0 0 2                       0
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)                                           0
  -0.2000000   1.0200000
           0           0
   1.0200000  -0.0900000
           0           0
-1BUS1B BUS12B            .24132.040971.2153 24.14 0 0 2                       0
-2      SH12B             .10642.21016.21231 24.14 0 0 2                       0
  -0.2000000   1.0200000
           0           0
   1.0200000  -0.0900000
           0           0
```

```
-1BUS1C BUS12C            .24132.040971.2153 24.14 0 0 2                       0
-2      SH12C             .10642.21016.21231 24.14 0 0 2                       0
  -0.2000000   1.0200000
           0           0
   1.0200000  -0.0900000
           0           0
BLANK card terminates circuit data
C
C ........................... Switch data ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  SRC1A BUS1A     1.E-3      9999.         0                                   0
  SRC1B BUS1B     1.E-3      9999.         0                                   0
  SRC1C BUS1C     1.E-3      9999.         0                                   0
BLANK card terminates switch data
C
C ........................... Source data ...................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <---Tstart<----Tstop
14THEVA       187.79      60.        0.        0.                -1.     9999.
14THEVB       187.79      60.     -120.        0.                -1.     9999.
14THEVC       187.79      60.      120.        0.                -1.     9999.
BLANK card terminates source data
C
C ........................... Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  SH12A SH12B SH12C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(b) EMTP data case.



(c) Bus 12 sheath voltages.

Figure 3.2: Energization of an uncoupled three phase 15 mile cable system connecting bus 1 and bus 12 of the sample 13 bus system using distributed parameter line model. A single phase cable model is used to represent each of the three phases in an uncoupled three phase cable system (armors are grounded).

```
C CABLE CONSTANTS input for crossbonded cable (3 major sections).
BEGIN NEW DATA CASE
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS                                                1
PUNCH
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2   -1    3    0    0                   2
C                       X
C   N    N    I         m         C
C   P    c    R         a         n
C   A    r    s         j        Ra
C   I    o    e         o        Sm
C --S<---s<---p<--------r<-------Ge
   -3    1    0 8.04672e3       0.U
C Number of conductors in each SC cable          N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    3    3    3
C Geometrical and physical data for 1st cable.
C ------R1<--------R2<--------R3<--------R4<--------R5<--------R6<--------R7
       .01    .02525     .0518   .055525     .0675     .0735
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
C ----rhoA<------muA<-----muI3<epsilonI3
   7.54E-8        1.
C Second and third cable
       .01    .02525     .0518   .055525     .0675     .0735
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
   7.54E-8        1.
       .01    .02525     .0518   .055525     .0675     .0735
   1.78E-8        1.        1.       3.5    2.8E-7        1.        1.       3.5
   7.54E-8        1.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4
        .6       -1.        .6        0.        .6        1.
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
            20.          1000.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) Crossbonded cable input data.

```
$VINTAGE, 1
  UIN  4                           0.00000E+00
 1UIN  1U 11 1                     0.25402E+00    0.56462E+00    0.72682E+00
 2UIN  2U 11 2                    -0.16846E-03   -0.93430E-05    0.00000E+00
                                   0.25409E+00    0.56462E+00    0.72682E+00
 3UIN  3U 11 3                    -0.80405E-04   -0.37770E-05    0.00000E+00
                                  -0.16862E-03   -0.99393E-05    0.00000E+00
                                   0.25402E+00    0.56462E+00    0.72682E+00
 4UIN  4U 11 4                     0.10227E+00    0.13759E+00   -0.72682E+00
                                  -0.16846E-03   -0.97406E-05    0.00000E+00
                                  -0.79937E-04   -0.37770E-05    0.00000E+00
                                   0.69846E+00    0.13140E+00    0.34011E+01
 5UIN  4U 11 5                    -0.16846E-03   -0.93430E-05    0.00000E+00
                                   0.10234E+00    0.13759E+00   -0.72682E+00
                                  -0.16815E-03   -0.95418E-05    0.00000E+00
                                  -0.16846E-03   -0.93430E-05    0.00000E+00
                                   0.69852E+00    0.13140E+00    0.34011E+01
 6UIN  4U 11 6                    -0.80405E-04   -0.37770E-05    0.00000E+00
                                  -0.16862E-03   -0.99393E-05    0.00000E+00
                                   0.10227E+00    0.13759E+00   -0.72682E+00
                                  -0.80405E-04   -0.37770E-05    0.00000E+00
                                  -0.16862E-03   -0.99393E-05    0.00000E+00
                                   0.69846E+00    0.13140E+00    0.34011E+01
 1U 11 1U 12 1UIN  1U 11 1
 2U 11 2U 12 2
 3U 11 3U 12 3
 4U 11 6U 12 4
 5U 11 4U 12 5
 6U 11 5U 12 6
 1U 12 1U 13 1UIN  1U 11 1
 2U 12 2U 13 2
 3U 12 3U 13 3
 4U 12 6U 13 4
 5U 12 4U 13 4
 6U 12 5U 13 4
  U 13 4      UIN  4
 1U 13 1U 21 1UIN  1U 11 1
 2U 13 2U 21 2
 3U 13 3U 21 3
 4U 13 4U 21 4
 5U 13 4U 21 5
 6U 13 4U 21 6
 1U 21 1U 22 1UIN  1U 11 1
 2U 21 2U 22 2
 3U 21 3U 22 3
 4U 21 6U 22 4
 5U 21 4U 22 5
 6U 21 5U 22 6
 1U 22 1U 23 1UIN  1U 11 1
 2U 22 2U 23 2
 3U 22 3U 23 3
 4U 22 6U 23 4
 5U 22 4U 23 4
 6U 22 5U 23 4
  U 23 4      UIN  4
 1U 23 1U 31 1UIN  1U 11 1
 2U 23 2U 31 2
 3U 23 3U 31 3
 4U 23 4U 31 4
 5U 23 4U 31 5
 6U 23 4U 31 6
 1U 31 1U 32 1UIN  1U 11 1
 2U 31 2U 32 2
 3U 31 3U 32 3
```

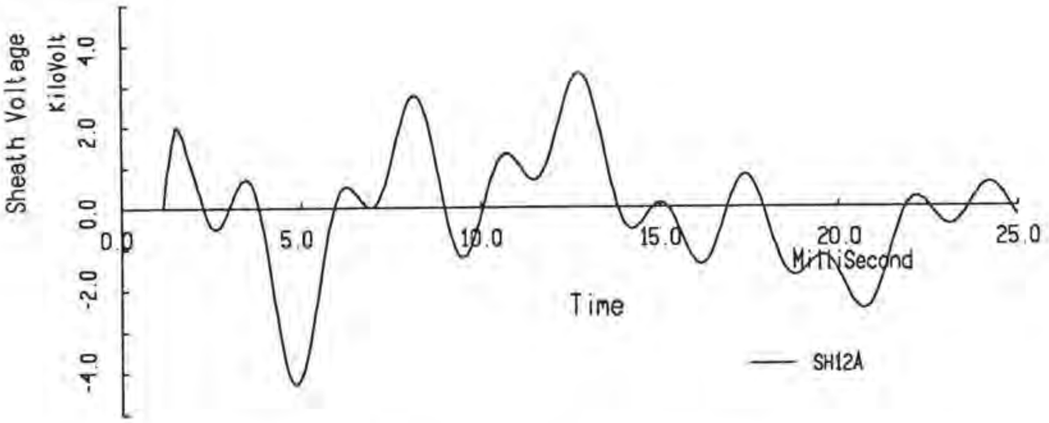
```
 4U 31 6U 32 4
 5U 31 4U 32 5
 6U 31 5U 32 6
 1U 32 1UOUT 1UIN  1U 11 1
 2U 32 2UOUT 2
 3U 32 3UOUT 3
 4U 32 6UOUT 4
 5U 32 4UOUT 4
 6U 32 5UOUT 4
  UOUT 4      UIN  4
$VINTAGE, 0
```

(b) Crossbonded cable output.

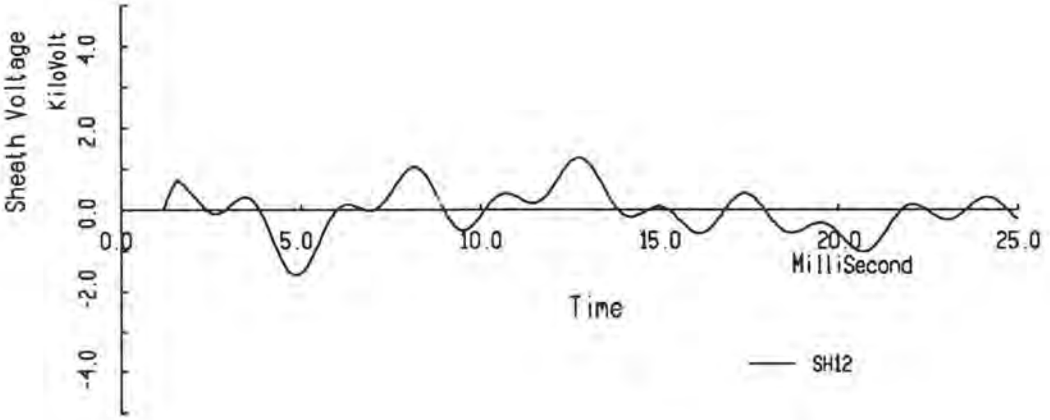
```
C Energization of phase "a" of a three phase 15 mile 230 kV cable (BUS 1 - BUS 12)
C connected to xfmr and RLC load.  Circuit data is obtained from the CABLE
C CONSTANTS punch output.  Note that the node names at the two ends of the punch
C data must be renamed appropriately to reflect the connectivity.
BEGIN NEW DATA CASE
C ----dt<---tmax<--------------------------------------------------------------->
  20.E-6  25.E-3
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                 <---Icat
     15       1                                               1
C
C ............................  Circuit data  ..................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   O
  BUS12ABUS13A                   70.16                                         0
  BUS12BBUS13BBUS12ABUS13A                                                     0
  BUS12CBUS13CBUS12ABUS13A                                                     0
  BUS13A                   211.6 421.0                                         0
  BUS13B      BUS13A                                                           0
  BUS13C      BUS13A                                                           0
        BUS13A                         3.353                                   0
        BUS13B      BUS13A                                                     0
        BUS13C      BUS13A                                                     0
  THEVA SRC1A              0.714 70.68                                         0
  THEVB SRC1B THEVA SRC1A                                                      0
  THEVC SRC1C THEVA SRC1A                                                      0
C
$VINTAGE, 1
 1BUS1A U 11 1                 0.25402E+00     0.56462E+00     0.72682E+00
 2BUS1B U 11 2                -0.16846E-03    -0.93430E-05     0.00000E+00
                               0.25409E+00     0.56462E+00     0.72682E+00
 3BUS1C U 11 3                -0.80405E-04    -0.37770E-05     0.00000E+00
                              -0.16862E-03    -0.99393E-05     0.00000E+00
                               0.25402E+00     0.56462E+00     0.72682E+00
 4SH1   U 11 4                 0.10227E+00     0.13759E+00    -0.72682E+00
                              -0.16846E-03    -0.97406E-05     0.00000E+00
                              -0.79937E-04    -0.37770E-05     0.00000E+00
                               0.69846E+00     0.13140E+00     0.34011E+01
 5SH1   U 11 5                -0.16846E-03    -0.93430E-05     0.00000E+00
                               0.10234E+00     0.13759E+00    -0.72682E+00
                              -0.16815E-03    -0.95418E-05     0.00000E+00
                              -0.16846E-03    -0.93430E-05     0.00000E+00
                               0.69852E+00     0.13140E+00     0.34011E+01
 6SH1   U 11 6                -0.80405E-04    -0.37770E-05     0.00000E+00
                              -0.16862E-03    -0.99393E-05     0.00000E+00
                               0.10227E+00     0.13759E+00    -0.72682E+00
                              -0.80405E-04    -0.37770E-05     0.00000E+00
                              -0.16862E-03    -0.99393E-05     0.00000E+00
                               0.69846E+00     0.13140E+00     0.34011E+01
 1U 11 1U 12 1BUS1A U 11 1
 2U 11 2U 12 2
 3U 11 3U 12 3
 4U 11 6U 12 4
 5U 11 4U 12 5
 6U 11 5U 12 6
 1U 12 1U 13 1BUS1A U 11 1
 2U 12 2U 13 2
 3U 12 3U 13 3
 4U 12 6U 13 4
 5U 12 4U 13 4
 6U 12 5U 13 4
 1U 13 1U 21 1BUS1A U 11 1
 2U 13 2U 21 2
 3U 13 3U 21 3
 4U 13 4U 21 4
 5U 13 4U 21 5
```

```
 6U 13 4U 21 6
 1U 21 1U 22 1BUS1A U 11 1
 2U 21 2U 22 2
 3U 21 3U 22 3
 4U 21 6U 22 4
 5U 21 4U 22 5
 6U 21 5U 22 6
 1U 22 1U 23 1BUS1A U 11 1
 2U 22 2U 23 2
 3U 22 3U 23 3
 4U 22 6U 23 4
 5U 22 4U 23 4
 6U 22 5U 23 4
 1U 23 1U 31 1BUS1A U 11 1
 2U 23 2U 31 2
 3U 23 3U 31 3
 4U 23 4U 31 4
 5U 23 4U 31 5
 6U 23 4U 31 6
 1U 31 1U 32 1BUS1A U 11 1
 2U 31 2U 32 2
 3U 31 3U 32 3
 4U 31 6U 32 4
 5U 31 4U 32 5
 6U 31 5U 32 6
 1U 32 1BUS12ABUS1A U 11 1
 2U 32 2BUS12B
 3U 32 3BUS12C
 4U 32 6SH12
 5U 32 4SH12
 6U 32 5SH12
$VINTAGE, 0
BLANK card terminates circuit data
C
C ...........................  Switch data  ..................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                 O
  SH1               -1.E-3      9999.        0                                0
  SRC1A BUS1A        1.E-3      9999.        0                                0
  SRC1B BUS1B        9999.      9999.        0                                0
  SRC1C BUS1C        9999.      9999.        0                                0
BLANK card terminates switch data
C
C ...........................  Source data  ..................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA        187.79       60.        0.         0.                 -1.     9999.
14THEVB        187.79       60.     -120.         0.                 -1.     9999.
14THEVC        187.79       60.      120.         0.                 -1.     9999.
BLANK card terminates source data
C
C ...........................  Output requests ..............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  SH12
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

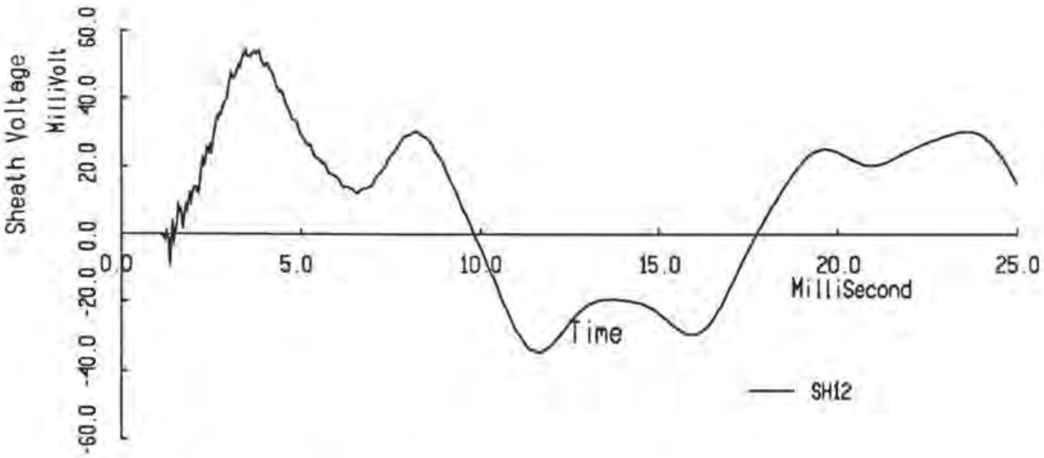
(c) EMTP data case.



(d) Bus 12 sheath voltage for energizing phase "a" (no crossbonding).



(e) Bus 12 sheath voltage for energizing phase "a" (crossbonded).



(f) Bus 12 sheath voltage for energizing all three phases (crossbonded). Notice the magnitude of the sheath voltage in (f) is much smaller than that of (d) and (e).

Figure 3.3: Energization of a 15 mile crossbonded cable.

Breaking up a distributed parameter line into shorter distributed parameter lines can produce significant inaccuracies when the ratio of travel time of a mode τ is not an exact multiple of the time step Δt used in the simulation [1]. Figure 3.4 illustrates the effect of dividing up a distributed parameter single mode line into 9 sections. Notice the pronounced effect on the receiving end voltage. This problem can be partially solved by using a smaller time step, as shown.

Finally, Figure 3.5 illustrates the case of energization of a symmetric pipe type cable, no sheaths, using a distributed parameter model.

All these examples have neglected two very important aspects of cable system modeling: the effect of frequency on the modal parameters of the cable, and the effect of frequency on the modal transformation matrices themselves. These effects are considered in a later section.

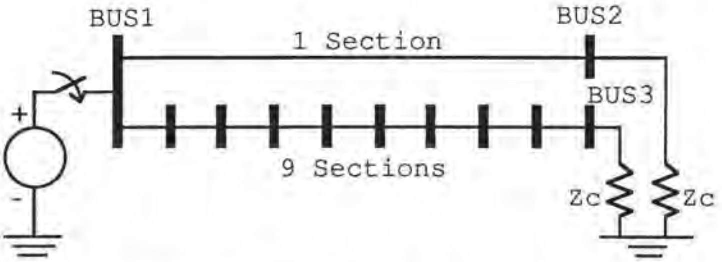
Problem 3.5: Modify one of the examples above to consider the case of a cable without armor.

Problem 3.6: Modify one of the examples above to study the effect of sheath grounding resistance.

Problem 3.7: Change the examples above to study the effect on overvoltage due to lightning.

Problem 3.8: Change the examples above to calculate circulating sheath currents.

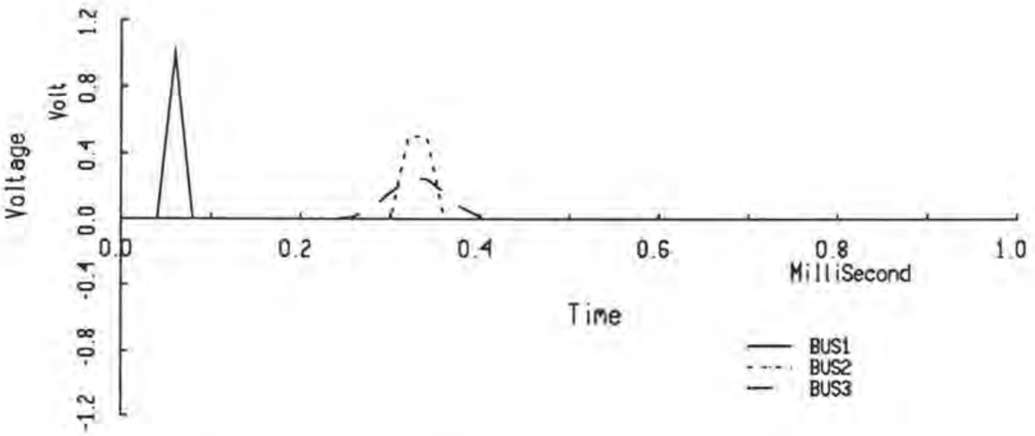
Problem 3.9: Reduce the 9 section model to a reasonable 3 section model.



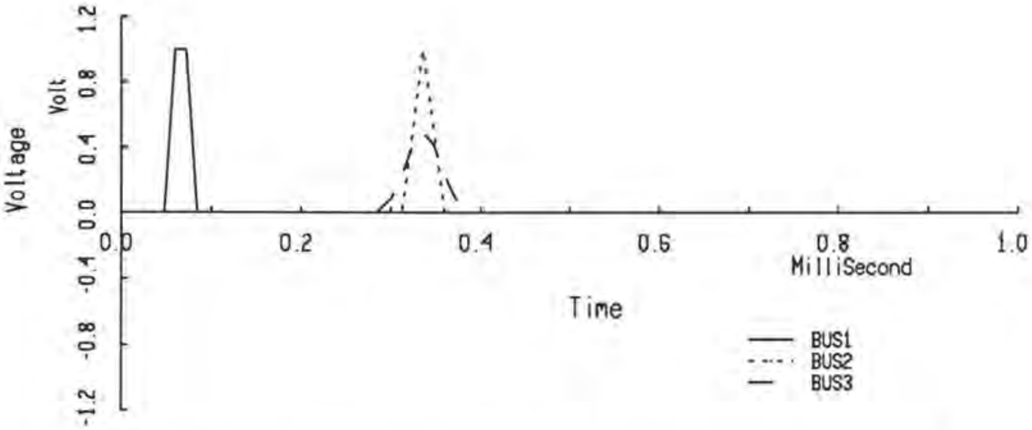
(a) Circuit diagram.

```
C Effect on breaking up distributed parameter line when tau is not an exact
C multiple of dt.  Comparing the receiving end voltages of a single distributed
C parameter line model to 9 distributed parameter lines model with voltage pulse
C input and both lines are terminated with the characteristic impedance.
BEGIN NEW DATA CASE
C ----dt<---tmax<--------------------------------------------------------------->
  20.E-6  1.0E-3
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                <---Icat
      15       1                                               1
C
C ............................ Circuit data ....................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                   0
  BUS1                        1.                                               0
  BUS2                        1.                                               0
  BUS3                        1.                                               0
C Distributed parameter line data
0
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0                       0
-1BUS1  BUS2              .00000    1..27E-3    9. 2 0 0                       0
-1BUS1  PI1               .00000    1..03E-3    1. 2 0 0                       0
-1PI1   PI2   BUS1  PI1                                                        0
-1PI2   PI3   BUS1  PI1                                                        0
-1PI3   PI4   BUS1  PI1                                                        0
-1PI4   PI5   BUS1  PI1                                                        0
-1PI5   PI6   BUS1  PI1                                                        0
-1PI6   PI7   BUS1  PI1                                                        0
-1PI7   PI8   BUS1  PI1                                                        0
-1PI8   BUS3  BUS1  PI1                                                        0
BLANK card terminates circuit data
C
C ............................ Switch data ....................................
BLANK card terminates switch data
C
C ............................ Source data ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
11BUS1        1.0000        0.        0.        0.              60.E-6    80.E-6
BLANK card terminates source data
C
C ............................ Output requests ................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS1  BUS2  BUS3
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(b) EMTP data case.



(c) Effect of dispersion of the impulse voltage at both bus 2 and bus 3 when τ is not an integer multiple of Δt.



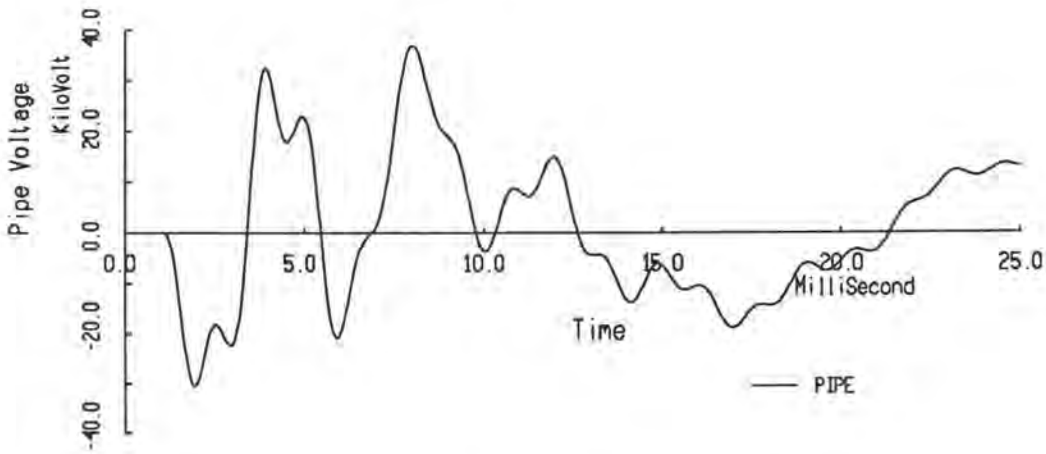
(d) By reducing Δt, while τ remains a non-integer multiple of Δt for both bus 2 and bus 3. The receiving end voltages resemble the sending end voltage much more closely.

Figure 3.4: Effect of dividing up distributed parameter lines into smaller sections with the travel time τ not an integer multiple of Δt. The propagation of a voltage pulse on a single mode line is illustrated.

```
C Energize phase "a" of a three phase 15 mile 230 kV pipe type cable (BUS 1 - BUS 12)
C connected to xfmr and RLC load.  Cable is modelled as distributed parameter
C line.  Circuit data is obtained from the "Table of modal quantities" in the
C CABLE CONSTANTS output.
C
C LINE  CONSTANTS MATRICES FOR FREQUENCY =   0.100000E+04 HZ
C
C          VOLTAGE TRANSFORMATION MATRICES : ABS(A) & ATAN(IMAG/REAL)
C               ACTUAL MODES TO NATURAL MODES:  AI
C ROW     -0.0000027       -0.0000027       -0.0000027        1.0000041
C  1      59.7025719       59.5227966       59.7025719        0.0003974
C ROW      0.6666676       -0.3333351       -0.3333325        0.0000000
C  2       0.0000087       -0.0001057        0.0001155      -74.0796967
C ROW      0.0000007       -0.5000021        0.5000021       -0.0000001
C  3      76.1543274        0.0000131       -0.0000609       11.6740599
C ROW      0.3333338        0.3333369        0.3333338       -0.9999710
C  4       0.0003818        0.0004259        0.0003856       -0.0031964
C
C           MODAL    PROPAGATION       MODAL IMPEDANCE            MODAL
C MODE    ATTENUATION  VELOCITY        REAL         IMAGINARY    SUSCEPTANCE
C            (DB/KM)      (M/S)              Z(OHM/M)              IMY(MHO/M)
C   1     0.13529E+00 0.23818E+08  0.988851E-03  0.834506E-02  0.831039E-05
C   2     0.90392E-02 0.23143E+09  0.965205E-04  0.125719E-02  0.585455E-06
C   3     0.90392E-02 0.23143E+09  0.723918E-04  0.942897E-03  0.780602E-06
C   4     0.85470E-02 0.24535E+09  0.625350E-04  0.812692E-03  0.805795E-06
C
C Notice that the modal impedance and the modal susceptance are in ohm/m and
C mho/m.  EMTP input with xopt = copt = 0 and ILine = 0 in the distribute-
C parameter line requires R' in ohm/unit length,  in A in mH/unit length, B in
C uF/unit length.  The unit length used here is kilometer.  Remember the modal
C quantities are calculated at 1000 Hz in this example.  Note also that the
C voltage transformation matrices are provided in the CABLE CONSTANTS output
C instead of current transformation matrices.  If we assume Transpose([Ti]) =
C Inverse([Tv]), then an approximate, real (the matrix [AI], i.e. Inverse([Tv]),
C is in polar coordinate) transformation matrix can be used.
BEGIN NEW DATA CASE
C ----dt<---tmax<---xopt<---copt-------------------------------------------->
  20.E-6  25.E-3      0       0
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                       <---Icat
     15       1                                                     1
C
C ...........................  Circuit data  ..................................
C Bus-->Bus-->Bus-->Bus--><----R<----L<----C                                  0
  BUS12ABUS13A                70.16                                           0
  BUS12BBUS13BBUS12ABUS13A                                                    0
  BUS12CBUS13CBUS12ABUS13A                                                    0
  BUS13A                211.6 421.0                                           0
  BUS13B      BUS13A                                                          0
  BUS13C      BUS13A                                                          0
        BUS13A                      3.353                                     0
        BUS13B      BUS13A                                                    0
        BUS13C      BUS13A                                                    0
  THEVA SRC1A           0.714 70.68                                           0
  THEVB SRC1B THEVA SRC1A                                                     0
  THEVC SRC1C THEVA SRC1A                                                     0
C Distributed parameter line data
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<-------------------->0
-1BUS1A BUS12A          .988851.32821.3226 24.14 0 0 4                        0
-2BUS1B BUS12B          .09652.20009.09318 24.14 0 0 4                        0
-3BUS1C BUS12C          .07239.15007.12424 24.14 0 0 4                        0
-4      PIPE            .06254.12934.12825 24.14 0 0 4                        0
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)
   0.0000000   0.6666666   0.0000000   0.3333333
          0.          0.          0.          0.
```

```
   0.0000000  -0.3333333  -0.5000000   0.3333333
          0.          0.          0.          0.
   0.0000000  -0.3333333   0.5000000   0.3333333
          0.          0.          0.          0.
   1.0000000   0.0000000   0.0000000  -1.0000000
          0.          0.          0.          0.
BLANK card terminates circuit data
C
C ............................ Switch data ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                  0
  SRC1A BUS1A      1.E-3     9999.        0                                   0
  SRC1B BUS1B      9999.     9999.        0                                   0
  SRC1C BUS1C      9999.     9999.        0                                   0
BLANK card terminates switch data
C
C ............................ Source data ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <---Tstart<----Tstop
14THEVA        187.79        60.        0.        0.                -1.     9999.
14THEVB        187.79        60.      -120.       0.                -1.     9999.
14THEVC        187.79        60.       120.       0.                -1.     9999.
BLANK card terminates source data
C
C ............................ Output requests ................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  PIPE
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(a) EMTP data case.



(b) Pipe voltage at bus 12.

Figure 3.5: Energization of phase "a" of a 15 mile 230 kV pipe type cable connecting bus 1 and bus 12.

3.3. Cross Bonded Cables

Most three phase cable systems consisting of three single phase cables have crossbonded sheaths. That is, at regular intervals the sheath from phase **a** is connected to the next cable section sheath from phase **b**, the sheath from phase **b** is connected to the one from phase **c**, and so on. The main purpose of crossbonding is to reduce losses due to sheath currents that would result if the sheaths are grounded at many points, while reducing the overvoltages that would result in ungrounded sheaths.

From the perspective of travelling waves, a crossbonded cable presents discontinuity points. For relatively low frequencies it may be possible to model the cables as homogeneous lines by averaging the effect of the sheaths and assuming that the sheaths, even though ungrounded, are connected to each other. For more accurate studies, it becomes necessary to represent the cable system as a nonhomogeneous transmission line. This section considers alternative methods for representing crossbonded cable systems in the EMTP. For additional information regarding crossbonded cable systems, refer to Nagaoka and Ametani [2].

A cable system can be subdivided into major sections and minor sections. A major section consists of the full rotation of the sheaths from phase **a** to phase **b** to phase **c** and back to phase **a**. Within each major section there are three minor sections. Figure 3.6 illustrates a crossbonded cable major section.

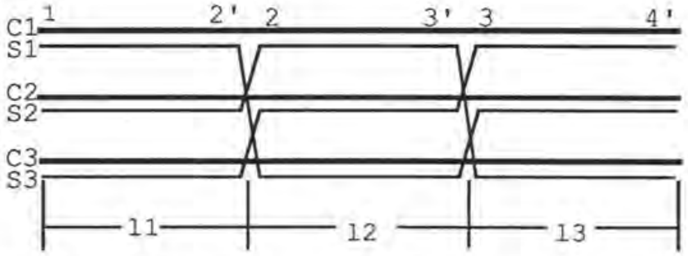


Figure 3.6: A crossbonded cable major section which consists of three minor sections.

Problem 3.10: Figure 3.7 illustrates the setup for a field test in a short cable system. The cable is 110 kV, 650 mm^2 oil filled cable with an aluminum sheath and a vinyl corrosion proof jacket. The cable is arranged vertically. The cable length is 788 m. An impulse voltage of 7.3 kV and a 0×40 μsec waveshape is applied between the center core and earth through a 500 Ω resistor. The cores are grounded through 500 Ω resistors, the sheaths are connected together and grounded through 10 Ω resistances at both ends. The earth resistivity is assumed to be 100 Ω-m. Figure 3.8 illustrates the result of field tests. Prepare data to reproduce these field tests and compare with those values given. If you use the EMTP you should get good but not perfect agreement with the field test results.

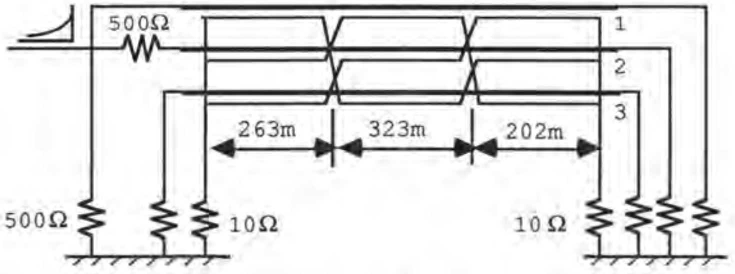


Figure 3.7: Field test setup on a short crossbonded cable.

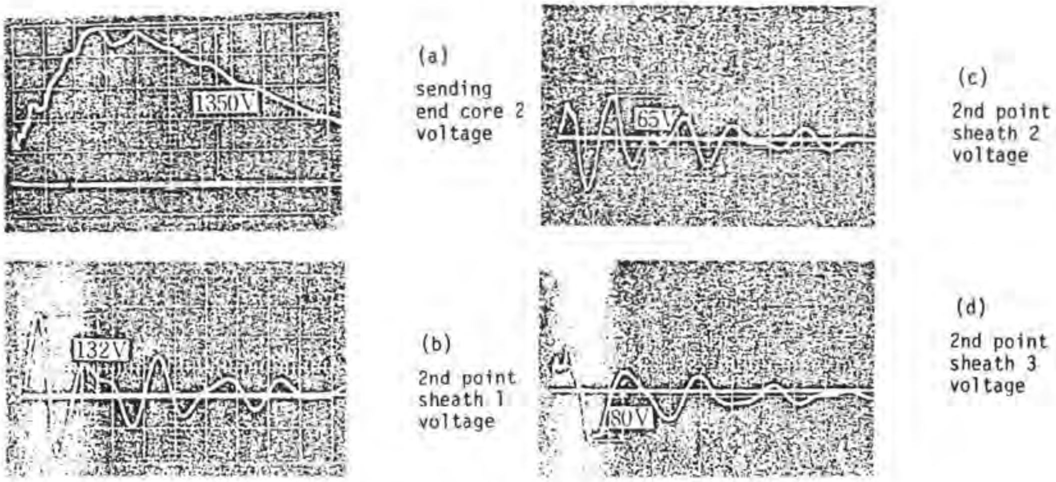
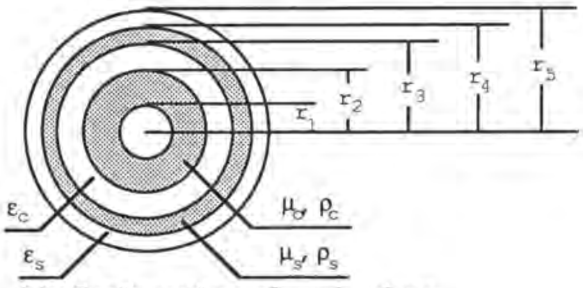


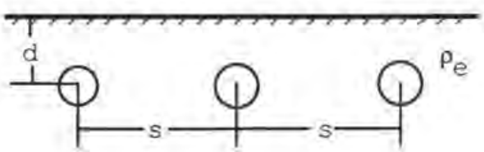
Figure 3.8: Field test results on crossbonded cables.

Problem 3.11: A unique feature of the last problem is that to get better accuracy you must represent the dielectric loss in the vinyl. How would you represent dielectric loss in the EMTP?

Problem 3.12: Figure 3.9 illustrates a longer cable system. The length of one minor section for this cable is 500 m and the total length is 12 km. Thus, the cable system consists of eight major sections. Apply a unit step voltage with no source impedance between the outer core and earth. All other cores are open-circuited and the sheaths are connected together and grounded through a 0.5 Ω resistor at both ends and grounded through a 10 Ω resistance at the intermediate points. Earth resistance is assumed to be 50 Ω-m. Figure 3.10 illustrates the results for the receiving end core voltages obtained in the Nagaoka and Ametani paper for the case of neglecting crossbonding and considering crossbonding in this cable system. Prepare data to reproduce these results and compare with the results given.

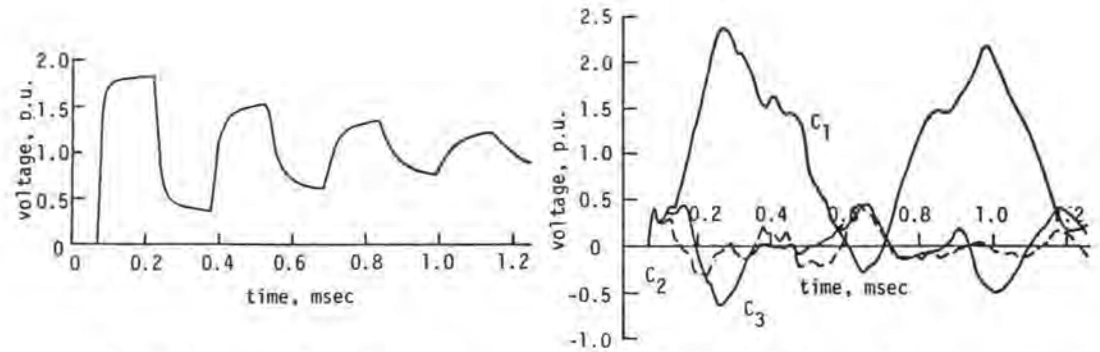


(a) Configuration of each phase.



(b) Configuration of all three phases.

Figure 3.9: A longer tested cable system with eight major sections.



A calculated result neglecting crossbonding

Calculated results including crossbonding when applying a source voltage to the outer core

Figure 3.10: Results obtained for test case as shown in Figure 3.9.

3.4. References

[1] Hermann W. Dommel et al, "Electromagnetic Transients Program Reference Book (EMTP Manual Theory)," Prepared for the Bonneville Power Administration, P. O. Box 3621, Portland, Oregon, 97208, August 1986.

[2] N. Nagaoka and A. Ametani, "Transient Calculations on Crossbonded Cables," IEEE Transactions on Power Apparatus and Systems, April 1983, pp. 779-787.

SECTION 4

ELECTROMAGNETIC INDUCTION STUDIES

An important use of the EMTP is to perform ordinary steady-state (phasor) studies in linear systems. Simple linear systems with single frequency sinusoidal sources can be analyzed under steady-state conditions. The setup is identical to transient studies. The only difference is that the *maximum simulation time* t_{max} in the miscellaneous data line should be zero (or negative) to prevent the EMTP from performing a time step simulation. The mechanics for preparing simple sinusoidal studies were explained in Workbook I.

One of the most interesting applications of the steady-state solution capability of the EMTP is to calculate induced voltages in overhead conductor and cable systems. This section illustrates how to perform these calculations. Three cases of increasing sophistication will be considered.

4.1. A Two Conductor Example

Consider a two conductor case. The first conductor has an applied sinusoidal 60 Hz voltage of $230/\sqrt{3}$ kV and is at at an average height of 10.16 m. The second conductor (perhaps a telephone line) is at a distance of 99.71 m from the first conductor and at an average height of 6.61 m above a 100 Ω-m ground (Figure 4.1).

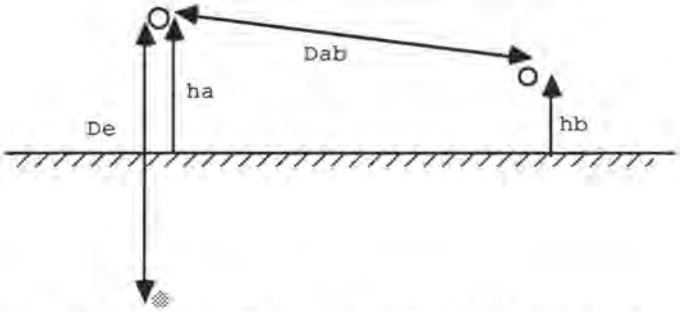


Figure 4.1: An overhead line with a nearby ungrounded conductor.

The parameters for this system of conductors can be calculated using the `LINE CONSTANTS` routine. However, the frequency and spacing are low enough in this example to allow us to truncate the series of Carson earth correction after the first term for the real part and the second term for the imaginary part. The resulting formulas are based on the definition of a quantity D_e as follows:

$$D_e = 658.87\sqrt{\frac{\rho}{f}}\ \mathrm{m}$$

Using this definition of the equivalent depth of return, we get the following expressions for the self and mutual inductances of the two conductors:

$$Z_a = r_c + 0.000987\ f + 0.002894\ f\ \log\left(\frac{D_e}{\mathrm{GMR}}\right)\ \Omega/\mathrm{km}$$

$$Z_{ab} = 0.000987\ f + 0.002894\ f\ \log\left(\frac{D_e}{D_{ab}}\right)\Omega/\mathrm{km}$$

From here we can obtain a direct expression for the induced series voltage along the telephone line:

$$V_b = \frac{f}{60}\left(0.0592 + j0.1736\ \log\left(\frac{D_e}{D_{ab}}\right)\right) I_a\ \mathrm{V/km}$$

For our specific example we assume a nominal line current through the phase conductor ($I_a = 900$ amps). Using this value for the current we can calculate the induced series voltage along the telephone line:

$$D_e = 850.6\ \mathrm{m}$$

$$V_b = 154.87\angle 69.81^\circ\ \mathrm{V/km}$$

This result will be compared with a similar result obtained using the EMTP as shown in Figure 4.2. To use the EMTP in this problem we first calculate the line parameters using the `LINE CONSTANTS` program. As long as we are only interested in the induced voltage in conductor number 2 (the telephone line) any value for resistance and internal reactance of concuctor number 2 can be used. If we were also interested in the current circulating in conductor number 2 when the conductor is shorted at both ends, then realistic values would be required. Using this data, we obtain the parameters of this system. The series resistances and inductances and shunt capacitances per unit length can be converted to actual values by multiplying with the line length, for which we assumed unit length (1 km) in this case. We then apply nominal voltage at the sending end of the $230\ \mathrm{kV}/\sqrt{3}$ line and at the receiving end we apply a load of 147.42 ohms. This load results in a line current of about 900 amps. To measure the voltage along the telephone line, we assume the telephone line is ungrounded and measure the voltage drop across the line.

Notice that we are requesting a printout of the steady-state values in the miscellaneous data lines, and that the value of t_{max} is negative. Also notice that in this study we elected to specify all inductances in ohms at 60 Hz and all capacitances in micro-mhos at 60 Hz, that is, the `XOPT` and `COPT` parameters in the miscellaneous data line were equal to 60. This is sometimes convenient for steady-state studies. Table 4.1 compares the EMTP results with the simplified calculation. The minor difference is caused by the fact that higher order terms in the Carson series are ignored in the simplified expressions. This is acceptabe at power frequecy for moderate spacings, but not at higher frequencies and wider spacings [1]. The EMTP also include capacitive coupling effects as well, as illustrated in Figure 4.2(c).

```
BEGIN NEW DATA CASE
LINE CONSTANTS
METRIC
C Conductor cards
C I               I                               V
C P             R X       R               H       T               S     A       N
C h  S          e T       e       D       o       o       V       e     l     N B
C a  k          s y       a       i       r       w       M       p     p     a u
C s  i          i p       c       a       i       e       i       a     h     m n
C e<-n<---------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  1  0.0 0.08005 2   1.143 2.81432     0.0   15.24    7.62
  2  0.5  62.601 2    0.03    0.06   99.71    7.62     6.1
BLANK card terminates conductor cards
C Frequency cards                                         M            I
C                                                       I u          M T
C                F         F      I        I I     D    PIt  I  I  I o r
C      R         r         C      C        Z C     i    iSu  D  P  P d n
C      h         e         a      P        P a     s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <------r p<----t <--rgl<-c<-t<-n<l<f
    100.      60.          1    1   1
BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) `LINE CONSTANTS` input data.

```
           SUSCEPTANCE MATRIX (MHO/  KM) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
                   ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT
   1   0.28828E-05
   2  -0.35876E-08   0.19614E-05

           IMPEDANCE MATRIX (OHM/  KM) FOR THE SYSTEM OF PHYSICAL CONDUCTORS
                   ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT
   1   0.13778E+00
       0.84734E+00
   2   0.56876E-01   0.62660E+02
       0.16321E+00   0.11213E+01
```

(b) `LINE CONSTANTS` output.

```
BEGIN NEW DATA CASE
C ---dt<---tmax<---xopt<---copt----------------------------------------------->
              0.      60.     60.
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                <---Icat
                               1
C ........................... Circuit data ....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C<----R<----L<----C<----R<----L<----C
  230L                    147.42                                               1
 1230S  230L              .1378 .84734 2.883
 2TelS  TelE              .0569 .16321-.0036 62.66 1.121 1.961                 2
BLANK card terminates circuit data
C ........................... Switch data .....................................
BLANK card terminates switch data
C ..........................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14230S       132.8E3       60.                                     -1.
BLANK card terminates source data
C ........................... Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  TelS  TelE
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(c) EMTP data case.

```
NODE              SOURCE NODE VOLTAGE                  INJECTED SOURCE CURRENT
NAME        RECTANGULAR          POLAR            RECTANGULAR          POLAR
230S        0.1328000E+06  0.1328000E+06       0.8999589E+03  0.8999717E+03
            0.0000000E+00         0.0000      -0.4785451E+01        -0.3047

TelS        0.2696885E+03  0.2792894E+03
            0.7618853E+03        15.0667

TelE        0.2176641E+03  0.2298986E+03
            0.7399813E+02       -18.7762

EMTP BRANCH-VOLTAGE OUTPUT FOLLOWS (COLUMN-80 PUNCHES ONLY)
      FROM         TO           MAGNITUDE        ANGLE IN
       BUS         BUS          OF PHASOR         DEGREES
      TelS         TelE       0.15553509E+03     70.467386
```

(d) Output of part (c).

Figure 4.2: Induction study using EMTP (two conductor case).

Table 4.1: Comparsion between the Induced Voltage and Current from the EMTP and from the Carson Truncated Series

	truncated series	EMTP
Current	900 A	899.97 A
Induced Voltage	154.9∠69.8°	155.5∠70.5°

4.2. Induction from a Three Phase Line

Consider our typical overhead line, as illustrated in Figure 4.3 below.

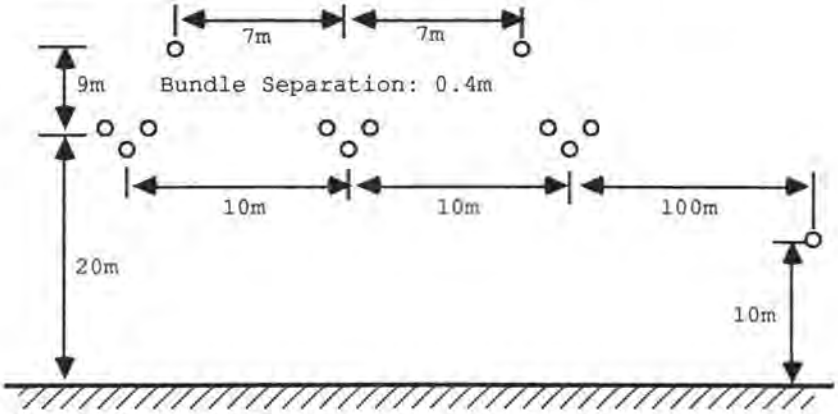


Figure 4.3: Overhead three phase line with nearby telephone line.

We have added a nearby conductor, simulating perhaps the presence of a communications line in the vicinity of the power line. The intent is to determine the longitudinally induced voltage in this nearby conductor for various currents in the power line.

Rather than setting up a four-phase Π circuit to study this case, similar to the two-phase Π circuit in section 4.1, we will use the special output request in `LINE CONSTANTS` which was provided specifically for such induction effects.

The setup for LINE CONSTANTS is shown in Figure 4.4(a), with a "1" in the column designated as "Mutual" on the frequency card to get the special output. Figure 4.4(b) shows this output from version 2.0 of the EMTP (the output from version 1.0 is somewhat less detailed).

From the value $|Z(POS)| = 0.012569$ Ω/km we can immediately see that a positive sequence current of 1000 A in the power line would induce a voltage of 12.57 V/km in the communication line. The worst induction effects come from zero sequence currents. In this case, $I_0 = 1000$A would induce 467.7 V/km. For general, unsymmetric currents, some calculations are required. With $I_a = 1000\angle 0°$, $I_b = 1000\angle -90°$, $I_c = 1000\angle 20°$, we would have to calculate:

$$-\frac{dV_4}{dx} = Z(4,1)\ I_a + Z(4,2)\ I_b + Z(4,3)\ I_c$$

or $|dV_4/dx| = 316.4$ V/km. Since we know that it is mostly the zero sequence current in unbalanced cases which produces the induction effects, we can also get a reasonable answer by first finding $I_0 = 682.8$ A and then $|dV_4/dx| = 319.3$ V/km with $|Z(ZERO)| = 0.46769$ Ω/km.

```
BEGIN NEW DATA CASE
LINE CONSTANTS
METRIC
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  0  0.5   3.750 4           0.950   -7.0     29.     29.
  0  0.5   3.750 4           0.950    7.0     29.     29.
  1  0.5  0.0701 4           3.058  -10.0     20.     20.      40.             3
  2  0.5  0.0701 4           3.058    0.0     20.     20.      40.             3
  3  0.5  0.0701 4           3.058   10.0     20.     20.      40.             3
  4  0.5  62.601 4            0.06   110.     10.     10.
BLANK card terminates conductor cards
C Frequency cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f
    100.       60.         1                              1
BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) Input data for LINE CONSTANTS calculation.

```
                              MUTUAL IMPEDANCES IN OHM/KM AT  0.60000E+02 HZ
          Z( 4, 1) =   0.73397E-01 + J   0.13084E+00        ABS(Z( 4, 1)) =   0.15002E+00
          Z( 4, 2) =   0.74489E-01 + J   0.13662E+00        ABS(Z( 4, 2)) =   0.15561E+00
          Z( 4, 3) =   0.73909E-01 + J   0.14430E+00        ABS(Z( 4, 3)) =   0.16212E+00
              MUTUAL IMPEDANCES IN OHM/KM FOR CURRENTS EXPRESSED IN SYMMETRICAL COMPONENTS
                         I(ZERO)  =  (I(1) + I(2) + I(3)) / 3  FOR CIRCUIT 1, ETC.

CIRCUIT  1.  EQUIVALENT PHASE CONDUCTORS  1  2  3
Z(POS)  - COMPLEX =  -0.74478E-02 + J  -0.10125E-01         Z(POS)  - ABS. =   0.12569E-01
Z(NEG)  - COMPLEX =   0.58438E-02 + J  -0.91207E-02         Z(NEG)  - ABS. =   0.10832E-01
Z(ZERO) - COMPLEX =   0.22180E+00 + J   0.41175E+00         Z(ZERO) - ABS. =   0.46769E+00
```

(b) Partial `LINE CONSTANTS` output from version 2.0 of the EMTP.

Figure 4.4: Induction study of a three phase line with a nearby telephone line using the EMTP.

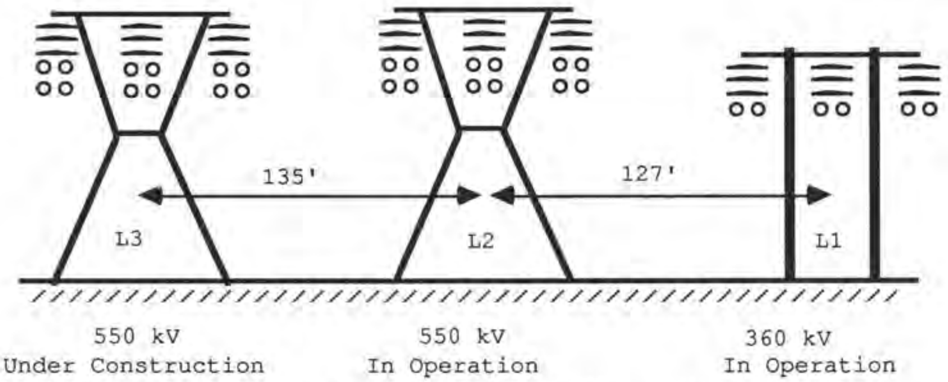
As we may observe, the induced voltages are considerably lower than before. The reason for this is that a three phase line operating under balanced conditions will induce very small voltages on distant lines. We observe further that under unbalanced conditions the induced voltages are considerably larger.

4.3. A 550 kV Line Case Study

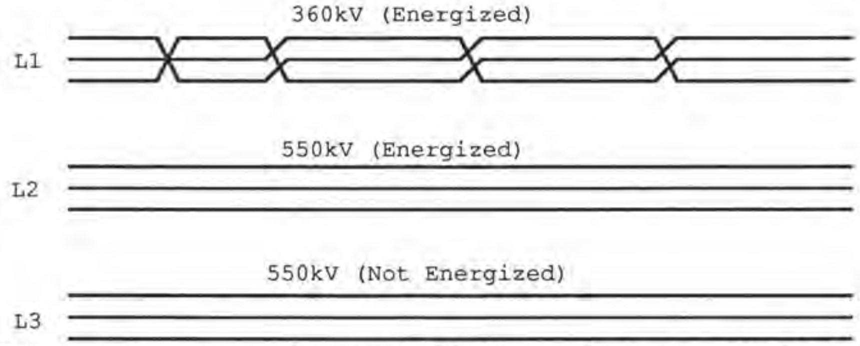
This 550 kV line case study has been used by Hermann Dommel since 1975 to illustrate the accuracy attainable in the calculation of induced voltages. The original case upon which these studies are based was done by Mr. B. Garrett, formerly of B. C. Hydro.

As the previous section has illustrated, balanced versus unbalanced conditions have a definite influence on the induced voltages. The main item to be illustrated by this example is that for an accurate calculation of induced voltages a knowledge of the transposition pattern is required. Figure 4.5 shows the tower configuration for the right of way, and the transposition pattern of each of the three lines in the study. The tables contain all the relevant information about the lines and conductors in question.

The input data for the calculation of the line parameters for these lines and the EMTP output is illustrated in Figure 4.6. To study the induction effects, five 9-phase Π circuits had to be created for the per-unit length matrices of Figure 4.6(b), by multiplying them with the length of each transposition section. The five sections were then connected by simply using proper node names at the transposition points for all three circuits L1, L2 and L3 (not just L1). Voltage sources were then added to one end of L1 and L2.



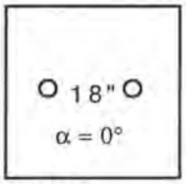
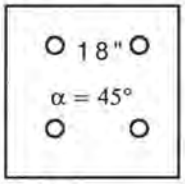
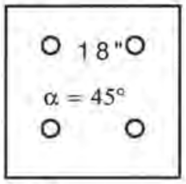
(a) Tower configuration for overhead line system.



(b) Transposition pattern for overhead line. Only the 360 kV line is transposed.

Circuit	Tower Height (feet)	Midspan Height (feet)	Phase Separation (feet)
L1	73	55	35
L2	76	33	39
L3	77	33	35

(c) Circuit height and separation.

Circuit	L1	L2	L3
# cond in bundle	2	4	4
Bundle Spacing			
Cond diameter	1.108"	0.95"	1.0"
Resistance	0.1288 Ω/mi	0.160 Ω/mi	0.151 Ω/mi
GMR	0.4476"	0.3876"	0.4260"
Earth resistivity	100 Ω-m		

(d) Line parameters.

Figure 4.5: Configuration of a 550 kV line used in induction study.

```
BEGIN NEW DATA CASE
LINE CONSTANTS
ENGLISH
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  1        0.151 2   0.426     1.0   -170.     77.     33.     18.   45.       4
  2        0.151 2   0.426     1.0   -135.     77.     33.     18.   45.       4
  3        0.151 2   0.426     1.0   -100.     77.     33.     18.   45.       4
  4        0.160 2  0.3876     .95    -39.     76.     33.     18.   45.       4
  5        0.160 2  0.3876     .95      0.     76.     33.     18.   45.       4
  6        0.160 2  0.3876     .95     39.     76.     33.     18.   45.       4
  7       0.1288 2  0.4476   1.108    91.5     73.     55.     18.             2
  8       0.1288 2  0.4476   1.108   126.5     73.     55.     18.             2
  9       0.1288 2  0.4476   1.108   161.5     73.     55.     18.             2
BLANK card terminates conductor cards
C Frequency cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f
    100.      60.          1     1   1
BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

(a) `LINE CONSTANTS` input data for the calculation of line parameters.

```
               SUSCEPTANCE MATRIX (MHO/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                          ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT
1  0.71663E-05
2 -0.14326E-05  0.74380E-05
3 -0.42584E-06 -0.14034E-05  0.72628E-05
4 -0.13250E-06 -0.24665E-06 -0.72500E-06  0.71940E-05
5 -0.70584E-07 -0.10561E-06 -0.23106E-06 -0.12534E-05  0.73336E-05
6 -0.46646E-07 -0.60840E-07 -0.10904E-06 -0.34582E-06 -0.12413E-05  0.72308E-05
7 -0.33861E-07 -0.39630E-07 -0.60864E-07 -0.12595E-06 -0.25520E-06 -0.75961E-06  0.58947E-05
8 -0.24843E-07 -0.27614E-07 -0.39711E-07 -0.70584E-07 -0.11897E-06 -0.27648E-06 -0.10813E-05  0.59885E-05
9 -0.22692E-07 -0.24189E-07 -0.33020E-07 -0.52278E-07 -0.76251E-07 -0.14230E-06 -0.39674E-06 -0.11153E-05  0.57883E-05
                    IMPEDANCE MATRIX (OHM/MILE) FOR THE SYSTEM OF EQUIVALENT PHASE CONDUCTORS
                          ROWS AND COLUMNS PROCEED IN SAME ORDER AS SORTED INPUT
1 0.12971E+00
  0.10201E+01
2 0.91924E-01 0.12972E+00
  0.53486E+00 0.10200E+01
3 0.91839E-01 0.91927E-01 0.12971E+00
  0.45084E+00 0.53485E+00 0.10201E+01
4 0.91648E-01 0.91787E-01 0.91895E-01 0.13198E+00
  0.37483E+00 0.41249E+00 0.46744E+00 0.10229E+01
5 0.91458E-01 0.91633E-01 0.91775E-01 0.91943E-01 0.13199E+00
  0.34327E+00 0.37118E+00 0.40753E+00 0.52170E+00 0.10229E+01
6 0.91228E-01 0.91437E-01 0.91615E-01 0.91845E-01 0.91942E-01 0.13198E+00
  0.31828E+00 0.34045E+00 0.36763E+00 0.43767E+00 0.52170E+00 0.10229E+01
7 0.90448E-01 0.90694E-01 0.90912E-01 0.91222E-01 0.91366E-01 0.91471E-01 0.15548E+00
  0.29155E+00 0.30884E+00 0.32905E+00 0.37512E+00 0.41747E+00 0.48217E+00 0.11421E+01
8 0.90178E-01 0.90450E-01 0.90695E-01 0.91060E-01 0.91241E-01 0.91381E-01 0.91051E-01 0.15548E+00
  0.27644E+00 0.29154E+00 0.30884E+00 0.34659E+00 0.37884E+00 0.42275E+00 0.53590E+00 0.11421E+01
9 0.89884E-01 0.90179E-01 0.90451E-01 0.90866E-01 0.91081E-01 0.91258E-01 0.90978E-01 0.91048E-01 0.15547E+00
  0.26303E+00 0.27643E+00 0.29154E+00 0.32351E+00 0.34953E+00 0.38269E+00 0.45181E+00 0.53591E+00 0.11422E+01
```

(b) Results of the line parameters calculation.

Figure 4.6: Line parameter calculations for the 550 kV line induction study.

Two studies were performed using this data, and later compared against field measurements. The first study involved calculation of induced voltages on line L3 assuming both ends were open. The second study involved the calculation of the currents in line L3 assuming that the right side of line L3 was grounded through a grounding resistance of about 5 ohms.

The following table compares calculated and measured values for this study. The calculated values were obtained both at nominal voltages and at the actual voltages measured. It is interesting to notice that although both sets of values are reasonably accurate, the values obtained using the nominal voltages were in fact closer to the true values.

Table 4.2: Comparison of Calculated and Measured Induced Voltages and Currents on a 550 kV Line

		Calculation		Measurement
Voltages on lines in operation	L1	360 kV	372 kV	372 kV
	L2	550 kV	535 kV	535 kV
Induced voltages on an open line L3	A	28.20 kV	27.46 kV	30 kV
	B	14.29 kV	13.83 kV	15 kV
	C	8.04 kV	7.83 kV	10 kV
Grounding currents for grounding through 5Ω at right side of L3	A	10.78 A	10.50 A	11 A
	B	3.26 A	3.17 A	5 A
	C	1.53 A	1.49 A	1 A

It is interesting to point out that, in contrast to the two previous studies in this section, the induced voltages in this case are mainly the result of electrostatic coupling rather than inductive coupling.

4.4. References

[1] IEEE Working Group, "Electromagnetic Effects of Overhead Transmission Lines. Practical Problems, Safeguards, and Methods of Calculation," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-93, pp. 892-904, May/June 1974.

SECTION 5

FREQUENCY DEPENDENT LINES

The parameters of overhead lines and cables are dependent on the frequency at which they are evaluated. This is mainly because "skin effect" is significant on both the ground and the conductors. Because skin effect on the ground is far more important, frequency dependence is more noticeable on those modes that involve ground currents. In the case of overhead lines, this is normally only the ground mode. In the case of cables, often more than one mode may have frequency dependent parameters. Furthermore, the very definition of each mode may depend on frequency, as was seen when the parameters of cables were described.

Considering frequency dependence is essential to both reasonable and accurate simulations. Perhaps the most noticeable effects of frequency dependence are its effect in "rounding" square pulses (steps) and reducing the height of "spikes" (impulses). Figure 5.1 illustrates the effect of frequency dependence on each of the nine modes of a three phase cable with sheath and armor, where each mode is excited at the sending end by means of an ideal square wave pulse. High frequency components travel at a different (usually faster) speed than slower frequency components. The result of this difference in travelling speeds on step waveforms is a general rounding of the waveform, as illustrated. The effect of these different travel speeds on spikes and impulses is a lower peak amplitude for the pulse, because all components contributing to the pulse peak value now arrive at different times. In these cases the importance of the high frequencies on the model is greatly exaggerated if constant parameters are assumed.

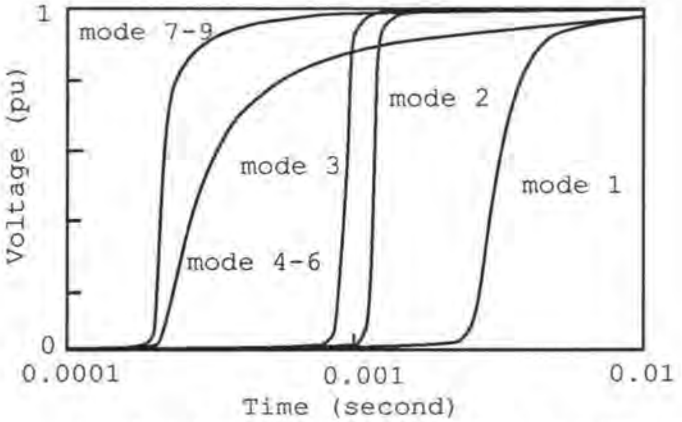


Figure 5.1: Step response of each mode for a three phase underground cable.

The EMTP has the capability for dealing with frequency dependence. This section describes the EMTP capabilities and how to use them.

5.1. Frequency Dependence of the Ground Return Mode

Table 5.1 illustrates the effect of frequency dependence on an extremely simple system consisting of a single copper conductor of radius 1 cm at a height of 10 m above ground.

Table 5.1: Effect of Frequency Dependence on Resistance and Inductance for a Single Overhead Conductor

Frequency (Hz)	Resistance (Ω/km)	Inductance (mH/km)
0.1	0.0702	3.099
1.0	0.0711	2.869
10.0	0.0799	2.640
100.0	0.1701	2.411
1000.0	1.0647	2.167
10000.0	8.0560	1.952
100000.0	52.4660	1.795
1000000.0	251.8800	1.709

This is, of course, an impractical case, except perhaps in the case of a dc line operating as a monopolar line without a metallic return. It represents, however, a good approximation to the parameters of the ground mode of a typical overhead line. Table 5.2 illustrates the zero sequence modal parameters of our sample 230 kV line used throughout this workbook. Table 5.3 illustrates the effect of frequency dependence on the positive sequence parameters of the sample line.

Table 5.2: Effect of Frequency Dependence on Resistance and Inductance of Zero Sequence of Sample Line

Frequency (Hz)	Resistance (Ω/km)	Inductance (mH/km)
0.1	0.0237	5.371
1.0	0.0264	4.679
10.0	0.0587	3.962
100.0	0.5417	2.910
1000.0	1.9200	1.940
10000.0	9.4230	1.725
100000.0	57.1250	1.547
1000000.0	242.2100	1.461

Table 5.3: Effect of Frequency Dependence on Resistance and Inductance of Positive Sequence of Sample Line

Frequency (Hz)	Resistance (Ω/km)	Inductance (mH/km)
0.1	0.0234	0.9243
1.0	0.0234	0.9243
10.0	0.0234	0.9243
100.0	0.0259	0.9231
1000.0	0.0710	0.9095
10000.0	0.2703	0.9023
100000.0	2.1040	0.8973
1000000.0	12.5400	0.8931

For the case of cables, all modes involving a partial return of current through ground are subject to a strong frequency dependent effect. Cable modes that do not involve ground return (as many cable modes are) are not subject to significant frequency dependent effects. However, because skin effect is comparatively more important in cables, all line modes exhibit a greater frequency dependent effect than overhead line modes. The effects of frequency on cable modal parameters were illustrated and discussed in the section on cables. Furthermore, the very definition of the meaning of a mode is affected by frequency. The dependence of the modal transformation matrices themselves on frequency was also described in the cables section.

5.2. Using `LINE CONSTANTS` to Obtain Frequency Dependent Parameters

The `LINE CONSTANTS` program can be made to automatically cycle through the calculation of parameters at a number of frequencies. This is accomplished by specifying a range of frequencies in the frequency data line. In addition the program can be made to produce data in a form directly usable by several of the frequency dependent models available in the EMTP, particularly the `JMARTI` model. The organization of data for a case where cycling over many frequencies is desired is as follows:

```
LINE CONSTANTS
...conductor data lines...
BLANK ends conductor data
...frequency data lines...
BLANK ends frequency data
```

The frequency data line contains the following information:

- The resistivity of the ground, ρ.
- The lowest frequency of interest.
- The number of frequency decades of interest.
- The number of points per decade that you wish the program to calculate.

The exact formats to be used to generate the desired output are described in the `LINE CONSTANTS` template. More often, however, you will want a direct link between the Marti models and the `LINE CONSTANTS` program. The organization of data for the direct connection of the `LINE CONSTANTS` program and the Marti model depends on whether the user wishes to assume transposition or not. This affects the calculation of the modal transformation matrices.

- If transposition is requested, there will be only two distinct modes of propagation (line and ground) regardless of the number of conductors, and the transformation matrices to convert actual quantities to modal quantities that are supplied by the `LINE CONSTANTS` program to the Marti model are pre-defined. Transposition should not be requested for cable systems when the sheath or armor are to be explicitly considered. Transposition in multi-circuit overhead lines yields (in version 1) unrealistic results.
- If transposition is not requested, then the `LINE CONSTANTS` program will calculate the modal transformation matrix. The present version of the Marti program requires a modal transformation matrix at a single frequency, and assumes it is valid for all frequencies. As described elsewhere, this is not very accurate for cables at low frequencies.

The setup for a Marti case under the assumption of uniform transposition is as follows:

```
BEGIN NEW DATA CASE
JMARTI SETUP
BRANCH optional node naming data line
LINE CONSTANTS
...conductor data lines...
BLANK ends conductor data
...frequency data line for fundamental frequency...
...frequency data line for frequency range of interest...
BLANK ends frequency data
BLANK ends LINE CONSTANTS
...Fitting data or "DEFAULT"...
BLANK ends setup data
BLANK ends all cases
```

The setup for a Marti case under the assumption of an untransposed configuration is as follows:

```
BEGIN NEW DATA CASE
JMARTI SETUP
BRANCH optional node naming data line
LINE CONSTANTS
...conductor data lines...
BLANK ends conductor data
...frequency data line for modal transformation matrix calculation...
...frequency data line for fundamental frequency...
...frequency data line for frequency range of interest...
BLANK ends frequency data
BLANK ends LINE CONSTANTS
...Fitting data or "DEFAULT"
BLANK ends setup data
BLANK ends all cases
```

Reasonable values to use in the frequency data lines are:

- Modal transformation matrix calculation frequency: 1 kHz.
- Fundamental frequency: 60 Hz.
- Frequency range: from 0.1 Hz, 8 decades at 10 points per decade. *Important: the present Marti model requires exactly 10, or a multiple of 10, points per decade.*

For further details, refer to the `JMARTI` template in Appendix A.

Problem 5.2: Prepare EMTP input data to request the preparation of data for use with the `JMARTI` model.

5.3. Using `CABLE CONSTANTS` to Obtain Frequency Dependent Parameters

The `CABLE CONSTANTS` program also has features that allow it to automatically cycle over many frequencies and to directly prepare input for use with the `JMARTI` models. The setup is quite similar to the `LINE CONSTANTS` setup. Notice, however, that the present `JMARTI` model was developed for constant modal transformation matrices, which is a questionable assumption for underground cables, as explained in section 6.3.

```
BEGIN NEW DATA CASE
JMARTI SETUP
BRANCH optional node naming data line
CABLE CONSTANTS
...miscellaneous data line...
...conductor data (several lines - format depends on type of cable)...
...frequency data (one or more data lines)...
BLANK ends conductors and frequencies data
BLANK ends CABLE CONSTANTS
...fitting data or "DEFAULT"...
BLANK ends setup data
BLANK ends all cases
```

In the Appendix we also include templates for data preparation of the frequency dependent `JMARTI` models with the `CABLE CONSTANTS`.

Problem 5.3: Prepare data to request frequency dependent cable using `CABLE CONSTANTS` and `JMARTI` model of the EMTP. Use cable data from section 3.

5.4. Representation of Frequency Dependence

The EMTP program works in the time domain. Yet, the parameters of lines and cables are obtained under the assumption of single frequency sinusoidal excitation (as well as linearity). This problem can be resolved if we recognize that any signal applied to the end of a line can be Fourier Transformed into the frequency domain. Therefore, we can proceed theoretically as follows:

- Determine the voltage or current signals at one end of a line.
- Perform a Fourier Transform of these signals.
- Perform a modal decomposition of these signals.
- Determine the behavior of the line for each mode. This requires a few simple products and sums in the frequency domain.
- Reconstruct the behavior of the line in the time domain.

Unfortunately, most often we do not know either the voltage or the current signal at either end. Rather, we only know that these two are related via the network in a rather complex manner. Furthermore, it is best to perform the entire process of calculation in the time domain if at all possible. What are products in the frequency domain become convolution operations in the time domain.

The earliest methods for considering frequency dependence were based on a simple convolution of the standard transmission line modal equations with voltages and currents. Because convolution is inherently slow, and because it had to be performed over a very long past history, these early methods were exceedingly slow. A significant improvement occurred by the realization that the terms that signal must be convolved with could be made to decay rather rapidly by an appropriate modification of the equations, which amounted to artificially terminating the lines on impedances close to their modal characteristic impedances at very high frequencies. This gives rise to the Dommel-Meyer convolution method, which used to be implemented in the EMTP as the `WEIGHTING` model. *This model is now obsolete and no longer available.*

During the next few years, an effort was made to improve on the speed of this model by the use of "recursive convolution," a mathematical technique that greatly reduced the amount of time required for convolution. This resulted in the Semlyen and Ametani models and the Hauer filter. The Semlyen model was based on approximating all signals as exponentials, where recursive convolution is directly applicable. The Ametani model used linear approximations and recursive convolution, and the Hauer filter which produced complex exponential approximations. All of these models were faster and worked well on selected problems, but were somewhat hard to use because of the "tuning" required, they failed under dc signal conditions (like on open lines), and had difficulty with short and long lines. Some of the deficiencies (such as the dc drift of the Semlyen model) were later corrected [1]. *These model are now considered obsolete.*

The latest entry into the field is the Marti model. The Marti model inherently eliminates the problem of convolution over long times and of multiple signals by perfectly terminating each and every mode at both ends on a lumped network whose impedance as a function of frequency perfectly matches the characteristic impedance of the line. This makes the convolution process a much simpler and efficient process. It also permits a considerably improved fit. This is nowadays the overwhelming choice for EMTP users, and the main model described in this workbook.

5.5. Convolution by the Dommel-Meyer and Earlier Methods

The Dommel-Meyer method represented the first major successful implementation of frequency dependence in the EMTP. Because of its importance in understanding all other frequency dependent methods, we present a brief description of the method. *This method is now obsolete and no longer available in the EMTP. It has been superseded by better methods. We describe it because it illustrates very nicely the concepts behind time domain convolution.*

The method is based on earlier efforts by Budner [2] and Snelson [3]. We describe the method in the context of a single mode line. Consider the transmission line in Figure 5.2.

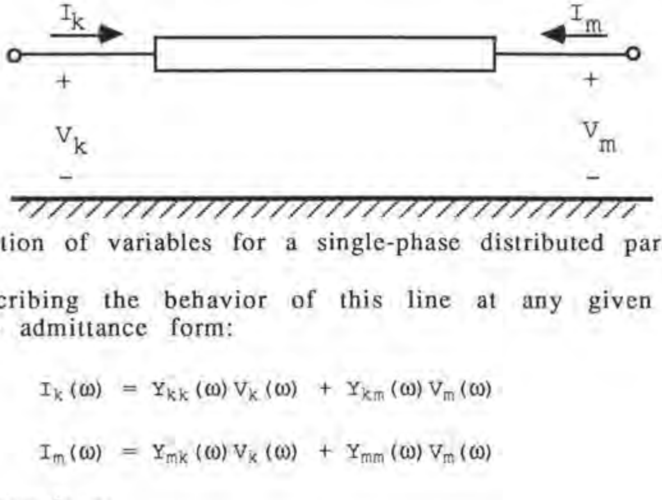


Figure 5.2: Definition of variables for a single-phase distributed parameter line.

The equations describing the behavior of this line at any given frequency can be expressed in either admittance form:

$$I_k(\omega) = Y_{kk}(\omega)V_k(\omega) + Y_{km}(\omega)V_m(\omega)$$

$$I_m(\omega) = Y_{mk}(\omega)V_k(\omega) + Y_{mm}(\omega)V_m(\omega)$$

Or in ABCD parameter form:

$$V_k(\omega) = A(\omega)V_m(\omega) - B(\omega)I_m(\omega)$$

$$I_k(\omega) = C(\omega)V_m(\omega) - D(\omega)I_m(\omega)$$

The expressions for the ABCD parameters in terms of the frequency dependent propagation constant and characteristic impedance are:

$$A(\omega) = D(\omega) = \cosh(\gamma(\omega)d)$$

$$B(\omega) = Z_c(\omega)\sinh(\gamma(\omega)d)$$

$$C(\omega) = \frac{1}{Z_c(\omega)}\sinh(\gamma(\omega)d)$$

$$Z_c(\omega) = \sqrt{\frac{R(\omega) + j\omega L(\omega)}{G(\omega) + j\omega C(\omega)}}$$

$$\gamma(\omega) = \sqrt{\left(R(\omega) + j\omega L(\omega)\right)\left(G(\omega) + j\omega C(\omega)\right)}$$

Similar expressions can be obtained for the $Y(\omega)$ parameters. It is possible to use the admittance form directly by finding a time dependent Norton equivalent of the line at each end by calculating $Y(\omega)$ and performing an inverse Fourier transform to obtain time functions $y(t)$. These time functions are then convolved with past history values of v_k and v_m to give the values of $i_k(t)$ and $i_m(t)$ at any time t ("*" denotes convolution):

$$i_k(t) = y_{kk}(t) * v_k(t) + y_{km}(t) * v_m(t)$$

$$i_m(t) = y_{mk}(t) * v_k(t) + y_{mm}(t) * v_m(t)$$

This is the Budner model. This model is correct, but requires extremely lengthy convolution computations, because the functions $y(t)$ do not decay rapidly. Snelson recognized this problem and suggested a transformation of variables that greatly improved upon the computational characteristics of the method. The transformation suggested by Snelson was to define new variables b and f based on Bergeron's "method of characteristics". These variables were defined as:

$$b_k = v_k - Z_1 i_k \qquad b_m = v_m - Z_1 i_m$$

$$f_k = v_k + Z_1 i_k \qquad f_m = v_m + Z_1 i_m$$

Where the constant Z_1 is defined as:

$$Z_1 = \lim_{\omega\to\infty} Z_c(j\omega)$$

Using this definition, the frequency domain relationships between the transformed variables are given by:

$$B_k(\omega) = A_2(\omega)F_k(\omega) + A_1(\omega)F_m(\omega)$$

$$B_m(\omega) = A_1(\omega)F_k(\omega) + A_2(\omega)F_m(\omega)$$

where:

$$A_1(\omega) = \frac{1}{\cosh(\gamma d) + \frac{1}{2}\left(\frac{Z_1}{Z_c} + \frac{Z_c}{Z_1}\right)\sinh(\gamma d)}$$

$$A_2(\omega) = \frac{1}{2}\left(\frac{Z_c}{Z_1} - \frac{Z_1}{Z_c}\right)\sinh(\gamma d)A_1(\omega)$$

and in the time domain:

$$b_k(t) = a_2(t) * f_k(t) + a_1(t) * f_m(t)$$

$$b_m(t) = a_1(t) * f_k(t) + a_2(t) * f_m(t)$$

Because of the particular choice of z_1, the expressions for a_1 and a_2 decay a lot more rapidly, and the required time domain convolution is more effective. Furthermore, the time domain functions a_1 and a_2 have a very nice time domain physical interpretation: they represent the receiving and sending end voltages of the response of the line to an impulse voltage at the sending end, when the line is terminated at both ends not with its characteristic impedance but with a fixed resistance of value z_1, as illustrated in Figure 5.3.

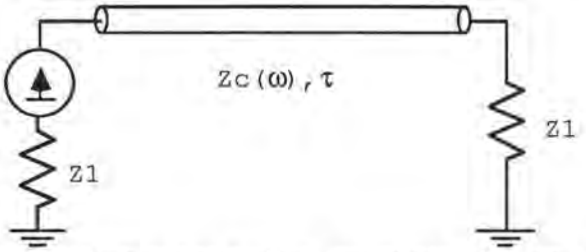


Figure 5.3: A distributed parameter line energized by an impulse function and terminated at both ends by a constant resistance.

A typical plot for a_1 and a_2 is shown in Figure 5.4.

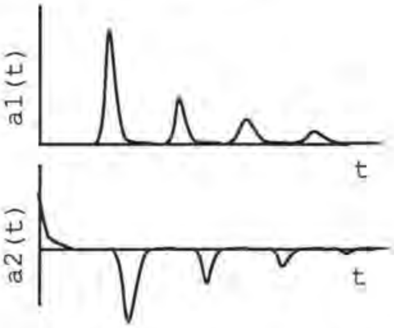


Figure 5.4: Typical time domain curves representing the convolution functions a_1 and a_2.

The efforts of Meyer and Dommel included not only an efficient way of incorporating the Snelson model into the EMTP by means of numerical convolution, but also the recognition that the "tails" of both functions could be approximated by decaying exponentials. It was then recognized that the convolution of an arbitrary function of time such as f_k or f_m with an exponential function can be done much more efficiently than the convolution of two arbitrary functions of time. The idea of convolving an arbitrary function of time with an exponential is that this process can be done recursively: The new convolution is nothing more than the old convolution plus some simple updating terms. Entire summations need not be evaluated.

5.6. The Marti Model

The complete theory of the Marti model is described in [4]. This section presents enough relevant information for the user to understand the philosophy of the model and how to use the built-in Marti model in the EMTP.

It has been mentioned that frequency dependence of the modal transformation matrices can be important, particularly for cable systems at low frequencies. The original Marti model (and its current implementation in the EMTP) do not address the issue of frequency dependence of the modal transformation matrices. Nevertheless, it has been pointed out by Magnusson [5] and Wasley [6] that reasonable solutions can be obtained for overhead lines with approximate real and constant transformation matrices. Thus, only constant frequency dependent modal transformation matrices are considered.

The fundamental idea of the Marti method is that if a frequency independent line is terminated by its characteristic impedance, there are no reflections at this termination. Similarly, if a frequency dependent line is terminated in a frequency dependent impedance that is equal at all frequencies to its *frequency dependent* characteristic impedance, no reflections will result from this line termination. Thus, the problem is largely one of synthesizing a network that has an input impedance equal to the characteristic impedance of each and every mode of the line or cable system at any frequency. That is, all that is required is to replace the constant resistance z_1 in the Dommel-Meyer model by a frequency dependent impedance and the calculation of frequency dependent effects simplifies considerably.

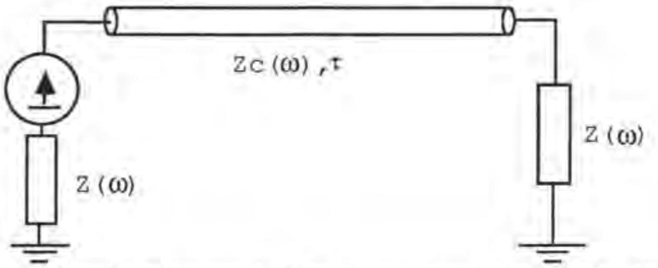


Figure 5.5: A distributed parameter line terminated at both ends in a frequency dependent impedance designed to match its characteristic impedance.

There are many techniques available for synthesizing passive networks that have any desired frequency spectrum. One of the goals of a Marti model must, however, be its ultimate simplicity. The work involved in the calculations within the frequency dependent characteristic impedance network must be lower than the corresponding work involved when using the Meyer-Dommel exact convolution method. One possible form to assume for the realization of the frequency dependent characteristic impedance is to use a Foster network, as illustrated in Figure 5.6.

Figure 5.6: A series Foster network used to synthesize a frequency dependent characteristic impedance.

The parameters of this network can be obtained by recognizing that the frequency dependent characteristic impedance of each mode of the line as obtained from the `LINE CONSTANTS` model can be expressed as:

$$Z_{eq}(s) = \frac{(s+z_1)(s+z_2)\ \ldots\ (s+z_n)}{(s+p_1)(s+p_2)\ \ldots\ (s+p_n)}$$

The break points p_i and z_i in this particular function are real, positive and simple. The values of the corresponding RC Foster network approximation to the characteristic impedance are given by:

$$Z_{eq}(s) = k_0 + \frac{k_1}{s+p_1} + \frac{k_2}{s+p_2} + \ldots + \frac{k_n}{s+p_n}$$

where:

$$R_0 = k_0 \qquad R_i = \frac{k_i}{p_i} \qquad C_i = \frac{1}{k_i}$$

Actually, a little more is required. The step response of the system must be characterized in a similar manner. That is, the propagation constant itself is frequency dependent. The propagation constant can be interpreted as the propagation characteristics of a unit impulse voltage along a line terminated in a perfect characteristic impedance. Because of the difference in propagation velocities of the different frequencies, an impulse will become non-ideal as it travels down a frequency dependent line. At a given point in the line, the voltage seen upon the application of a unit step at one end of the line is a function of time, as illustrated in Figure 5.7.

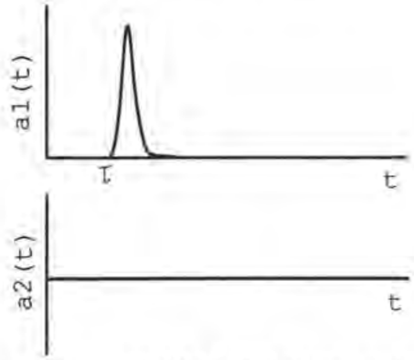


Figure 5.7: The impulse response weighting functions using the Marti formulation.

This function of time can be called $a_1(t)$. Notice that this function is zero up until a certain time τ. Thus, it is desirable to define a new function p as follows:

$$p(t-\tau) = a_1(t)$$

Or, in the frequency domain:

$$A_1(\omega) = P(\omega)\ e^{-j\omega\tau}$$

The function P can be expressed as follows:

$$P(\omega) = H\,\frac{(s+z_1)(s+z_2)\ \ldots\ (s+z_n)}{(s+p_1)(s+p_2)\ \ldots\ (s+p_m)}$$

This function can then be expanded into a sum of terms using a partial fraction expansion, and subsequently converted into an approximate time domain expression:

$$a_1(t) = \left(k_1 e^{-p_1(t-\tau)} + k_2 e^{-p_2(t-\tau)} + \ldots + k_m e^{-p_m(t-\tau)}\right) u(t-\tau)$$

This requires convolving arbitrary functions of time with sums of exponentials. But we have already said that convolving arbitrary functions of time with sums of exponentials can be done quite efficiently by using a recursive algorithm.

The Marti model derives its accuracy and numerical efficiency from two sources. By expressing the propagation function $a_1(t)$ as a sum of exponentials, recursive time domain convolution can be used by the EMTP. By using a better frequency dependent characteristic impedance, all reflections are eliminated, thereby shortening the period over which convolutions are necessary and eliminating the need for the $a_2(t)$ function. In exchange for these benefits, the characteristic impedance is now a network rather than a simple resistance or impedance.

5.7. Approximate Frequency Dependent Models

One of the limitations to the effectiveness of the Marti model is that when widely different propagation velocities occur, a substantial number of terms must be used to represent the approximating propagation function. A paper by Luis Marti [7] (Jose Marti's brother) has investigated the effect of reduced order frequency dependent modelling and of developing approximate frequency dependent models. This paper also deals with the creation of approximate frequency dependent models when only fundamental frequency data is available, without any details about line construction. It is of interest to see how this is done, since this model will become available in version 2.0 of the EMTP.

The accurate evaluation of frequency dependence effects requires that the tower and conductor configurations be known. However, if the parameters at power frequency are known, it is possible to determine some tower/conductor configuration of an equivalent line with an identical power frequency response as the given line. If the tower configuration of this equivalent line is close enough to that of the original line, the line parameters for both lines should agree quite well over the entire frequency range. Using the truncated Carson series for earth return effects, as discussed in section 4.1, and ignoring the effect of skin effect on the conductors, the approximate formulas for the sequence line inductance and capacitance are given by:

$$L_1 = 2\times10^{-4} \ln\left(\frac{d}{GMR}\right) \qquad L_0 = 2\times10^{-4} n \ln\left(\frac{e^{0.6159315}\sqrt{\frac{\rho}{f}}}{4\times10^{-4}\pi\sqrt{5}\,\sqrt[n]{GMR\,d^{n-1}}}\right)$$

$$C_1 = \frac{2\pi\,\varepsilon_0}{\ln\left(\frac{2hd}{rD}\right)} \qquad C_0 = \frac{2\pi\,\varepsilon_0}{\ln\left(\frac{2hD^{n-1}}{rd^{n-1}}\right)}$$

n	number of phases
d	GMD among all n phase conductor bundles
r	equivalent radius of each phase bundle
GMR	equivalent geometric mean radius of each phase bundle
h	geometric mean height
ρ	ground resistivity
f	frequency

where the following relationship applies:

$$D^2 = (2h)^2 + d^2$$

These equations can be explicitly backsolved for the desired equivalent line approximate dimensions:

$$d = \sqrt[n]{a_1 a_2} \qquad \mathrm{GMR} = \frac{d}{a_1}$$

$$D = \sqrt[n]{\frac{a_4}{a_3}}\, d \qquad h = \frac{1}{2}\sqrt{D^2 - d^2}$$

$$r = \frac{2hd}{a_3 D}$$

where

$$a_1 = \exp\left(\frac{L_1}{2\times10^{-4}}\right) \qquad a_2 = \frac{e^{0.6159315n}\left(\frac{\rho}{f}\right)^{n/2}}{\left(4\times10^{-4}\pi\sqrt{5}\right)^{n}\exp\left(\frac{L_0}{2\times10^{-4}}\right)}$$

$$a_3 = \exp\left(\frac{2\pi\varepsilon_0}{C_1}\right) \qquad a_4 = \exp\left(\frac{2\pi\varepsilon_0}{C_0}\right)$$

After this is done, we can proceed to find a frequency dependent equivalent as in all previous cases, except that a high degree of accuracy is probably not warranted.

Problem 5.4: Considering the positive and negative sequence parameters of our sample line, use the backsolving formulas of Marti to obtain an equivalent line. Compare the dimensions of this equivalent line with the actual dimensions of the line.

Problem 5.5: Apply the backsolving formulas to the parameters of a cable.

A final word concerns recent developments in the study of frequency dependence in systems where the frequency dependence of the transformation matrix is important, such as some cable systems. The work has been done by Luis Marti [8], and is a direct extension of the Jose Marti model except that matrix operations are used instead of scalar operations, and the synthesis of elements of the transfer matrices does not require a physical interpretation. The work is currently being implemented into the DCG/EPRI EMTP, but may very well be in future versions.

5.8. References

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[6] R. G. Wasley and S. Selvavinayagamoorthy, "Approximate Frequency Response Values for Transmission Line Transient Analysis," Proc. IEEE, vol. 121, pp. 281-286, April 1974.

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[8] L. Marti, "Simulation of Transients in Underground Cables with Frequency Dependent Modal Transformation Matrices," IEEE 1987 Winter Power Meeting, New Orleans, Lousiana, Feb 1-6, 1987.

SECTION 6

USING FREQUENCY DEPENDENT LINES

Using the frequency dependent line models in the EMTP is always a two step process. The first step is to obtain frequency dependent parameters of the line or cable based on the physical characteristic of the line or cable, and the second step is to incorporate this model into an EMTP simulation. For each of the models that follow we will describe both steps briefly. However, we will emphasize the Marti model, as experience has determined that this is the most practical of all. The use of the other models should be reserved for special circumstances that may warrant their use.

6.1. Using the Marti Model

Like the `WEIGHTING` model, to use the Marti model (known as the `JMARTI` model in the EMTP), you must first prepare a `LINE CONSTANTS` or `CABLE CONSTANTS` case that will automatically produce a description of the equivalent to be used in the EMTP itself. However, unlike the `WEIGHTING` model, the `JMARTI` model uses the length of the line within the calculations of the equivalent, therefore a different model must be obtained for every line length of interest. (The `WEIGHTING` model allows a user to develop a single model per configuration, with the line length added later.) The results of this preliminary step are also sent to the standard *punch output* of the EMTP.

Because of the manner in which the Marti model operates, an elaborate fitting process over a wide range of frequencies must take place. Obtaining the Marti model of a given line is often a very slow and time consuming process. You should obtain the Marti model of a line only when you are sure of the line parameters and once you have determined that frequency dependence is important. The file containing the Marti model should be saved for all future representations of the line, so the time consuming construction of the Marti line model need not be repeated.

The templates enclosed in Appendix A illustrate how to prepare data to set up a `JMARTI` model. A template is included for interpreting the data output from a `JMARTI` setup run, and Figure 6.1 illustrates a sample `JMARTI` setup run for our 120 mile overhead line from bus 1 to bus 2 and portion of the raw output. Normally, a user does not need to be concerned with the interpretation of this data, therefore the template can be considered to be strictly of educational value, or to be used if a dedicated user wanted to bypass the use of the `JMARTI SETUP` run and prepare data for the model directly.

```
C JMARTI SETUP for simulation of a frequency dependent line between BUS 1 and
C BUS 2.
BEGIN NEW DATA CASE
JMARTI SETUP
C --->  Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->
BRANCH  BKR1A BUS2A BKR1B BUS2B BKR1C BUS2C
LINE CONSTANTS
METRIC
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  0   .5  3.7500 4           0.950     -7.     29.     29.
  0   .5  3.7500 4           0.950      7.     29.     29.
  1   .5  0.0701 4           3.058    -10.     20.     20.     40.             3
  2   .5  0.0701 4           3.058      0.     20.     20.     40.             3
  3   .5  0.0701 4           3.058     10.     20.     20.     40.             3
BLANK card terminates conductor cards
C Frequency cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f
    100.     5000.         1                   193.1                 1
    100.       60.         1                   193.1                 1
    100.        .1         1                   193.1         7 10    1
BLANK card terminates frequency cards
BLANK card terminates LINE CONSTANTS study
DEFAULT
BLANK card terminates JMARTI SETUP cases
BLANK card terminates EMTP solution-mode
```

(a) Input data for `JMARTI SETUP`.

```
C    PUNCHED CARD OUTPUT OF "JMARTI SETUP" WHICH BEGAN AT  10.21.59   7/15/87
C METRIC
C   0   .5  3.7500 4            0.950     -7.     29.     29.
C   0   .5  3.7500 4            0.950      7.     29.     29.
C   1   .5  0.0701 4            3.058    -10.     20.     20.     40.
C   2   .5  0.0701 4            3.058      0.     20.     20.     40.
C   3   .5  0.0701 4            3.058     10.     20.     20.     40.
C
C     100.     5000.       1                      193.1                1
C     100.       60.       1                      193.1                1
C     100.        .1       1                      193.1           7 10   1
C
-1BKR1A BUS2A                 1.                         -2 3     Mode #1 data
     21       0.42965340228359800000E+03                          Zeroes and poles of Zc
  0.27145503228937260OE+03  0.14851297941986180OE+04  0.29539479789245830OE+03
 -0.75692370960668710OE+02 -0.27492065614761290OE+03  0.69683112309635070OE+01

... Data for Zc zero and pole representation omitted ...

  0.13738662470098100OE+06  0.34512381891216060OE+06  0.15803279121537890OE+07
     18       0.67948995974685420000E-03                          Zeroes and poles of γ
  0.27086009620070140OE-04  0.10826064744116790OE+00  0.12994037258713980OE+01
  0.29056416564282130OE+01  0.20115532140641370OE+02  0.73316788621973730OE+02

... Data for γ zero and pole representation omitted ...

  0.47310160096125220OE+05  0.47357025631186680OE+05  0.60143644762176490OE+05
-2BKR1B BUS2B                 1.                         -2 3     Mode #2 data
     16       0.29060431259269810000E+03
  0.25031004187792520OE+03  0.11834086544601570OE+04  0.12029982610640050OE+03

... Data for Zc and γ, mode #2 omitted ...

  0.35288334086042500OE+06  0.74387102628583640OE+06  0.81851816129877370OE+06
  0.81932898695459080OE+06
-3BKR1C BUS2C                 1.                         -2 3     Mode #3 data
     14       0.24549913673305340000E+03
  0.24065702045224650OE+03  0.10627771479538710OE+04  0.21045507495094880OE+03
 -0.80881644163361990OE+00  0.76674676959115560OE+02 -0.69629703447131820OE+02

... Data for Zc and γ, mode #3 omitted ...

  0.24715367859857290OE+07  0.32015752815730120OE+07  0.38253460286204430OE+07
  0.52080393299857970OE+08
  0.60087103 -0.70710558 -0.40738047       Ti Transformation Matrix
  0.00000000  0.00000000  0.00000000
  0.52716819 -0.00000164  0.81736412
  0.00000000  0.00000000  0.00000000
  0.60087245  0.70710798 -0.40737826
  0.00000000  0.00000000  0.00000000
```

(b) Portion of the JMARTI SETUP output.

Figure 6.1: JMARTI setup for a 120 mile line between bus 1 and bus 2.

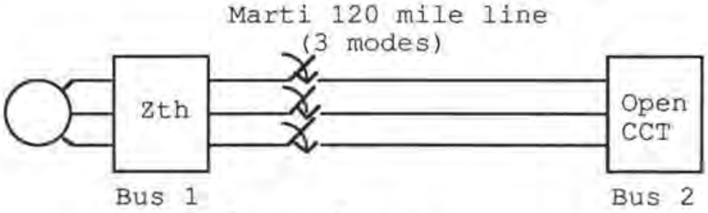
Setup runs should be used judiciously. To give an indication of why we suggest limiting these runs to those strictly necessary, the time it took to obtain this file was 45 minutes on an Apollo DN320 node. For reference, a 1000 point simulation using this model will take less than 10 minutes on the same computer.

6.2. Examples Using the Marti Model

Using the `JMARTI` model is as simple as inserting the output of a `JMARTI` setup into the EMTP simulation data. In most cases you need not worry about the details of the meaning of the information in the model data lines, as this information is automatically generated for you.

Problem 6.1: Illustrate how to represent our typical 230 kV line as a `JMARTI` line in the energization of the open circuited line from bus 1 to bus 2, assuming that the output from a `JMARTI` setup study is in file `MARTI.DAT`.

If you do everything correctly, Figure 6.2 illustrates the results that you will get from the energization of this `JMARTI` line.



(a) System diagram.

```
C Energization phase "a" of a 230 kv 120 mile frequency dependent line from an
C ideal source using MARTI line model.
BEGIN NEW DATA CASE
C ----dt<---tmax<------------------------------------------------------------->
  20.E-6  25.E-3
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                <---Icat
      15       1       0       0       0                       1
C
C ...........................  Circuit data  ...................................
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<-----Blank----------->0
C    PUNCHED CARD OUTPUT OF "JMARTI SETUP" WHICH BEGAN AT  10.21.59   7/15/87
C METRIC
C   0   .5  3.7500 4          0.950     -7.     29.     29.
C   0   .5  3.7500 4          0.950      7.     29.     29.
C   1   .5  0.0701 4          3.058    -10.     20.     20.     40.
C   2   .5  0.0701 4          3.058      0.     20.     20.     40.
C   3   .5  0.0701 4          3.058     10.     20.     20.     40.
C     100.     5000.         1                  193.1                1
C     100.       60.         1                  193.1                1
C     100.        .1         1                  193.1         7 10   1
-1BKR1A BUS2A                 1.                    -2 3
      21      0.42965340228359800000E+03
  0.27145503228937260OE+03  0.14851297941986180OE+04  0.29539479789245830OE+03
 -0.75692370960668710OE+02 -0.27492065614761290OE+03  0.69683112309635070OE+01

...data suppressed...

  0.11155843950903340OE+05  0.14128486511497270OE+05  0.22202365260499350OE+05
  0.47310160096125220OE+05  0.47357025631186680OE+05  0.60143644762176490OE+05
-2BKR1B BUS2B                 1.                    -2 3
      16      0.29060431259269810000E+03
  0.25031004187792520OE+03  0.11834086544601570OE+04  0.12029982610640050OE+03
  0.54784455598084910OE+02  0.77012280619808390OE+02 -0.53416838236379110OE+02

...data suppressed...

  0.35288334086042500OE+06  0.74387102628583640OE+06  0.81851816129877370OE+06
  0.81932898695459080OE+06
-3BKR1C BUS2C                 1.                    -2 3
      14      0.24549913673305340000E+03
  0.24065702045224650OE+03  0.10627771479538710OE+04  0.21045507495094880OE+03
 -0.80881644163361990OE+00  0.76674676959115560OE+02 -0.69629703447131820OE+02

...data suppressed...

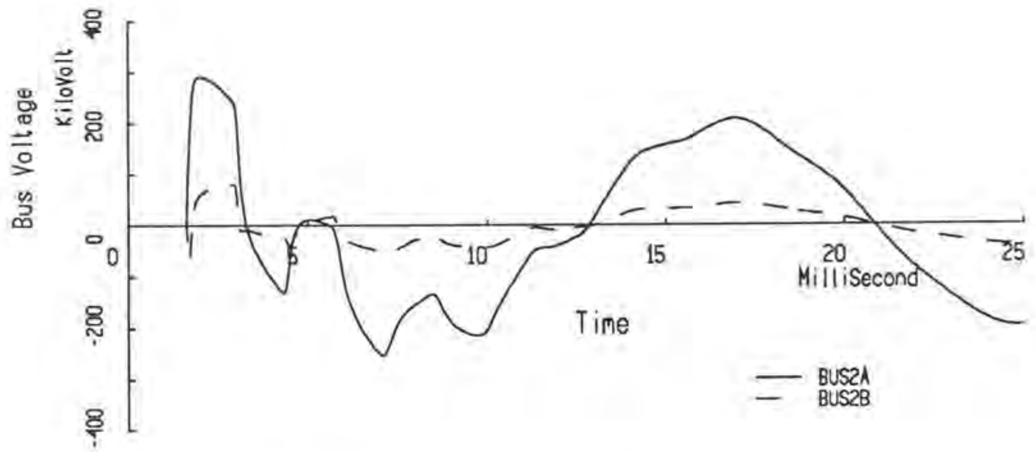
  0.24715367859857290OE+07  0.32015752815730120OE+07  0.38253460286204430OE+07
  0.52080393299857970OE+08
  0.60087103 -0.70710558 -0.40738047
  0.00000000  0.00000000  0.00000000
  0.52716819 -0.00000164  0.81736412
  0.00000000  0.00000000  0.00000000
  0.60087245  0.70710798 -0.40737826
  0.00000000  0.00000000  0.00000000
BLANK card terminates circuit data
C
C ...........................  Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                    0
  BUS1A BKR1A      1.E-3     9999.         0                                    0
  BUS1B BKR1B      9999.     9999.         0                                    0
  BUS1C BKR1C      9999.     9999.         0                                    0
BLANK card terminates switch data
C
C ...........................Source data  ......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <----Tstart<----Tstop
```

```
14BUS1A       187.79       60.        0.        0.                 -1.     9999.
14BUS1B       187.79       60.     -120.        0.                 -1.     9999.
14BUS1C       187.79       60.      120.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................. Output requests ..................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS2A BUS2B
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

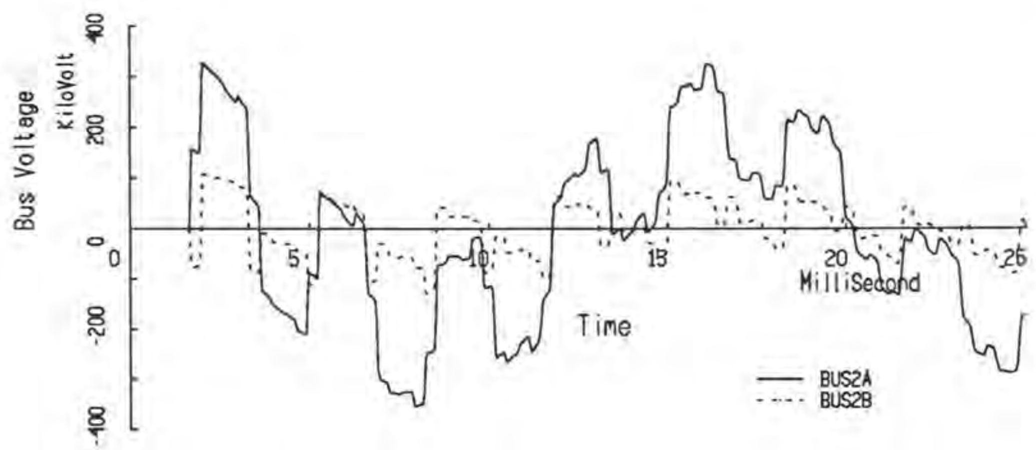
(b) EMTP data case of a Marti line.

```
C Energization of a 230 kv 120 mile line from an ideal source using three
C phase distributed line model (with actual units).
BEGIN NEW DATA CASE
C ----dt<---tmax<------------------------------------------------------------->
  20.E-6  25.E-3
C -Iprnt<--Iplot<-Idoubl<-KssOut<-MaxOut                         <---Icat
      15       1       0       0       0                                1
C
C ............................. Circuit data ......................................
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<-----Blank----------->0
-1BKR1A BUS2A             0.31673.2220.00787 193.1 0 0 0                       0
-2BKR1B BUS2B             0.02430.9238.01260 193.1 0 0 0                       0
-3BKR1C BUS2C                                                                  0
BLANK card terminates circuit data
C
C ............................. Switch data .......................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  BUS1A BKR1A      1.E-3     9999.         0                                   0
  BUS1B BKR1B      9999.     9999.         0                                   0
  BUS1C BKR1C      9999.     9999.         0                                   0
BLANK card terminates switch data
C
C ............................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop
14BUS1A       187.79       60.        0.        0.                 -1.     9999.
14BUS1B       187.79       60.     -120.        0.                 -1.     9999.
14BUS1C       187.79       60.      120.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................. Output requests ..................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS2A BUS2B
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(c) EMTP data case of a constant parameters line.



(d) Bus 2 voltages (Marti line).



(e) Bus 2 voltages (constant parameters line).

Figure 6.2: Energization of an overhead Marti line compared with energization of same line with constant distributed parameters.

6.3. The Marti Model and Cables[1]

The `JMARTI` model can also be used with underground cables. It must be realized, though, that this model is based on the assumption that the modal transformation matrices are constant. In the low to mid frequency ranges (e.g., dc to 500 Hz) this is not the case for most underground cables (see Figure 6.3).

---

[1] Section contributed by L. Marti, Ontario Hydro

Version 1.0 of the EMTP does not have a general-purpose model capable of representing the frequency dependence of the modal transformation matrices. Therefore, care must be taken to access the frequency range and type of transient simulation of interest in order to make an appropriate judgement on the validity of the results obtained. The general guidelines suggested for the choice of a transformation matrix in the case of overhead transmission lines are also applicable for the case of underground cables [1].

The new FDQ (Frequency Dependent Q-matrix) model developed by L. Marti is capable of reproducing the frequency-dependent behavior of the modal transformation matrices for underground cables, and its first implementation stage (i.e., support routines to generate input data for FDQ model) should become available in version 3.0, or in an intermediate update of version 2.0.

We illustrate an example of the determination of sheath overvoltages on a cable system with the energization of a three-phase crossbonded cable (the length of the cable is 15 miles). The `JMARTI` model is used, and the modal transformation matrices evaluated at three different frequencies are considered. Figure 6.4 (a) shows the data file used to generate input data for the `JMARTI` model, and Figure 6.4 (b) shows the corresponding EMTP data file for the transient simulation. Figure 6.5 (a) and (b) illustrate the results for all three cases. The solid-trace curves correspond to the results obtained with the FDQ model.

It is interesting to note that the phase voltages obtained when the modal transformation matrices are evaluated at 60 Hz and at 5 kHz are fairly close to the correct values for this particular simulation.

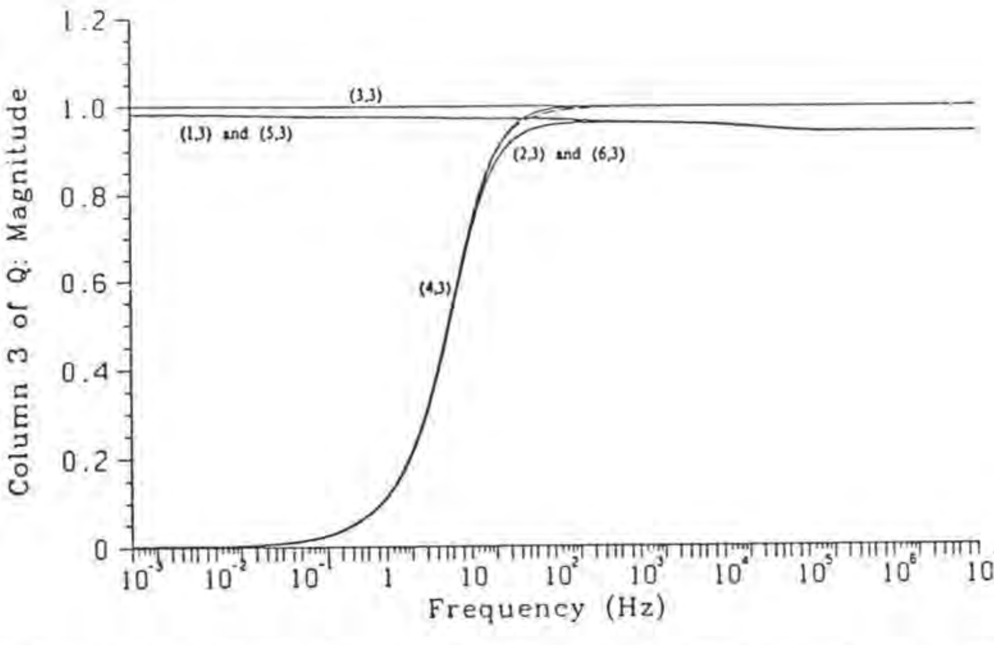


Figure 6.3: Magnitude of the elements of column 3 of the modal transformation matrix Q ("T_i") for a 3-phase underground cable.

```
C JMARTI SETUP for simulation of a 230 kV frequency dependent cable.  Data is
C obtained from L. Marti PhD thesis.
BEGIN NEW DATA CASE
JMARTI SETUP
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS                                                1
C Miscelaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2   -1    3    0    1    1    1    0    0
C Number of conductors in each SC cable          N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6
    2    2    2
C Geometrical and physical data for the cables.
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
        .0     .0234     .0385     .0414     .0484
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2
  .017e-6         1.        1.       3.5    .21e-6        1.        1.        8.
C Cable number 2 and 3.
        .0     .0234     .0385     .0414     .0484
  .017e-6         1.        1.       3.5    .21e-6        1.        1.        8.
        .0     .0234     .0385     .0414     .0484
  .017e-6         1.        1.       3.5    .21e-6        1.        1.        8.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4
       1.2        0.       1.2       .25       1.2        .5
C Frequency cards
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN
            50.          5000.               8045.
            50.            60.               8045.
            50.           .001    9   10     8045.
BLANK Card ends conductor data case
BLANK Card ends CABLE CONSTANTS study
C Fitting parameters
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr
                              30                               1       1
BLANK card terminates JMARTI SETUP cases
BLANK terminates EMTP solution-mode
```

(a) Setup data for JMARTI fitting of cable data produced by CABLE CONSTANTS. Modal transformation matrix evaluated at 5 kHz.

```
C
C        Crossbonded cable. Three major sections. Transformation matrix evaluated
C        at 5 kHz. Simultaneous energization.
C
BEGIN NEW DATA CASE
C
20.0D-06 30.D-03
     100       1       1       1       0                       1               0
C
C
C    Transformer:
C
  BUS1A BUS13A                  70.16                                          0
  BUS1B BUS13B                  70.16                                          0
  BUS1C BUS13C                  70.16                                          0
C
C    Load:
C
  BUS13A                  211.6 421.0                                          0
  BUS13B                  211.6 421.0                                          0
  BUS13C                  211.6 421.0                                          0
C
C    Source impedance:
C
  THEVA SRC1A             0.714 70.68                                          0
  THEVB SRC1B             0.714 70.68                                          0
  THEVC SRC1C             0.714 70.68                                          0
C
C    Crossbonded cable follows (length of minor section = 5 miles):
C
C    CA1========CA2   CA2=======================CA3   CA3====================CA4
C    CB1========CB2   CB2=======================CB3   CB3====================CB4
C    CC1========CC2   CC2=======================CC3   CC3====================CC4
C
C    SA1--------SA2   SB2-----------------------SB3   SC3--------------------SC4
C                  \   /                           \   /
C                   \ /                             \ /
C                    X                               X
C                   / \                             / \
C                  /   \                           /   \
C    SB1--------SB2     \   SC2-----------------SC3   SC3   SA3--------------SA4
C                        \   /                           \   /
C                         \ /                             \ /
C                          X                               X
C                         / \                             / \
C                        /   \                           /   \
C    SC1--------------SC2   SA2-----------------------SA3   SB3--------------SB4
C
C       Sheaths will be connected to the same bus at sending and
C       receiving ends. That is,
C       SA1 = SB1 = SC1 = SH1
C       SA4 = SB4 = SC4 = SH2
C       CA1 = BUS1A, CB1 = BUS1B, CC1 = BUS1C
C       CA4 = BUS12A, CB4 = BUS12B, CC4 = BU12C
C
C    First minor section
C
```

```
C    PUNCHED CARD OUTPUT OF "JMARTI SETUP" WHICH BEGAN AT  13.18.08  05/05/88
C     2   -1    3    0    1    1    1    0    0
C     2    2    2
C 0.0        .0234      .0385      .0414      .0484
C 0.0170E-06       1.0       1.0      3.50 0.2100E-06      1.0       1.0      8
C 0.0        .0234      .0385      .0414      .0484
C 0.0170E-06       1.0       1.0      3.50 0.2100E-06      1.0       1.0      8
C 0.0        .0234      .0385      .0414      .0484
C 0.0170E-06       1.0       1.0      3.50 0.2100E-06      1.0       1.0      8
C 1.20      0.0       1.20      0.25      1.20      0.50
C 50.0          5000.0                    8.0450
C 50.0          60.000                    8.0450
C 50.0          .00100           09   10 8.0450
C
C
-1BUS1A CA2                  1.                   -2 6
     29      0.97435532274387117724E+01
  0.324845041486718272E+01  0.532369438867618339E+01  0.103845662432646890E+02
 -0.452096751975580569E+01 -0.144085662950685547E+01  0.112526728814101276E-01

... data suppressed ...

 -2BUS1B CB2                  1.                   -2 6
     28      0.66120466904821970644E+01
  0.422154688244597953E+01  0.873462205461687691E+01  0.564163236998125992E+02
 -0.515144888156124985E+02 -0.734737238389434558E-02  0.206033562939642697E+00

... data suppressed ...

 -3BUS1C CC2                  1.                   -2 6
     28      0.67878580567061135298E+01
  0.512228719505935115E+01  0.113503523331301532E+02  0.403426484634941085E+02
 -0.333702932385177053E+02 -0.148445963026856004E+00  0.223544002113141231E+00

... data suppressed ...

 -4SH1   SA2                  1.                   -2 6
     28      0.10372792405772891300E+02
  0.846683837002287376E+01  0.341981147373410703E+02  0.163860739419773594E+03
 -0.143933337064547423E+03  0.120217754691452959E-01  0.463436208761054673E+00

... data suppressed ...

 -5SH1   SB2                  1.                   -2 6
     28      0.80047848476222540626E+01
  0.697703985987199438E+01  0.261158146462782970E+02  0.125755738893907582E+03
 -0.110540379725417164E+03  0.931728069726929595E-02  0.356682853697234528E+00

... data suppressed ...

 -6SH1   SC2                  1.                   -2 6
     28      0.56364079609982908892E+01
  0.536182484229522316E+01  0.180953001937747575E+02  0.872356194755239702E+02
 -0.766710575690975382E+02  0.700778457224919473E-02  0.246248009909569826E+00

  data suppressed ...

  0.00001275 -0.00030727 -0.00031981 -0.33731759  0.49969130  0.33762853
```

```
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.00002114  0.00000000  0.00061287  0.64770680  0.00000000  0.35165821
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.00001275  0.00030727 -0.00031981 -0.33731759 -0.49969130  0.33762853
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.33761917 -0.49971155 -0.33735496  0.33982797 -0.50203160 -0.33772289
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.35167694  0.00000000  0.64777413 -0.65251826  0.00000000 -0.35181321
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.33761917  0.49971155 -0.33735496  0.33982797  0.50203160 -0.33772289
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
 C
 C     Second minor section
 C
 -1CA2   CA3                     1.                       -2 6
       29        0.97435532274387117724E+01
   0.32484504148671827E+01  0.53236943886761833E+01  0.10384566243264689E+02
   0.45209675197558056E+01 -0.14408566295068554E+01  0.11252672881410127E-01

... data suppressed ...

  -2CB2   CB3                     1.                       -2 6
       28        0.66120466904821970644E+01
   0.42215468824459795E+01  0.87346220546168769E+01  0.56416323699812599E+02
  -0.51514488815612498E+02 -0.73473723838943455E-02  0.20603356293964269E+00

... data suppressed ...

  -3CC2   CC3                     1.                       -2 6
       28        0.67878580567061135298E+01
   0.51222871950593511E+01  0.11350352333130153E+02  0.40342648463494108E+02
  -0.33370293238517705E+02 -0.14844596302685600E+00  0.22354400211314123E+00

... data suppressed ...

  -4SB2   SB3                     1.                       -2 6
       28        0.10372792405772891300E+02
   0.84668383700228737E+01  0.34198114737341070E+02  0.16386073941977359E+03
  -0.14393333706454742E+03  0.12021775469145295E-01  0.46343620876105467E+00

... data suppressed ...

  -5SC2   SC3                     1.                       -2 6
       28        0.80047848476222540626E+01
   0.69770398598719943E+01  0.26115814646278297E+02  0.12575573889390758E+03
  -0.11054037972541716E+03  0.93172806972692959E-02  0.35668285369723452E+00

... data suppressed ...

  -6SA2   SA3                     1.                       -2 6
       28        0.56364079609982908892E+01
   0.53618248422952231E+01  0.18095300193774757E+02  0.87235619475523970E+02
  -0.76671057569097538E+02  0.70077845722491947E-02  0.24624800990956982E+00

... data suppressed ...

   0.00001275 -0.00030727 -0.00031981 -0.33731759  0.49969130  0.33762853
   0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
   0.00002114  0.00000000  0.00061287  0.64770680  0.00000000  0.35165821
```

```
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.00001275  0.00030727 -0.00031981 -0.33731759 -0.49969130  0.33762853
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.33761917 -0.49971155 -0.33735496  0.33982797 -0.50203160 -0.33772289
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.35167694  0.00000000  0.64777413 -0.65251826  0.00000000 -0.35181321
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.33761917  0.49971155 -0.33735496  0.33982797  0.50203160 -0.33772289
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
C
C     Third minor section
C
-1CA3   BUS12A                  1.                      -2 6
     29        0.97435532274387117724E+01
  0.324845041486718272E+01  0.532369438867618339E+01  0.103845662432646890E+02
 -0.452096751975580569E+01 -0.144085662950685547E+01  0.112526728814101276E-01
... data suppressed ...

-2CB3   BUS12B                  1.                      -2 6
     28        0.66120466904821970644E+01
  0.422154688244597953E+01  0.873462205461687691E+01  0.564163236998125992E+02
 -0.515144888156124985E+02 -0.734737238389434558E-02  0.206033562939642697E+00

... data suppressed ...

-3CC3   BUS12C                  1.                      -2 6
     28        0.67878580567061135298E+01
  0.512228719505935115E+01  0.113503523331301532E+02  0.403426484634941085E+02
 -0.333702932385177053E+02 -0.148445963026856004E+00  0.223544002113141231E+00

... data suppressed ...

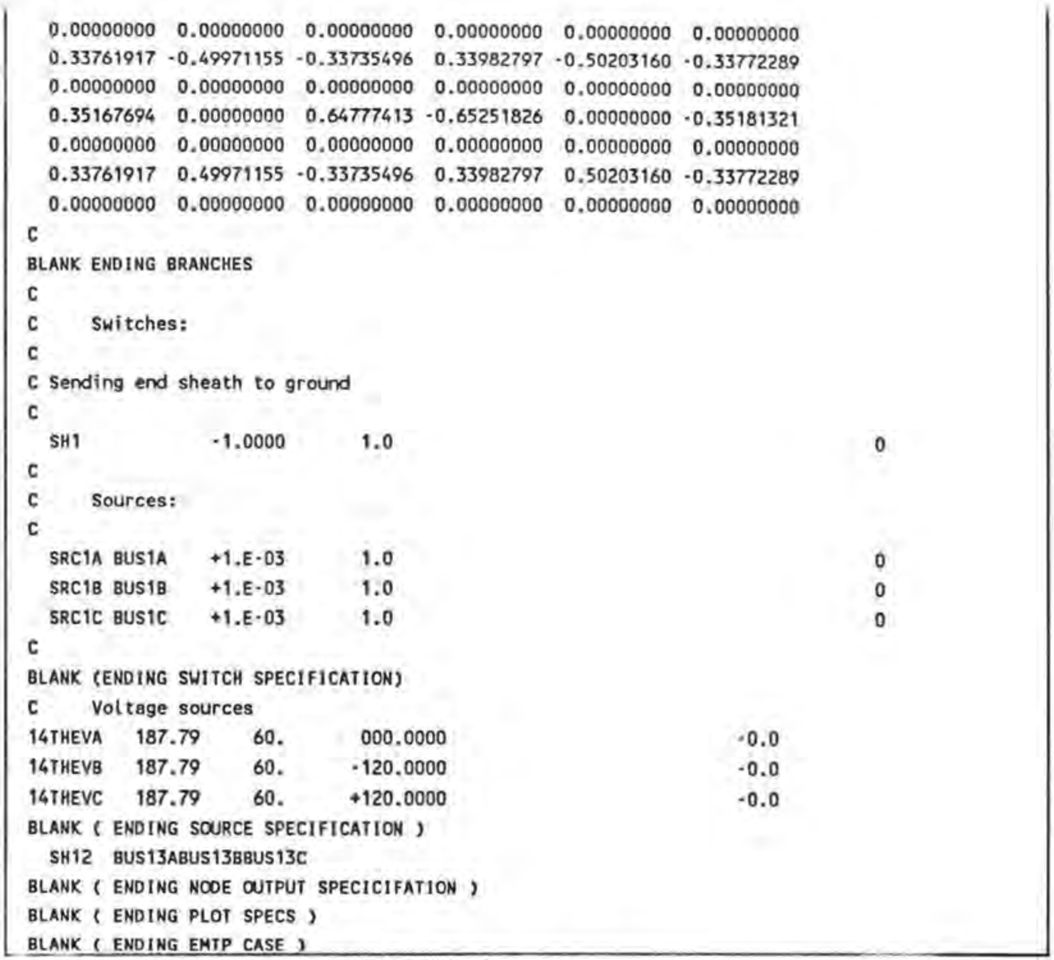
-4SC3   SH12                    1.                      -2 6
     28        0.10372792405772891300E+02
  0.846683837002287376E+01  0.341981147373410703E+02  0.163860739419773594E+03
 -0.143933337064547423E+03  0.120217754691452959E-01  0.463436208761054673E+00
... data suppressed ...

-5SA3   SH12                    1.                      -2 6
     28        0.80047848476222540626E+01
  0.697703985987199438E+01  0.261158146462782970E+02  0.125755738893907582E+03
 -0.110540379725417164E+03  0.931728069726929595E-02  0.356682853697234528E+00
... data suppressed ...

-6SB3   SH12                    1.                      -2 6
     28        0.56364079609982908892E+01
  0.536182484229522316E+01  0.180953001937747575E+02  0.872356194755239702E+02
 -0.766710575690975382E+02  0.700778457224919473E-02  0.246248009909569826E+00

... data suppressed ...

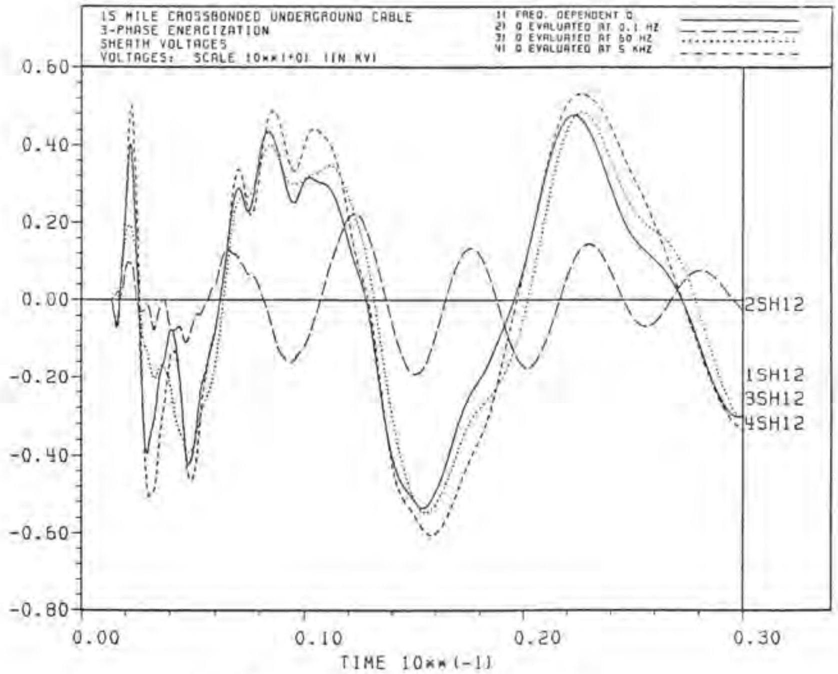
  0.00001275 -0.00030727 -0.00031981 -0.33731759  0.49969130  0.33762853
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.00002114  0.00000000  0.00061287  0.64770680  0.00000000  0.35165821
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.00001275  0.00030727 -0.00031981 -0.33731759 -0.49969130  0.33762853
```



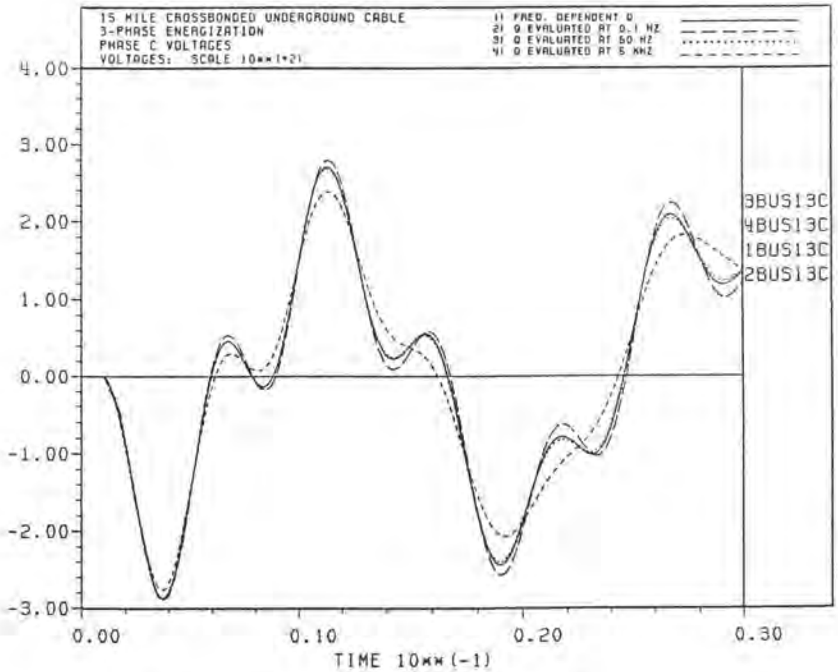
```
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.33761917 -0.49971155 -0.33735496  0.33982797 -0.50203160 -0.33772289
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.35167694  0.00000000  0.64777413 -0.65251826  0.00000000 -0.35181321
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.33761917  0.49971155 -0.33735496  0.33982797  0.50203160 -0.33772289
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
C
BLANK ENDING BRANCHES
C
C     Switches:
C
C Sending end sheath to ground
C
  SH1            -1.0000        1.0                                             0
C
C     Sources:
C
  SRC1A BUS1A    +1.E-03        1.0                                             0
  SRC1B BUS1B    +1.E-03        1.0                                             0
  SRC1C BUS1C    +1.E-03        1.0                                             0
C
BLANK (ENDING SWITCH SPECIFICATION)
C     Voltage sources
14THEVA   187.79    60.         000.0000                           -0.0
14THEVB   187.79    60.        -120.0000                           -0.0
14THEVC   187.79    60.        +120.0000                           -0.0
BLANK ( ENDING SOURCE SPECIFICATION )
  SH12  BUS13ABUS13BBUS13C
BLANK ( ENDING NODE OUTPUT SPECICIFATION )
BLANK ( ENDING PLOT SPECS )
BLANK ( ENDING EMTP CASE )
```

(b) EMTP data case.

Figure 6.4: Energization of a 15 mile frequency dependent, crossbonded cable connecting bus 1 and bus 12. The cable is crossbonded manually into three minor sections.



(a) Sheath voltages at bus 12.



(b) Voltages at bus 13 (phase c).

Figure 6.5: Energization of a 15 mile frequency dependent, crossbonded cable connecting bus 1 and bus 12. Compare effects of frequency dependency of modal transformation matrices. The constant modal transformation matrices are evaluated at 0.1 Hz, 60 Hz and 5 kHz. Solid trace corresponds to the fully frequency dependent cable model.

6.4. References

[1] H.W. Dommel, J.R. Marti, L. Marti and V. Brandwajn, "Approximate Transformation Matrices for Unbalanced Transmission Lines", Proceedings of the Ninth Power Systems Computation Conference, Cascais, Portugal, 30 August - 4 September 1987]

SECTION 7

STATISTICAL STUDIES USING THE EMTP

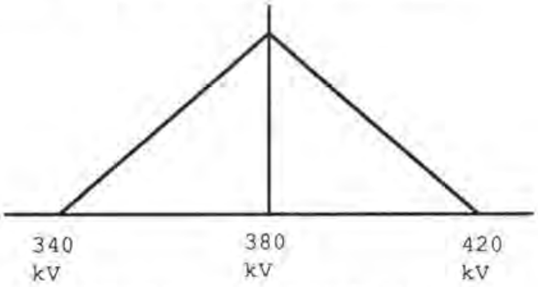
The EMTP can be used to perform repetitive studies in much the same manner as one would use a TNA. This section describes how to use the EMTP to perform these types of studies.

7.1. Using the EMTP as a TNA - Pros and Cons

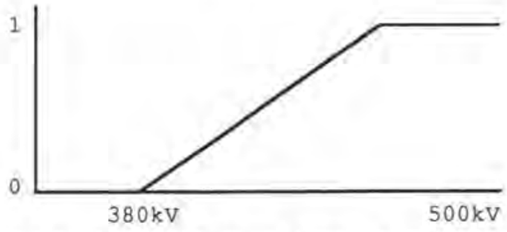
The great virtue of a Transient Network Analyzer is its ability of repetitively performing a great number of simulations with slight variations in parameters, particularly slight variations in exact breaker operating times. By performing a large number of simulations, a user can determine a statistical distribution of overvoltages at any point in the system. By combining the statistical distribution of overvoltages with the statistical properties of the insulating media, it becomes possible to determine the probability of a flashover, an insulation failure or a breaker restrike. Let $p(fl|V)$ be the known probability of a flashover given a known overvoltage, and let $p(V)$ be the probability of getting any given overvoltage. The overall probability of flashover $p(fl)$ can be obtained from:

$$p(fl) = \int_{-\infty}^{\infty} p(fl|V)\, p(V)\, dV$$

Problem 7.1: Given the statistical distribution of voltages illustrated in Figure 7.1, determine the true probability that a flashover will occur.



(a) Distributions of overvoltages.



(b) Probability of flashover as a function of voltage.

Figure 7.1: Distribution of voltages and probability of flashover.

The EMTP permits the same kind of statistical studies to be performed. Once a simulation has been set up, many repetitive simulations with statistical breaker switching times can be specified. The difference between the EMTP and the TNA is that EMTP simulations are generally easier to set up but much slower to execute. Therefore an EMTP statistical study can consume vast amounts of computing resources. Nevertheless, EMTP statistical studies are often viable alternatives to TNA simulations.

To use the EMTP to perform a statistical study you should have prepared a well tested and developed case. Furthermore, careful consideration should have been given to simulation step sizes and to initialization of the simulation.

Initialization of a simulation often represents a nontrivial effort, particularly when nonlinear components or detailed machine models are present. When performing statistical studies it is often the case that many simulations will share the exact same initialization. Statistical studies have been designed so that the initialization part of the simulations need not be repeated for every repetitive simulation.

Another important aspect of statistical simulations is the presentation of results. Clearly, you cannot be interested in detailed time domain plots for every one of the simulations. The EMTP (and most TNA's) have the ability of letting you request what quantities you want to see statistically tabulated. In a typical statistical simulation you will have one or more breakers closed or open at random within an interval, and will monitor a few voltages. You will be interested in tabulating the peak values of the overvoltages developed, and produce appropriate statistical distributions and histograms for these overvoltages.

7.2. Setting Up a Simple Statistical Study

A statistics study is set up by a simple request in the miscellaneous data lines. To prepare a statistics study you must perform the following steps:

- Specify a parameter `NENERG > 0` in the integer miscellaneous data line (refer to section 7.4 for `NENERG < 0`).
- If `NENERG` is greater than zero, then specify a third miscellaneous data line where you tell the EMTP the following:
    - Whether you want to see a listing of all the actual randomly selected switching times.
    - The number of desired energizations.
    - Whether you want a uniform random distribution of switching times or a Gaussian one.
    - The distribution parameters, that is, a window in time (specified in degrees) over which the switching times will be allowed to vary.
    - The tabulation increment for showing the cumulative distribution of peak voltages. The main result of a statistic simulation is a set of cumulative distributions of various voltages (e.g., how many of the energizations have resulted in a voltage within a given voltage range). This parameter gives the size of the voltage ranges to be used.
    - The maximum voltage to tabulate.

A statistics study must also have at least one `STATISTICS` switch. See `STATISTICS` template in Appendix A for details.

It is not only possible to set up a single breaker with a random operating time. It is also possible to establish a sequence of breaker actions, all related to each other and with random operating times. The only additional requirement is the need to specify a "reference" breaker for all dependent breakers, and all times in the dependent breakers become relative to the reference breaker.

7.3. An Example of Statistical Studies

A specific example of the use of statistical switches is illustrated. Figure 7.2 illustrates the input data and the printer output for statistical studies. Notice that summary tables of voltage ranges and printer plots of statistical distributions of overvoltages are given.

```
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   50E-6  50.E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      15       1       1       0       0                       0      50
C ---ISw<--ITest<--IDist<--AIncr<-XMaxMx<-DegMin<-DegMax<-StatFr<-SigMax<--NSeed
       1       0       0      0.      0.      0.    180.     60.      0.       0
C
C ............................ Circuit data .....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  SRC   BUS1S              .6925 70.14                                         0
  BUS1  BUS12             .5819022.171                                         0
  BUS12 BUS13                   70.161                                         0
  BUS1                                .07596                                   0
  BUS12                               .07596                                   0
  BUS13                   251.28219.02                                         0
BLANK card terminates circuit data
C
C ............................ Switch data .....................................
C Independent switches.
C Bus1->Bus2-><--Tc mean<--Std Dev<--------I<--------><-------->Targe>
  BUS1S BUS1         6.E-3   1.5E-3         0          STATISTICS
BLANK card terminates switch data
C
C ............................Source data .......................................
C                    Infinite bus (behind equivalent impedance)
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop
14SRC        187.79        60.        0.        0.                 -1.     9999.
BLANK card terminates source data
C
C ............................ Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS1  BUS13
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates STATISTIC output
BLANK card terminates EMTP solution-mode
```

(a) EMTP data case.

```
                              RANDOM SWITCHING TIMES FOR ENERGIZATION NUMBER    1
                                 1    0.133813E-01
 177.2340      0.216031E+03 0.198759E+03
TIMES OF MAXIMA :
               0.167500E-01 0.168000E-01

                              RANDOM SWITCHING TIMES FOR ENERGIZATION NUMBER    2
                                 1    0.128106E-01
 160.8350      0.195090E+03 0.182020E+03
TIMES OF MAXIMA :
               0.168500E-01 0.168500E-01

                              RANDOM SWITCHING TIMES FOR ENERGIZATION NUMBER    3
                                 1    0.892882E-02
  79.3503     -0.284059E+03-0.222655E+03
TIMES OF MAXIMA :
               0.930000E-02 0.985000E-02

{Switch  data omitted}

 STATISTICAL DISTRIBUTION OF PEAK VOLTAGE AT NODE  'BUS13 '.
   BASE VOLTAGE FOR PER-UNIT PRINTOUT =    0.18779E+03
 INTERVAL   VOLTAGE      VOLTAGE IN      FREQUENCY CUMULATIVE       PER CENT
   NUMBER  IN PER UNIT  PHYSICAL UNITS   (DENSITY)  FREQUENCY .GE. CURRENT VALUE
       18     0.85000    0.159621E+03       0          0          100.000
       19     0.90000    0.169011E+03       2          2           96.000
       20     0.95000    0.178400E+03       8         10           80.000
       21     1.00000    0.187790E+03       6         16           68.000
       22     1.05000    0.197179E+03       5         21           58.000
       23     1.10000    0.206569E+03       6         27           46.000
       24     1.15000    0.215959E+03      10         37           26.000
       25     1.20000    0.225348E+03       1         38           24.000
       26     1.25000    0.234737E+03       4         42           16.000
       27     1.30000    0.244127E+03       8         50            0.000

DISTRIBUTION PARAMETERS FOR THE ABOVE DATA.    GROUPED DATA   UNGROUPED DATA
                                      MEAN =     1.1070000       1.1338343
                                  VARIANCE =     0.0158173       0.0150272
                             STD DEVIATION =     0.1257670       0.1225854
```

```
                                                  SAMPLE CURVE SYMBOLS---A,B,C
                                                  THEORETICAL CURVE SYMBOL---D
                                                  COMMON CURVE SYMBOL--------*
       SWITCH 'BUS1S '  TO  'BUS1  '
       0.2207E+00 SWITCH CLOSINGS/COL
                  COLUMNS
          5   10   15   20   25   30
     +----+----+----+----+----+----+
     *
     *
     *
     *
     AD
     A D
     A   D
     A       D
     1           D     A
     1                 D                      A
     1                       AD
     1                      A    D
     1   0.400E-02          A      D
     1                          AD
     1             A         D
     1        A        D
     1           D              A
     1       D              A
     A   D
     A D
     AD
     *
     *
     *
     *
    TIME
  0.3333E-03
   SEC/LINE
KOLMOGOROV-SMIRNOV TEST RESULT             0.904646E+00
```

(b) Portion of `STATISTICS` output.

Figure 7.2: Simple example on EMTP `STATISTICS` study with one independent switch.

7.4. Systematic Studies

As an alternative to statistical studies, it is often more convenient to let a breaker go through a predetermined sequence of closing times automatically. This is often more cost effective than a statistical simulation. A coarse systematic study can also be used to precede a statistical study to determine reasonable ranges of the expected overvoltages prior to a really large simulation. Systematic studies are indicated by a parameter `NENERG < 0` in the miscellaneous data card. This card must be followed by another specifying the desired number of energizations.

In addition, similar to the `STATISTICS` study, a list of `SYSTEMATIC` switches must be specified in the switch data. Refer to the `SYSTEMATIC` template in Appendix A for the detail input formats.

SECTION 8

CIRCUIT BREAKER MODELS

A switch capable of opening at a zero current crossing is the first simple model for a circuit breaker. This model is adequate for many types of EMTP studies. However, when questions arise that require a more detailed representation of the exact operation of a breaker, more detailed models of breakers become necessary. This section describes efforts in the direction of more detailed breaker models.

8.1. The Objective of a Circuit Breaker Model

Circuit breaker models can be used to study both the effect of the breaker on a system and the effect of a system on a circuit breaker. The main objective of a circuit breaker model from the standpoint of a system is to determine all voltages and currents that are produced within the system as a result of breaker action. The main objective from the breaker viewpoint is to determine whether the breaker will be successful when operating within a given system under a given set of conditions.

Several levels of breaker model complexity are possible when considering breaker models:

- The first is to consider an ideal breaking action that is completely independent of the arc within the breaker. Here the breaker can be represented as an ideal switch that opens at the first zero current crossing after a signal to open is given. The voltage across the breaker can then be determined and compared with a pre-specified Transient Recovery Voltage (TRV) withstand capability for the breaker. If the voltage across the breaker is below the TRV withstand curve, the action is considered successful. This model can be easily implemented with the built-in ideal switch model within the EMTP. This model fails to recognize the effect of the system on the arc and the effect of the arc on the system.

- A more elaborate breaker model can be obtained by representing the arc as a time varying resistance or inductance. This resistance or inductance time variation is determined ahead of time based on the characteristics of the breaker and perhaps based upon the knowledge of the initial interrupting current. This type of model is capable of representing the effect of the arc on the system, but requires advanced knowledge of the effect of the system on the arc. This model is easy to implement in the EMTP using the time varying resistance model. However, data for this model is not always easy to obtain, and the model still requires the use of precomputed TRV curves to determine the adequacy of the breaker.

- The most interesting model for a breaker is a model that is capable of representing the breaker as a dynamically varying resistance or conductance, with a value that is dependent on the past history of voltages and currents in the arc itself. Only recently has this type of model become feasible, since only recently has enough data been published to allow for the developments of these types of models. In this model both the effect of the arc on the system and the effect of the system on the arc are represented. No precomputed TRV curves are required. These models may be developed only to determine initial arc quenching, or may also be valid to determine arc reignition due to insufficient voltage withstand capability of the dielectric between the parted contacts.

The dynamic breaker model is most important in the following cases:

- To represent the interruption of small inductive currents, also known as current chopping. An approximate study of chopping can be done with ideal switches by forcing the current to zero prematurely using the I_e option of the ideal switch. However, this method is not accurate. Furthermore, the exact instant of chopping cannot be predicted in advance, particularly for three phase breakers.
- When the arcing time of interruption will be significant. When interrupting large short circuit currents, an arc may flow for several milliseconds after contact separation, and the arc itself may affect the interruption process.
- In cases where a "natural" zero current crossing is not expected over some significant time, as in the case where the current has a large unidirectional component, or the case of a dc circuit breaker.

8.2. TRV Calculations When the Arc is Considered

Several models have been developed over the last few years to represent the dynamic behavior of arcs. These models are mostly empirical, and have been reasonably validated using test data. Three models of this type are presented in [1]. The three models considered for representation of arc behavior for implementation in the EMTP include:

- Avdonin model. This model is based on the following equation for arc resistance:

$$\frac{dr}{dt} = \frac{r^{(1-\alpha)}}{A} - vi\,\frac{r^{(1-\alpha-\beta)}}{AB}$$

where α, β, A and B are parameters determined from breaker tests or at least from a knowledge of the breaker type and voltage class. The variable r represents the arc resistance, and v and i are the arc voltage and current.

- Urbanek model. This model is based on the following equation for arc conductance:

$$\frac{dg}{dt} = \frac{1}{\theta}\left(\frac{vi}{V^2} - g - \frac{P}{V^2}\left(1 - \left(\frac{v}{\zeta}\right)^2 - \frac{2\theta v}{\zeta^2}\frac{dv}{dt}\right)\right)$$

  where θ, ζ and V are parameters determined from breaker tests or at least from a knowledge of the breaker type and voltage class. The variable g represents the arc conductance, and v and i are the arc voltage and current.

- Kopplin Model. This model is based on the following equation for arc conductance:

$$\frac{dg}{dt} = \frac{g}{\tau(g)}\left(\frac{vi}{P(g)} - 1\right)$$

$$\tau(g) = k_t(g + 0.0005)^{0.25}$$

$$P(g) = k_p(g + 0.0005)^{0.6}$$

Each of these models has its advantages and disadvantages, as well as range of validity. For example, the Advonin model (which is based on earlier formulas by Mayr) is quite simple, but is considered unable of representing arc restrikes adequately.

These models will be built into version 2.0 of the EMTP. In the meantime it is possible for a determined user to implement these models by using TACS, as done in [2 and 3].

8.3. Obtaining Parameter Values for Dynamic Arc Models

To use a dynamic arc model one must first obtain the parameters that represent the model. Much work remains to be done in this area to standardize these calculations. The Phaniraj/Phadke reference has estimated some of these parameters by matching test performance of certain breakers to the models given. The procedure is as follows:

- Assume the desired form for a model.
- Obtain test results for a certain breaker test.
- Sample the breaker test results at a large number of instants.
- Simulate the test conditions as well as possible.
- Adjust the model parameters using a Least Squares Error criteria to minimize the error obtainable from the model and from the simulation.

After this adjustment of parameters, the model can be considered reasonably valid under other conditions. Reasonable values for use with different breaker types for 69 kV class breakers are shown in Table 8.1 and 8.2.

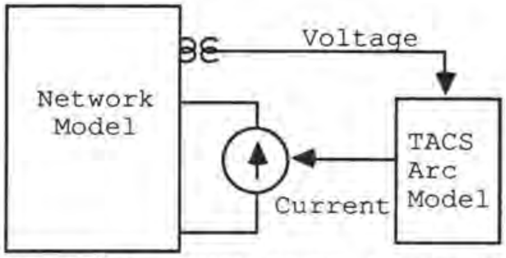
Table 8.1: Parameters for Advonin Model from Reference

	A	B	α	β
Air	6.0E-6	1.6E7	-0.20	-0.50
Oil	6.0E-6	1.0E8	-0.15	-0.60
SF_6	1.3E-6	1.0E6	-0.15	-0.28

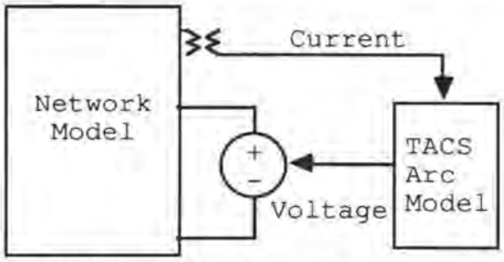
Table 8.2: Paremeters for Urbanek Model from Reference

P	V	θ	ζ
3.04E4	8000.0	2.0E6	45.0E4

Until these models are implemented in the EMTP, it is possible to use TACS to represent the breaker. The representation of the breaker can be obtained by means of a TACS controlled current source with an open breaker across it for the purpose of measuring the voltage across the arc. Figure 8.1 illustrates the setup required to represent a breaker using TACS controlled sources. This type of representation is not expected to be computationally accurate or particularly efficient. At present, time steps smaller than 0.2 μs are to be recommended for use with the breaker models.



(a) Voltage controlled current source representation.

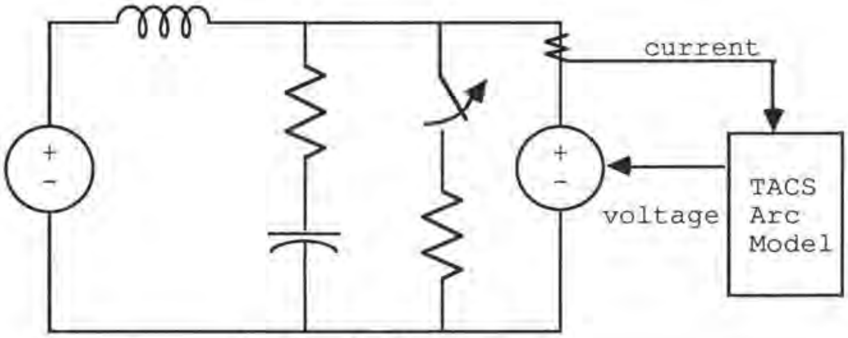


(b) Current controlled voltage source representation.

Figure 8.1: TACS representations of an arc.

8.4. An Example of Breaker Model Representation

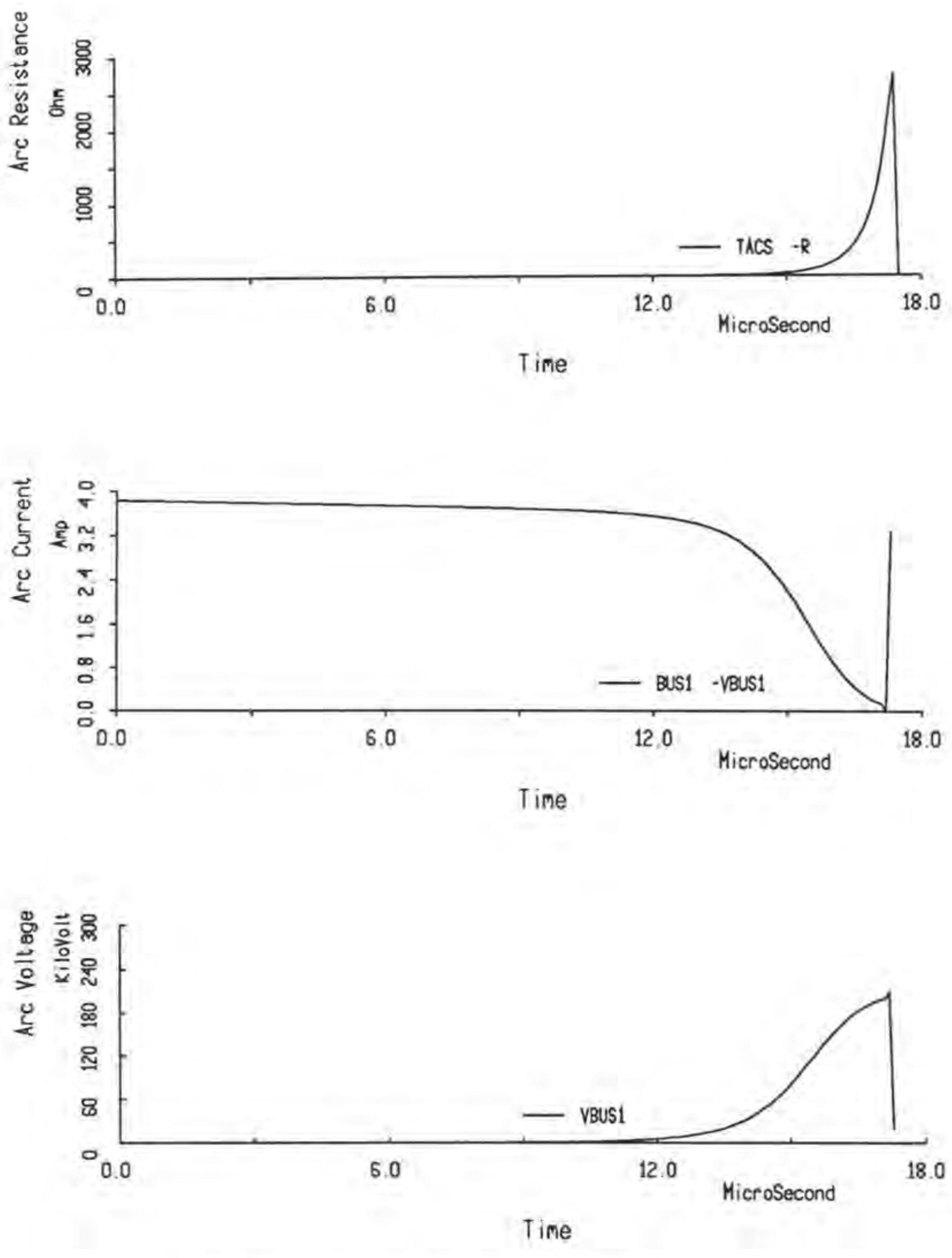
A specific example using the TACS methodology for arc representation has been tested using the EMTP. The following pages illustrate this example. Notice in particular that, unless considerably more attention is paid to the form of the model, the model breaks down with serious numerical errors as the current approaches true zero. The results up until that point are, however, quite credible. The first example involves the simulation of the Advonin equation using TACS. We defer the details of TACS simulation until Workbook IV, but we include a simple diagram of the system and a complete listing of the input data and the output from the simulation in Figure 8.2.



(a) Circuit Diagram.

```
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   .1E-6  14.E-5
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
       1       1                                               1
TACS HYBRID
C S_block
 1RP      +INT2   -INT1
       1.0
       0.0       1.0
C Z_block
  R       +RP                                          1.0 1.E-2  1.E7
C Switch_Current
91BUS1                     60.
C S_Functions
88INT1  =((ABS(BUS1))**2)*(R**2.43)/(1.3E-6 * 1.0E6)
88INT2  =R**1.15/1.3E-6
98VBUS1 =BUS1*R
C TACS_output
33VBUS1 R
C Initial Conditions
77VBUS1          0.0
77R            1.E-2
BLANK card terminates TACS data
C ............................ Circuit data ....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  SRC   BUS1                       6.9
  BUS1                     57.38       1.055
  VBUS1P                   .0001
BLANK card terminates circuit data
C ............................ Switch data .....................................
C Bus1->Bus2-><---Tclose<----Topen<-------Ie<-------------------------------->0
  BUS1  VBUS1       -1.      9999.                                          1
  VBUS1 VBUS1P      -1.         0.    1.E20
BLANK card terminates switch data
C ...........................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop
14SRC         106.14     60.     174.6        0.                  -1.     9999.
C TACS_EMTP_Vsource
60VBUS1                                                             -1.     9999.
BLANK card terminates source data
C ............................ Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS1  VBUS1
BLANK card terminates output request
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

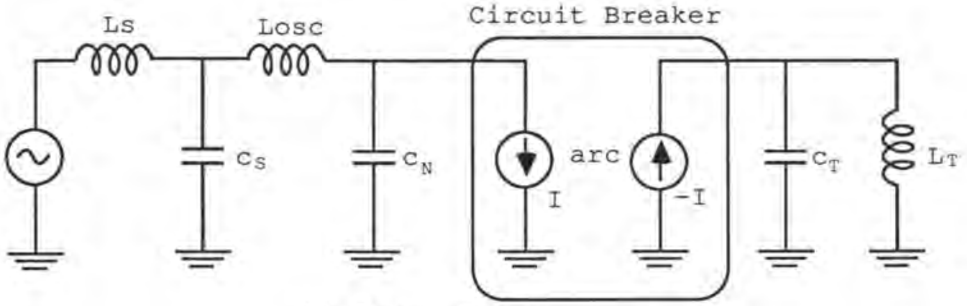
(b) TACS model.



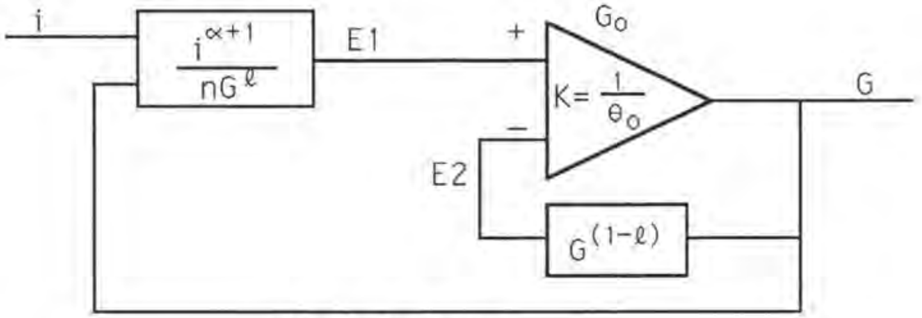
(c) Arc resistance, current and voltage.

Figure 8.2: A TACS representation of a SF_6 breaker using Advonin method.

The following example uses the Salles-Teixeira method to model a breaker [3]. The results obtained by Teixeira are reproduced and shown in Figure 8.3.



(a) System diagram.

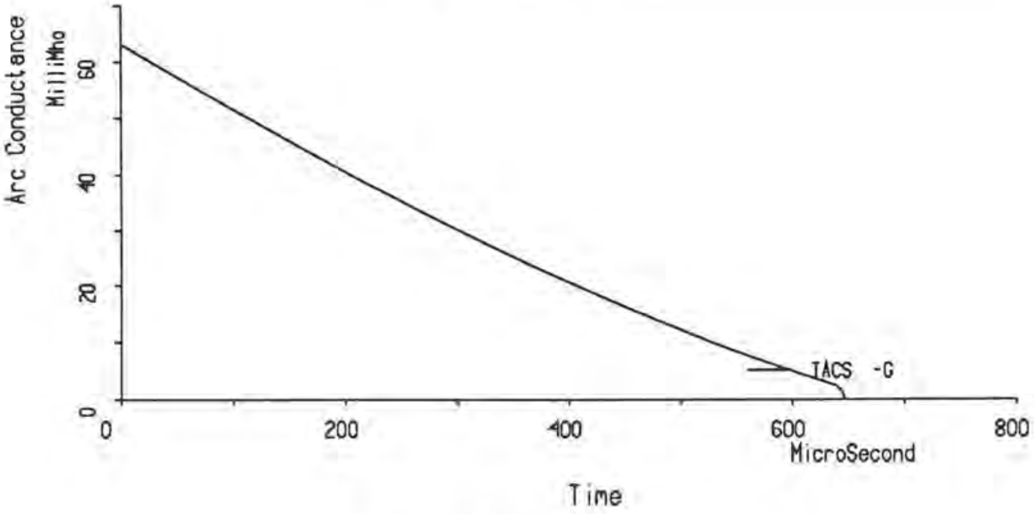


(b) Block diagram.

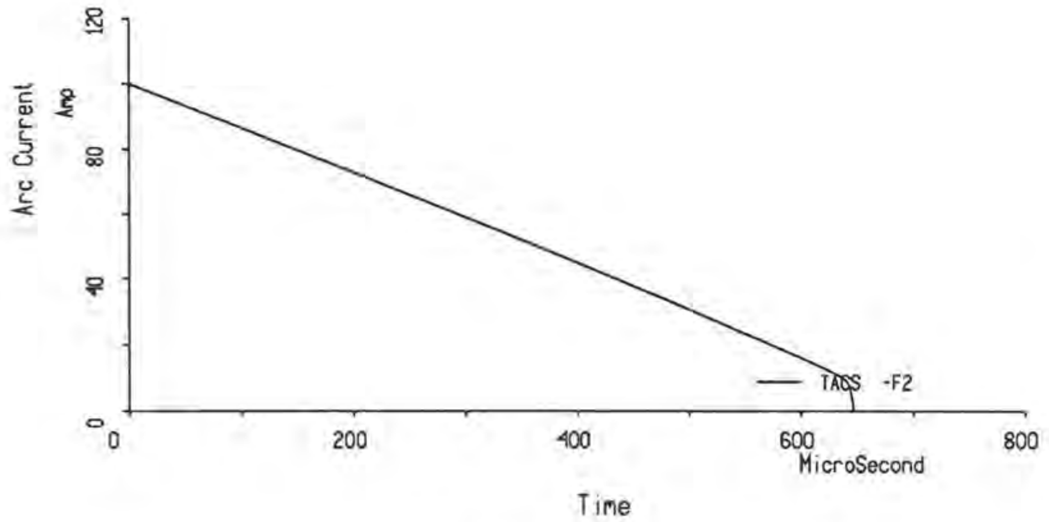
```
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   .4E-7   1.E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      15       1                                                1
TACS HYBRID
C Z_block
  DV       +V2     -V1
C S_block
 1G        +E1     -E2     +E3                     139.E3
      1.0
      0.0       1.0
 1SUP      +B      -C                                    -3.5E3 3.5E3
      1.0
      0.0       1.0
C Node_Voltage
90V1
90V2
C S_Functions
88GAP     = ABS(DV*G)
88G1      = G*NOT(-G)+1.E-8*NOT(G)
88E2      = (G1**.571)*NOT(-G)
88E1      = ((GAP**1.39958)/(10000.05*(G1**.429)))*NOT(-G)
88VV      = ABS(DV)
88B       = NOT(G)*763358776.6
88C       = NOT(-G)*SUP*1.E7
88E3      = NOT(SUP+650000.-VV)*NOT(G)*3.59712
98F1      = G*DV*NOT(-G)
98F2      = -F1
C TACS_output
33G     F2    DV    SUP   E1    E2    E3
C Initial Conditions
77SUP            0.0
77G          .062751
77G1         .062751
77F1       -99.99999
77F2        99.99999
77V1       -65434.88
77V2       -67028.48
77DV       -1593.6
BLANK card terminates TACS data
C
C ............................ Circuit data ...................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  TEN   CAP                         1.0                                        1
  CAP   F1                          .01                                        1
C This inductor has to be defined from ground to node, otherwise its initial
C condition won't be considered by the EMTP program.
        F2                         500.                                        1
  CAP                                     3.0
  F1                                      .04
  F2                                      .04
  V1    F1                    1.0
  V2    F2                    1.0
BLANK card terminates circuit data
C
C ............................ Switch data .....................................
C Bus1->Bus2-><---Tclose<----Topen<-------Ie<------------------------------->0
BLANK card terminates switch data
C
C ............................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <----Tstart<----Tstop
14TEN         70000.       60.  159.4414        0.                  -1.     9999.
```

```
C TACS_EMTP_Vsource
60F1    -1                                                             -1.       9999.
60F2    -1                                                             -1.       9999.
BLANK card terminates source data
C Initial_conditions
C Bus--><--------Volt(0)
 2CAP     -65436.22
 2F2      -67028.48
 2F1      -65434.88
C Bus1->Bus2-><---------------A<---------------B<---------------C<---------------D
 3TEN   CAP     72.18339
 3CAP   F1      99.95371
 3      F2      -100.285
 3CAP                             -65436.22
 3F2                              -67028.48
 3F1                              -65434.68
C
C ...........................  Output requests ...................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  CAP   F1    F2
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(c) TACS input data.



(d) Arc conductance.



(c) Arc current.

Figure 8.3: TACS representation of Salles-Teixeira breaker model.

8.5. Pre-Strike During Breaker Closure

An important refinement in the simulation of switch closing is the prestrike phenomenon. As the contacts of a breaker close and the gap between them gets smaller, breakdown will occur as soon as the voltage across the gap exceeds its dielectric strength. "Electrical closing" therefore happens before "mechanical closing," as illustrated in Figure 8.4.

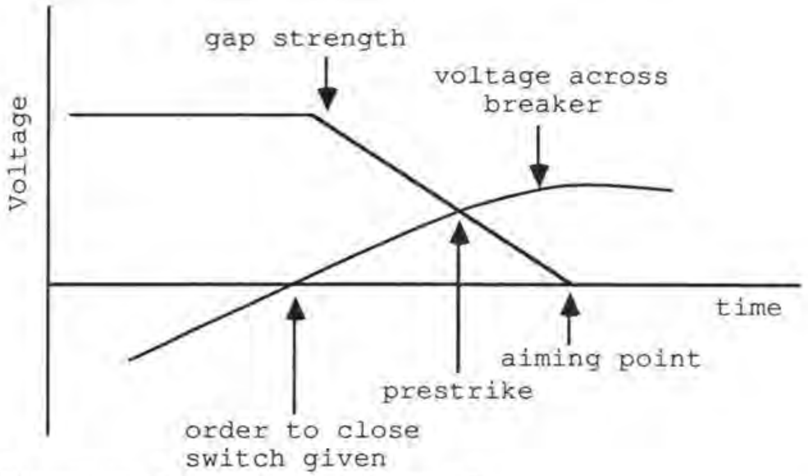


Figure 8.4: Illustration of prestriking phenomena.

The main effect of prestrikes on network transients is that the probability distribution of voltage closing instants will be skewed and not uniformly distributed. Assume that the order to close a given breaker will occur randomly within a cycle, and that the mechanical closing time will be equally random. Even for a single phase operation, the electrical closings will not be uniformly distributed within the voltage cycle, as illustrated in Figure 8.5.

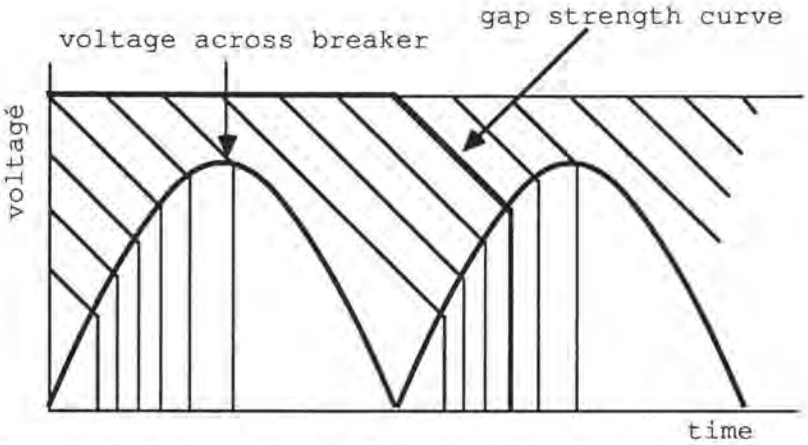
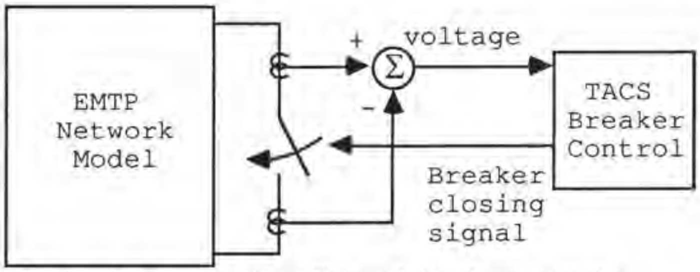


Figure 8.5: Influence of prestrikes on the probability distribution of electrical closing times.

For a multi-phase breaker, the determination of the probability distribution of true breaker closing times is more complicated to determine, and is likely to require a statistical simulation using the EMTP.

This view of prestrike phenomena assumes that the only item of interest is the effect of the closing time. For most purposes, the prestrike itself can be represented as an ideal switch closure. However, for certain studies it may be of interest to represent the prestrike arc conductance, and to recognize that during prestrike an oscillatory arc current behavior may be induced at a very high frequency (in the GigaHertz range). This oscillatory current may result in multiple quenchings and restrikes prior to the ultimate metallic contact. This type of study detail is not necessary in most cases, as the EMTP is unable to accurately represent these phenomena at this time for most components.

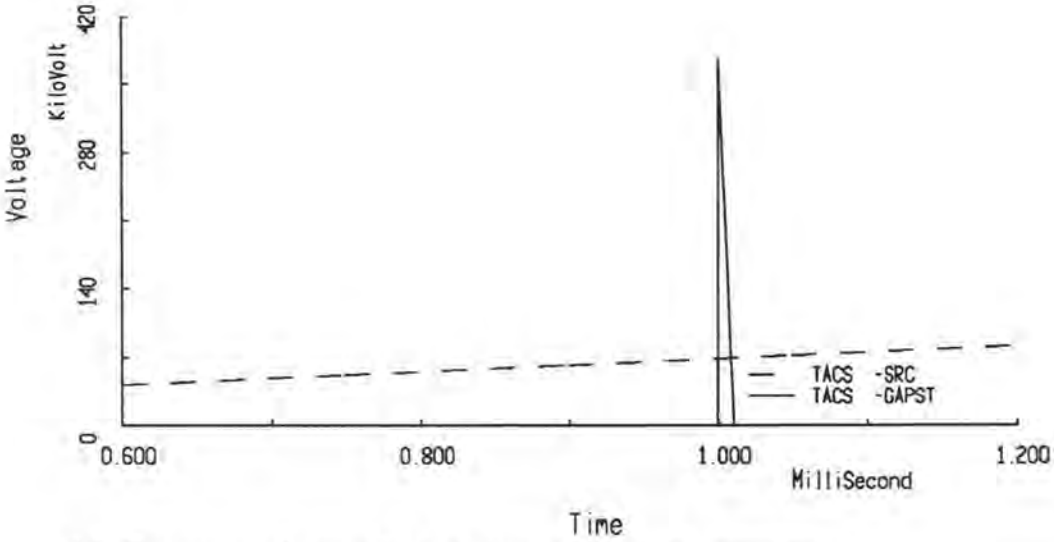
Simple prestrike phenomena can be simulated using ordinary EMTP components, such as ordinary switches and ordinary voltage sources. However, more complex studies, such as forcing a breaker to close when the voltage magnitude across the gap reaches a certain time-dependent strength, can be simulated using TACS. The following listings and figures illustrate how to do this.



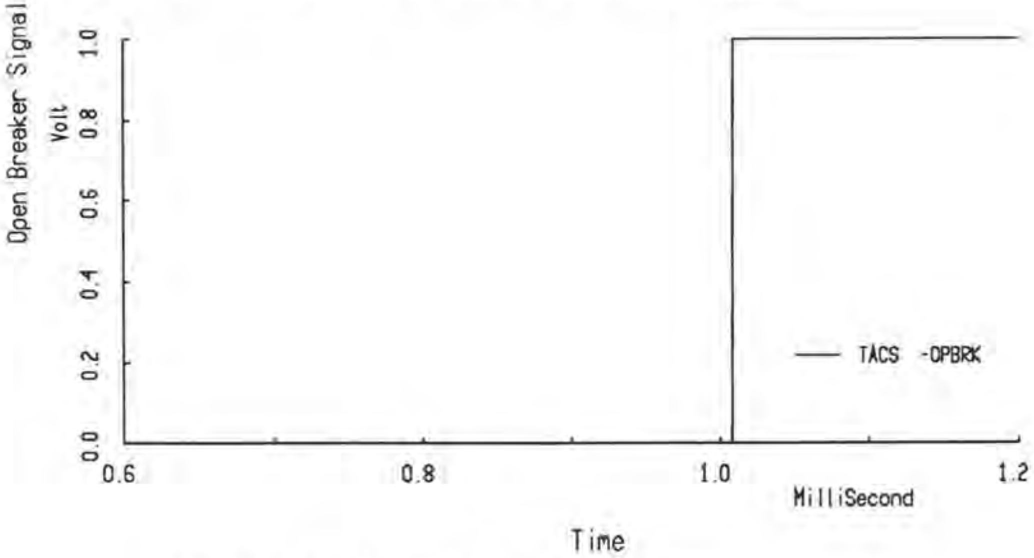
(a) A circuit to test the effect of breaker prestrike.

```
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   10E-7  1.5E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      15       1       0       0       0                       1
TACS HYBRID
C Z_block
  GAPST   +STEP   -RAMP1  +RAMP2
C Step_sgl
11STEP          377.                                             1.E-3   1.01E-3
24RAMP1         377.    10.E-6                                   1.E-3
24RAMP2         377.    10.E-6                                 1.01E-3
C Node_V
90SRC            0.0       60.
C Fortran Functions
88SIGNAL  =(GAPST.GT.0).AND.((GAPST-ABS(SRC)).LE.0)
C Accumulator and Counter
98OPBRK 65+SIGNAL
C TACS_output
33SRC   GAPST OPBRK
BLANK card terminates TACS data
C
C ............................ Circuit data ....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  SRCP                    304.05411.23                                         0
BLANK card terminates circuit data
C
C ............................ Switch data ....................................
C Bus1->Bus2-><---Tclose<----Topen<-------Ie<------------------------------->0
13SRC   SRCP                                                          OPBRK   13
BLANK card terminates switch data
C
C ...........................Source data ......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop
14SRC        187.79        60.      -90.        0.             -1.       9999.
BLANK card terminates source data
C
C ............................ Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  SRCP
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

(b) EMTP data case.



(c) Comparator input which detects moment of prestrike.



(d) Signal produced by prestrike detector.

Figure 8.6: Representation of breaker prestrike phenomena.

8.6. References

[1] V. Phaniraj and A. G. Phadke, "Modelling of Circuit Breakers in the Electromagnetic Transients Program," PICA 1987, Montreal Canada]

[2] M. Kizilcay, "Dynamic Arc Modeling in the EMTP," EMTP Newsletter July 1985.

[3] J. Salles Teixeira, "Dynamic Arc Model in the EMTP," EMTP Newsletter, Vol 4, pp. 14-27, Nov. 1983.

SECTION 9

FREQUENCY DEPENDENT SOURCE REPRESENTATION

Whenever a complex system is represented in a simulation, there is always a question as to how much further out should the system be represented. In all cases, at some point it becomes necessary to either completely ignore or simplify the representation of the system beyond a certain point. Traditional methods for the representation of the "rest of the system" have been based on short circuit equivalents. This chapter describes a methodology that permits the representation of the reduced part of the system in a far more accurate manner without having to explicitly retain a large portion of the system. As in all cases before, however, good judgment in the application of these techniques is imperative.

Seldom can an entire system be represented in a transient simulation. Often only a small portion of the system is represented in detail, while the majority of the system is simply omitted from further consideration or represented using a simple equivalent. Simple equivalents suitable for representation using the EMTP are often obtained from short circuit information based on fundamental frequency data using the methods described in Workbook I. Strictly speaking, these equivalents are not suitable for representation at frequencies other than the one for which they were obtained. The degree of accuracy of the equivalent depends to a great degree on the complexity of the system that the equivalent is intended to represent. The high frequency behavior of these equivalents deteriorates as the complexity of the system at the equivalent bus increases.

This chapter describes a new kind of equivalent, based on the idea that any equivalent suitable for transient studies ought to match the performance of the system over a reasonably wide range of frequencies. The details of these equivalents are described in a prize-winning paper by A. S. Morched and V. Brandwajn [1].

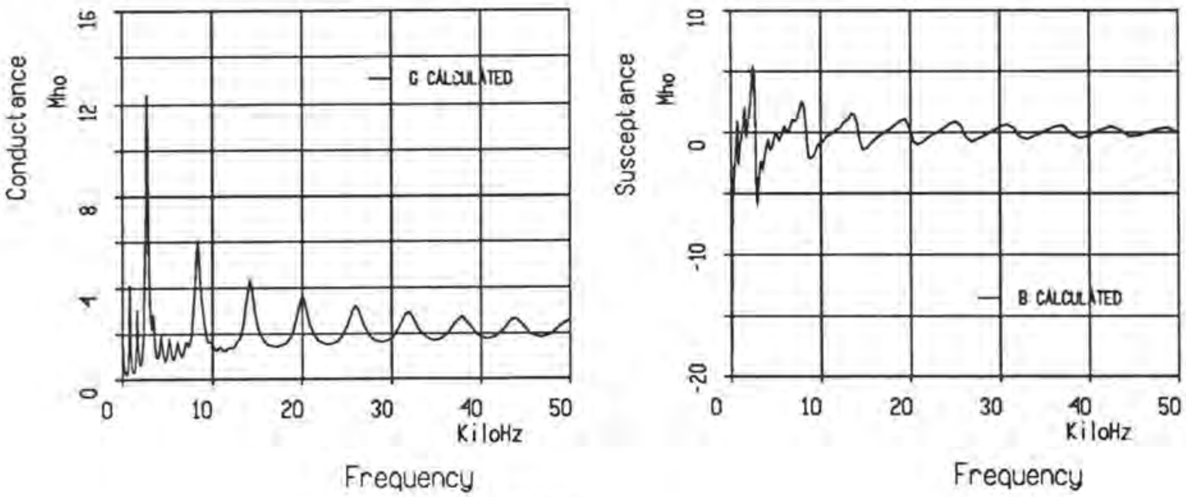
As a word of caution, most equivalents (including the ones in this chapter) are usually not meant to represent nonlinear behavior. The equivalents are only suitable for largely linear portions of the system, or for situations where the nonlinearities are not important.

9.1. The Nature of a Multi-Frequency Single Port Passive Equivalent

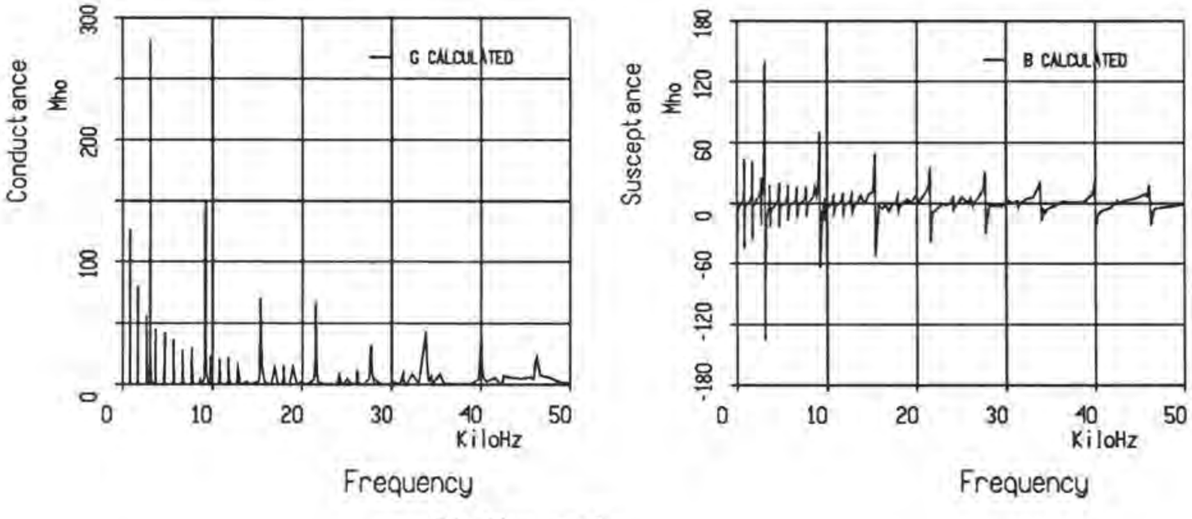
Any linear passive single port network has a behavior entirely describable by a frequency dependent impedance or admittance, as indicated in Figure 9.1. This applies to networks consisting of both lumped value components as well as to networks consisting of distributed parameter components.

Figure 9.1: The form of the equivalent for a single port network.

The frequency dependent behavior of the equivalent admittance may be a complex function of frequency, with numerous poles and zeroes, or it may be a quite simple function of frequency. In general, a system with distributed parameter lines (whether these lines themselves have frequency dependent parameters or not), will exhibit numerous poles and zeroes. In fact, there will be an infinite number of them all the way to infinite frequency. However, the behavior at very high frequencies is seldom of interest, mainly because of attenuation and losses. Figure 9.2 illustrates the possible behavior of the admittance as a function of frequency, expressed in rectangular form. The next section describes a method that can be used to obtain these plots.



(a) Ground mode.



(b) Line mode.

Figure 9.2: Possible admittance of the exact network as a function of frequency.

While either admittance or impedance values can be used, the use of admittances is more natural within the context of the EMTP and more consistent with network representations.

Once the frequency dependent behavior of an impedance is determined, there remains the question of how to implement this dependence. Undoubtedly, one possibility is to simply not reduce the network in the first place. However, a second possibility is to come up with a network *hopefully simpler than the original network* that exhibits the same behavior as is described by the admittance $Y(\omega)$. While there are many possible ways of attaining this behavior, one of the simplest and best understood is the use of a Foster network. In this case, a parallel Foster network representation can be selected. The form of this Foster network is illustrated in Figure 9.3.

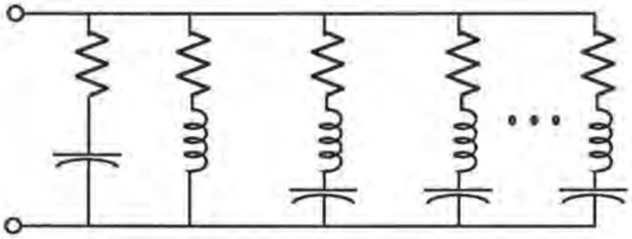


Figure 9.3: The structure of the Foster network.

While this representation is likely to lead to arbitrarily accurate equivalents (depending on the desired number of equivalent branches) it may be difficult to determine the values of the RLC components. A simpler lossless network can be used as a first approximation by neglecting the losses. This network is represented in Figure 9.4.

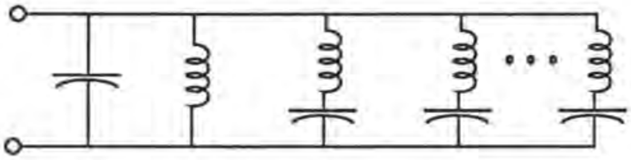


Figure 9.4: The structure of the lossless Foster network.

If we assume that the original network is lossless as well and that it has a finite number of poles and zeroes, the admittance of the original lossless network as a function of frequency may be expressed as:

$$Y(s) = K_\infty \left(\frac{\prod_{i=1}^{N} s^2 + \omega_{pi}^2}{s \prod_{i=1}^{N} s^2 + \omega_{si}^2} \right)$$

where ω_{pi} and ω_{si} are the angular frequencies of the parallel and series resonances obtained from the frequency response of the circuit. That is, they are the frequencies at which the imaginary part of the admittance of the actual circuit vanishes or reaches a resonant peak. The constant K_∞ is determined from the power frequency impedance. This expression can be expanded using a partial fraction expansion as:

$$Y(s) = K_\infty s + \frac{K_0}{s} + \sum_{i=1}^{N} \frac{k_i s}{s^2 + \omega_{si}^2}$$

From another viewpoint, the admittance of the above equivalent circuit can be written as:

$$Y(s) = C_\infty s + \frac{1}{L_0 s} + \sum_{i=1}^{N} \frac{\frac{s}{L_i}}{\frac{s^2 + 1}{L_i C_i}}$$

By equating values of these last two expressions, the values of all inductances and resistances can be determined.

The resistive elements can be obtained by iterative refinement. At resonant frequencies the resistive term dominates the behavior. Thus, an approximate value for a resistance is equal to the known real part of the equivalent impedance at the resonant frequency, ignoring other branches. The refinement step includes the incorporation of the effect of other branches.

9.2. Multi-port, Three Phase Active Networks

While the principle of equivalencing based on the synthesis of an equivalent RLC circuit can be understood from the previous section, the practical matter of implementing these equivalents in active multi-port three phase systems requires further explanation.

We consider each aspect of the extension of this work. First, consider the extension to a simple single phase multi-port network. The extension to a multi-port network is quite straightforward. Simply replace the scalar frequency dependent admittance $Y(\omega)$ by a frequency dependent admittance matrix $[Y(\omega)]$. The process can be best understood if we first begin with the entire system admittance matrix:

$$[Y_{syst}(\omega)] = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1n} \\ Y_{21} & Y_{22} & \dots & Y_{2n} \\ & \dots & & \\ Y_{n1} & Y_{n2} & \dots & Y_{nn} \end{bmatrix}$$

This admittance matrix can be obtained from a knowledge of the model for each and every component of the system and from a suitable method for aggregating these components. For a complete reference on how to construct these aggregate models without the help of the EMTP, refer to [2]. Each term of this matrix may be frequency dependent. The matrix can be reduced in principle to any desired size by one of two methods without any loss of accuracy at any frequency:

- Invert the matrix, delete the rows and columns that correspond to the nodes that are to be eliminated, and re-invert the resulting smaller impedance matrix. An example is shown in section 2.6.1.
- Order the matrix so the desired terms to be retained are in the lower right hand corner. Then perform a partial LDU factorization of the matrix up until the point where the equivalent is desired.

In the case of a single port equivalent, the resulting equivalent matrix will be a 1 by 1 matrix, or a scalar admittance. In the case of a multi-port equivalent, the resultant matrix will be a matrix of dimension equal to the number of ports. The methodology is the same for both.

While the explanation above may be suitable to explain how to obtain an equivalent as a function of frequency, in practice the procedure cannot be done in symbolic form. Expressions valid for all frequencies are quite difficult to obtain. Instead, we settle for determination of the equivalents at a number of specific frequencies using the above method applied to specific matrices.

A second aspect of actual equivalents is that it has been determined that it is most reasonable to revert back to the use of symmetrical components in the definition of equivalents. This is a most natural objective, since often the information about a system is known primarily in this manner. Thus, in this section we will restrict our attention to either the positive or the zero sequence networks in the determination of the equivalents. The implication of this is that the equivalents obtained for sequence components are not directly useable in a phase component analysis. Given that the intent is to use equivalents to represent in an approximate manner reasonably remote parts of the system the use of symmetrical components can be amply justified.

9.3. Application to the Sample System

We now apply the concept of frequency dependent equivalents to the sample system used in this workbook. Two cases will be considered:

- The simultaneous energization of line 1-2 with the breaker at bus 2 open.
- The sequential energization of line 1-2 with the breaker at bus 2 open.

The network from bus 1 to buses 12 and 7, the transformer and generator at bus 1 and the transformer and load at bus 12 will be replaced by a frequency dependent equivalent at bus 1. Figure 9.5 illustrates this case once more. Only line 1-2 will be represented in detail using frequency dependent line model. This is not necessarily the best thing to do. You may prefer to still represent a greater portion of the system before constructing the equivalent. However, with this type of equivalent good results can be obtained even in this extreme case.

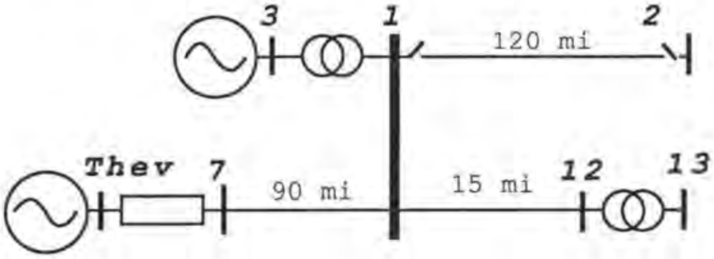
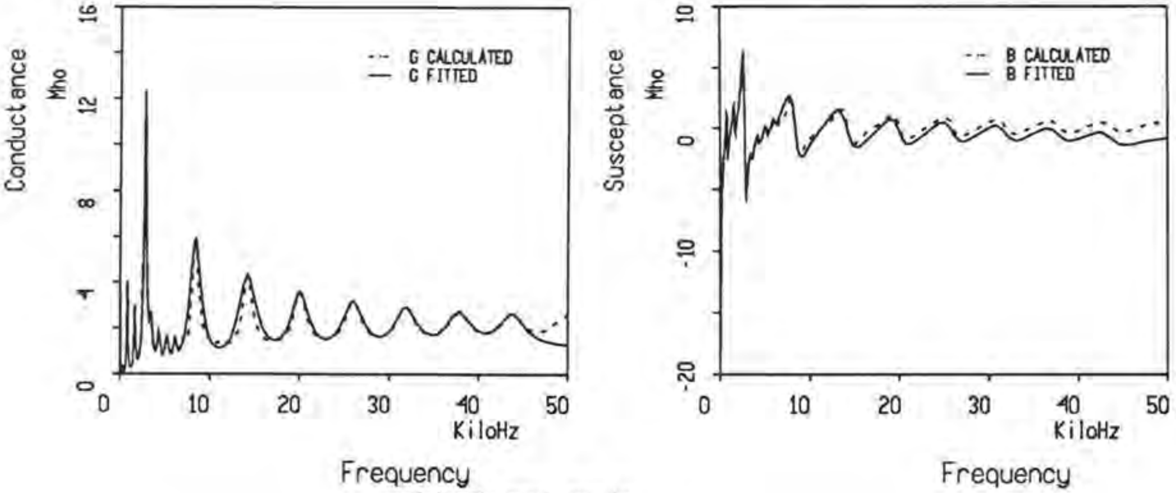


Figure 9.5: Circuit diagram before determination of frequency dependent equivalent.

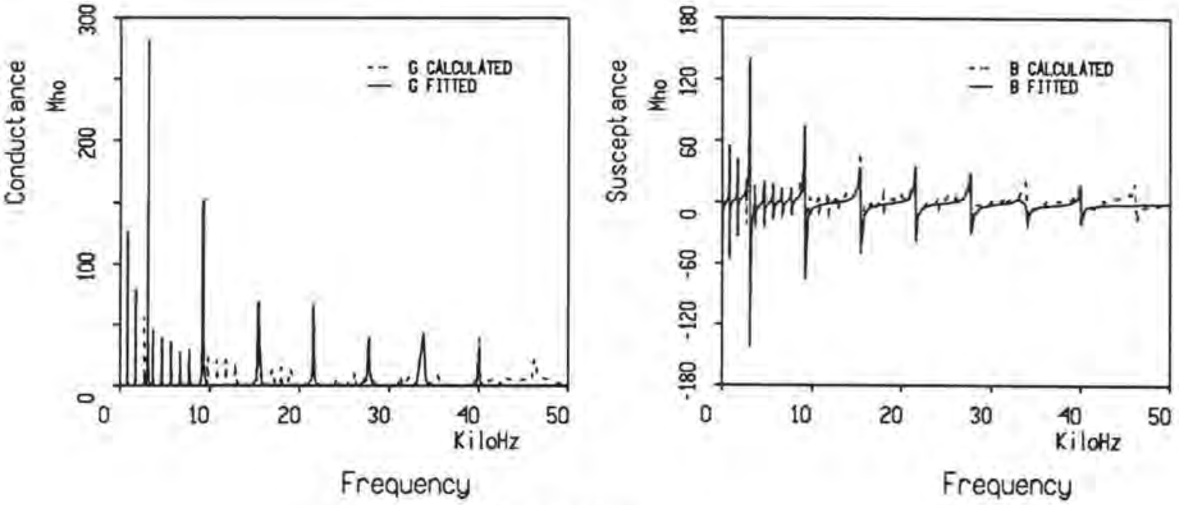
For reference, the frequency response of the equivalencing system as seen from bus 1 has been obtained. Figure 9.6 compares in the frequency domain the response of the system with that of the equivalent system. This data can be obtained from the FDNA program when `ICOM` in the output option card is non-zero.

The data to request execution of the FDNA program is presented in Figure 9.7. For clarity comments have been included in anticipation that this feature will be available at some time. *All comments should be discarded and all* BLANK*s replaced by blank lines prior to execution of the FDNA program.* The organization of the data for the FDNA program is as follows:

```
Case Description Information
Description of frequency ranges and output requests
Description of the geometry of lines (in LINE CONSTANTS format)
Description of lumped parameter branches, series and shunt
```



(a) Ground mode.



(b) Line mode.

Figure 9.6: Real and imaginary components of the network admittance as a function of frequency. The figures illustrate the frequency response as obtained from the complete network and the frequency response as obtained from the equivalent. Notice excellent agreement between the two at almost all frequencies.

Notice the values of the linear series and shunt branches in Figure 9.7 are in per unit. The FDNA program assumes per unit values if BASE is left blank.

```
C FDNA input data.
C   Notice: The current version of FDNA program does not accept comments in
C   the input data.  So, this template serves only as a guide line.
C   All comment lines must be removed before actual run, and all BLANKs have
C   to be replaced by a blank line.
C Study identifications.
C Label------------------------------------------------------------------------>
Frequency Dependent Network Equivalent applies to 13 bus sample system.
Equivalent circuit as seen from BUS 1.
C -FileId
Fig9_9
C Maxima and minima selection.
C ---REjct<-----RMxd<-----RMxi<-----RMnd<----RMni1<----RMni2

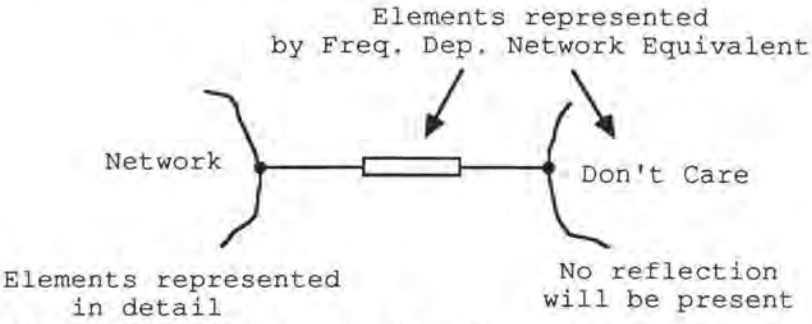
C Output options specification.
C Prt<Plot<Scal<-Old<Resu<-Cap<Prt2<Prt3<Icom
    0    0    0    0    0    0    0    0    1
C Reference bus data.
C RfNam><------RefkV
  BUS1          230.
C Frequency range over which the network admittance is approximated.
C --StrFeq<NDec<DPrt<---RefFrq
        5.    4  100       60.
C Right-of-way cards.
C R/W Name---><--Len<-NCCT<-Data<-IPrt
  LINE1-7     144.84     1     0     0
C From->To---><BaskV
  BUS1  BUS7    230.
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d
  0  0.5   3.750 4           0.950   -7.0     29.     29.
  0  0.5   3.750 4           0.950    7.0     29.     29.
  1  0.5  0.0701 4           3.058  -10.0     20.     20.       40.            3
  2  0.5  0.0701 4           3.058    0.0     20.     20.       40.            3
  3  0.5  0.0701 4           3.058   10.0     20.     20.       40.            3
BLANK card terminates conductor cards
C Frequency Cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f
    100.
C Reapeat for each R/W
  LINE1-12     24.14     1     0     0
  BUS1  BUS12   230.
  0  0.5   3.750 4           0.950   -7.0     29.     29.
  0  0.5   3.750 4           0.950    7.0     29.     29.
  1  0.5  0.0701 4           3.058  -10.0     20.     20.       40.            3
  2  0.5  0.0701 4           3.058    0.0     20.     20.       40.            3
  3  0.5  0.0701 4           3.058   10.0     20.     20.       40.            3
BLANK card terminates conductor cards
    100.
BLANK card terminates right-of-way cards
C Linear series branches.
C From->To--->RFrom>RTo--><---R0<---X0<---B0<---R1<---X1<---B1<-Base
  BUS12 BUS13                     0.05              0.05
BLANK card terminates linear series branches.
C Shunt branches.
```

```
C From-><----------------><---R0<---X0<---B0<---R1<---X1<---B1<-Base
  BUS1                            0.05              0.11
  BUS7                    2.48-41.69-2      1.24-42.85-2
  BUS13                      1.9  0.62         1.9  0.62
BLANK card terminates shunt branches and FDNA data case.
```

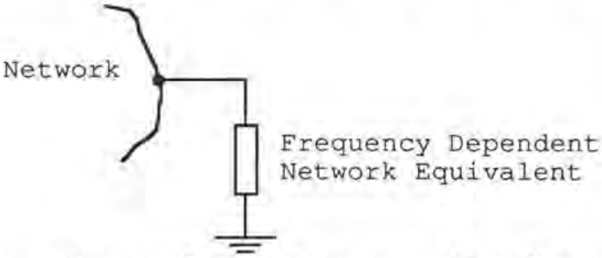
Figure 9.7: Input data for the FDNA program.

> **Important: At present comments are not allowed within FDNA program data. Comments have been added above for clarity, but these must be removed by the user prior to execution of the FDNA program.**

Several conventions apply to the naming of nodes within the FDNA file description. In particular, as mentioned earlier, less important lines are best represented simply by a shunt impedance equal to their characteristic impedance. This characteristic impedance may very well be frequency dependent. These lines are said to be connected to a portion of the network we do not care about, and from which we do not expect to get significant reflections. Figure 9.8 illustrates this situation. These lines are specified to the FDNA program as if they were connected to ground (a "blank" name for the node name associated with the external or "don't care" end of the line).



(a) A transmission line connected to the external network.



(b) Entire line and external network as seen from line represented as a single frequency dependent shunt characteristic impedance.

Figure 9.8: Representation of lines from network of interest to an external network.

The output from the execution of the FDNA program is presented in Figure 9.9 and 9.10. Both printed and "punched" output are produced. Neither output contains information about the R_1 resistances. These must be added by the user if desired. *Note: it is expected that the new version of the FDNA program implemented in version 2.0 of DCG/EPRI EMTP makes the addition of shunt resistances completely unnecessary.* Also note that the output of the version 1.0 FDNA program assumes that a user wishes to use ohms at fundamental frequency instead of mH and μF for inductors and capacitors. Therefore either the miscellaneous data line and the remainder of the data must be modified to specify nonzero XOPT and COPT, or else the output of the FDNA program must be converted.

```
1      ONTARIO HYDRO FREQUENCY DEPENDENT NETWORK ADMITTANCE PROGRAM
       STUDY IDENTIFICATION:
        Frequency Dependent Network Equivalent applies to 13 bus sample system.
                Equivalent circuit as seen from BUS 1.
       DATE OF STUDY:  1/27/88
 EIGENVECTORS COMPUTED FOR FREQ., HZ =        0.11679E+05
 ADMITTANCE CALCULATION TABLE OF FREQUENCIES
    REFERENCE FREQUENCY, HZ =                 0.60000E+02
    STARTING FREQUENCY, HZ =                  0.50000E+01
    NUMBER OF DECADES =                                 4
    NUMBER OF POINTS PER DECADE =                     100
    LOGARITHMIC DIVISION                                *
 RECORD OF SORTED INPUT DATA                       RIGHT-OF-WAY   1  LINE1-7
     PHASE NUMBER R-TYPE RESISTANCE X-TYPE X OR GMR DIAMETER X-COORD. Y-COORD.
   1        1         0.5000  0.11282    4     0.00000  1.20391  -33.187   64.959
   2        2         0.5000  0.11282    4     0.00000  1.20391   -0.379   64.959
   3        3         0.5000  0.11282    4     0.00000  1.20391   32.429   64.959

..Some output omitted...

IMPEDANCES ARE BASED ON EARTH RESIS OF 100 OHM-M AND CORRECTION FACTOR=  0.000001

...Some output omitted...

  MODE 0 REPRESENTED BY 16 BRANCHES
          R1               L               C
    1   0.208717E-02   0.116836E-03   0.000000E+00
    2   0.250162E+00   0.301366E-03   0.122968E-03
    3   0.358222E+00   0.295314E-03   0.314494E-04

...Some output omitted ...

   14   0.623327E+00   0.299825E-04   0.591891E-06
   15   0.688639E+00   0.315400E-04   0.419830E-06
   16   0.547032E+00   0.000000E+00   0.700508E-05
  MODE 1 REPRESENTED BY 17 BRANCHES
          R1               L               C
    1   0.311715E-02   0.157391E-03   0.000000E+00
    2   0.793247E-02   0.115273E-03   0.326347E-03
    3   0.124902E-01   0.183529E-03   0.463946E-04

...Some output omitted...

   15   0.237398E-01   0.181762E-04   0.121956E-05
   16   0.232792E-01   0.427164E-04   0.370694E-06
   17   0.156015E+01   0.000000E+00   0.140129E-04
```

Figure 9.9: Portion of printed output of the FDNA program showing input data and resultant equivalent circuit.

```
C Output file of the FDNA program (*.RLC).
  BRANCHES
C  MODE 0, 16 BRANCHES
C  R[1I] IN OHMS   X[L] IN OHMS  W[C] IN MICROMHOS
  0.11041110E+01  0.23300430E+02  0.00000000E+00
  0.13233590E+03  0.60100930E+02  0.87633040E+02
  0.18949940E+03  0.58894000E+02  0.22412350E+02
  0.43466590E+02  0.81913900E+01  0.57077610E+02
  0.30875570E+03  0.39577160E+02  0.75900370E+01
  0.39670970E+03  0.54517280E+02  0.34624520E+01
  0.46391820E+03  0.63882180E+02  0.20334730E+01
  0.61079680E+03  0.86588520E+02  0.10967230E+01
  0.93525710E+02  0.37230230E+01  0.13707830E+02
  0.13784150E+03  0.33291340E+01  0.53766550E+01
  0.18653590E+03  0.44654650E+01  0.20102920E+01
  0.23002340E+03  0.48424680E+01  0.11063090E+01
  0.28103780E+03  0.56013860E+01  0.63416500E+00
  0.32973980E+03  0.59793550E+01  0.42181030E+00
  0.36429010E+03  0.62899770E+01  0.29919110E+00
  0.28937970E+03  0.00000000E+00  0.49921600E+01
            9999
C  MODE 1, 17 BRANCHES
C  R[1I] IN OHMS   X[L] IN OHMS  W[C] IN MICROMHOS
  0.16489740E+01  0.31388170E+02  0.00000000E+00
  0.41962770E+01  0.22988750E+02  0.23257090E+03
  0.66073090E+01  0.36600790E+02  0.33063030E+02
  0.26366940E+02  0.55181400E+02  0.91268910E+01
  0.18652860E+01  0.34454150E+01  0.10889510E+03
  0.11686270E+02  0.31689500E+02  0.83800240E+01
  0.12535710E+02  0.29574200E+02  0.55509180E+01
  0.14171060E+02  0.28927610E+02  0.38399520E+01
  0.16635070E+02  0.30463960E+02  0.26263230E+01
  0.19414290E+02  0.29371250E+02  0.20588860E+01
  0.34044470E+01  0.32856480E+01  0.12878460E+02
  0.66002190E+01  0.30705470E+01  0.49559800E+01
  0.71454760E+01  0.43301070E+01  0.17944610E+01
  0.95515140E+01  0.35548430E+01  0.13217690E+01
  0.12558380E+02  0.36248400E+01  0.86911550E+00
  0.12314700E+02  0.85188660E+01  0.26417440E+00
  0.82532070E+03  0.00000000E+00  0.99862700E+01
            9999
```

Figure 9.10: Complete "punched output" file of the FDNA program.

Figure 9.11 illustrates the input data for the representation of the original case with a complete detailed representation of all lines using Marti model (without any frequency dependent equivalents). Figure 9.12 illustrates the input data for the frequency dependent equivalent. Notice that the FDNA data is represented as data of type `51, 52, 53` (mutual branches), and a flag "`-6666.`" is used, along with a keyword "`BRANCHES`" to signal the start of the FDNA data.

```
C Reference case using JMarti frequency dependent line model to model line 1-2
C line 1-7 and line 1-12.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   5.E-6  25.E-3     60.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25       1                                               1
C
C ............................ Circuit data  ...................................
C Bus1->Bus2-><----------><----R<----------L
51BUS3A BUS1A                 0.        26.45
52BUS3B BUS1B                 0.        58.19
53BUS3C BUS1C
C Bus1->Bus2-><----------><----R<----------L
51THEVA BUS7A             0.1310       8.9289
52THEVB BUS7B             0.0658      15.0718
53THEVC BUS7C
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS12ABUS13A                0. 26.45
  BUS12BBUS13BBUS12ABUS13A
  BUS12CBUS13CBUS12ABUS13A
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BUS13A                  251.27 82.59
  BUS13B      BUS13A
  BUS13C      BUS13A
-1BKR1A BUS2A                 1.                     -2
      21       0.43099080760236140000E+03
  0.27118705643263190OE+03  0.14905184235656990OE+04  0.29625622338095910OE+03
 -0.75663249692904630OE+02 -0.27603766837163850OE+03  0.69872289752998860OE+01

... Some data omitted ...

-2BKR1B BUS2B                 1.                     -2
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
 -0.62160153081381400OE+02  0.97331626490090370OE+02 -0.30679522148884750OE+02

... Some data omitted ...

-3BKR1C BUS2C                 1.                     -2
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
 -0.62160153081381400OE+02  0.97331626490090370OE+02 -0.30679522148884750OE+02

... Some data omitted ...

-1BUS1A BUS7A                 1.                     -2
      21       0.43099080760236140000E+03
  0.27118705643263190OE+03  0.14905184235656990OE+04  0.29625622338095910OE+03
 -0.75663249692904630OE+02 -0.27603766837163850OE+03  0.69872289752998860OE+01

 ...  Some data omitted ...

-2BUS1B BUS7B                 1.                     -2
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
 -0.62160153081381400OE+02  0.97331626490090370OE+02 -0.30679522148884750OE+02

... Some data omitted ...

-3BUS1C BUS7C                 1.                     -2
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
```

```
 -0.621601530813814000E+02  0.973316264900903700E+02 -0.306795221488847500E+02

... Some data omitted ...

-1BUS1A BUS12A                 1.                     -2
      21       0.426476267281217200000E+03
  0.271187973391609000E+03  0.155775216694037000E+04  0.585660271640634000E+02
  0.126791731105130600E+04 -0.144489089820815700E+04  0.500739274344443300E+01

... Some data omitted ...

-2BUS1B BUS12B                 1.                     -2
      14       0.265953404884260000000E+03
  0.244649718440138100E+03  0.110671256423716900E+04  0.231405194922499400E+03
 -0.638628320431304900E+02  0.983339995031863500E+02 -0.313478185881458100E+02

... Some data omitted ...

-3BUS1C BUS12C                 1.                     -2
      14       0.265953404884260000000E+03
  0.244649718440138100E+03  0.110671256423716900E+04  0.231405194922499400E+03
 -0.638628320431304900E+02  0.983339995031863500E+02 -0.313478185881458100E+02

... Some data omitted ...
BLANK card terminates circuit data
C
C ............................  Switch data  ......................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                     0
  BUS1A BKR1A     1.0E-3     9999.        0                                      0
  BUS1B BKR1B     2.5E-3     9999.        0                                      0
  BUS1C BKR1C     2.5E-3     9999.        0                                      0
BLANK card terminates switch data
C
C ............................Source data  .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14BUS3A       187.79        60.         0.        0.                -1.      9999.
14BUS3B       187.79        60.      -120.        0.                -1.      9999.
14BUS3C       187.79        60.       120.        0.                -1.      9999.
14THEVA       187.79        60.         0.        0.                -1.      9999.
14THEVB       187.79        60.      -120.        0.                -1.      9999.
14THEVC       187.79        60.       120.        0.                -1.      9999.
BLANK card terminates source data
C
C ............................  Output requests ..................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS2A BUS2B BUS2C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

Figure 9.11: EMTP input data for energization of a 120 mile line connecting bus 1 and bus 2. Marti model is used to represent all lines.

```
C Example of using frequency depdendent network equivalent model.  Line 1-2 is
C represented by a JMarti frequent dependent line.  Line 1-7, line 1-12, and
C those components beyond bus 1 and 12 are represented by a freq. depependent
C equivalent Elements beyond bus 7 is represented by a short circuit equivalent in
C FDNA.
BEGIN NEW DATA CASE
C ............................ Miscelaneous data .............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   5.E-6  25.E-3     60.       60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25      1                                                  1
C ........................ Branch Connection Cards ............................
C Bus1->Bus2-><----------><Code1<------Code2
51SCEQA BUS1A             -6666.       -6666.
52SCEQB BUS1B             -6666.       -6666.
53SCEQC BUS1C             -6666.       -6666.
 BRANCHES
C  MODE 0, 16 BRANCHES
C  R[1I] IN OHMS   X[L] IN OHMS  W[C] IN MICROMHOS
  0.11041110E+01  0.23300430E+02  0.00000000E+00
  0.13233590E+03  0.60100930E+02  0.87633040E+02
  0.18949940E+03  0.58894000E+02  0.22412350E+02
  0.43466590E+02  0.81913900E+01  0.57077610E+02
  0.30875570E+03  0.39577160E+02  0.75900370E+01
  0.39670970E+03  0.54517280E+02  0.34624520E+01
  0.46391820E+03  0.63882180E+02  0.20334730E+01
  0.61079680E+03  0.86588520E+02  0.10967230E+01
  0.93525710E+02  0.37230230E+01  0.13707830E+02
  0.13784150E+03  0.33291340E+01  0.53766550E+01
  0.18653590E+03  0.44654650E+01  0.20102920E+01
  0.23002340E+03  0.48424680E+01  0.11063090E+01
  0.28103780E+03  0.56013860E+01  0.63416500E+00
  0.32973980E+03  0.59793550E+01  0.42181030E+00
  0.36429010E+03  0.62899770E+01  0.29919110E+00
  0.28937970E+03  0.00000000E+00  0.49921600E+01
            9999
C  MODE 1, 17 BRANCHES
C  R[1I] IN OHMS   X[L] IN OHMS  W[C] IN MICROMHOS
  0.16489740E+01  0.31388170E+02  0.00000000E+00
  0.41962770E+01  0.22988750E+02  0.23257090E+03
  0.66073090E+01  0.36600790E+02  0.33063030E+02
  0.26366940E+02  0.55181400E+02  0.91268910E+01
  0.18652860E+01  0.34454150E+01  0.10889510E+03
  0.11686270E+02  0.31689500E+02  0.83800240E+01
  0.12535710E+02  0.29574200E+02  0.55509180E+01
  0.14171060E+02  0.28927610E+02  0.38399520E+01
  0.16635070E+02  0.30463960E+02  0.26263230E+01
  0.19414290E+02  0.29371250E+02  0.20588860E+01
  0.34044470E+01  0.32856480E+01  0.12878460E+02
  0.66002190E+01  0.30705470E+01  0.49559800E+01
  0.71454760E+01  0.43301070E+01  0.17944610E+01
  0.95515140E+01  0.35548430E+01  0.13217690E+01
  0.12558380E+02  0.36248400E+01  0.86911550E+00
  0.12314700E+02  0.85188660E+01  0.26417440E+00
  0.82532070E+03  0.00000000E+00  0.99862700E+01
            9999
-1BKR1A BUS2A                 1.                      -2
      21       0.43099080760236140000E+03
  0.27118705643263190OE+03  0.14905184235656990OE+04  0.29625622338095910OE+03
 -0.75663249692904630OE+02 -0.27603766837163850OE+03  0.69872289752998860OE+01

... Some data omitted ...

-2BKR1B BUS2B                 1.                      -2
```

```
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
 -0.62160153081381400OE+02  0.97331626490090370OE+02 -0.30679522148884750OE+02

... Some data omitted ...

-3BKR1C BUS2C                     1.                      -2
      14       0.26622093557900560000E+03
  0.24464992232421910OE+03  0.11082262854305800OE+04  0.22851110850353840OE+03
 -0.62160153081381400OE+02  0.97331626490090370OE+02 -0.30679522148884750OE+02

... Some data omitted ...
BLANK card terminates circuit data
C
C ...........................  Switch data  .....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                    0
  BUS1A BKR1A     1.0E-3     9999.         0                                    0
  BUS1B BKR1B     2.5E-3     9999.         0                                    0
  BUS1C BKR1C     2.5E-3     9999.         0                                    0
BLANK card terminates switch data
C
C ..........................Source data  ......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14SCEQA        187.79        60.        0.         0.                 -1.    9999.
14SCEQB        187.79        60.     -120.         0.                 -1.    9999.
14SCEQC        187.79        60.      120.         0.                 -1.    9999.
BLANK card terminates source data
C
C ...........................  Output requests ..................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS2A BUS2B BUS2C
BLANK card terminates output requests
BLANK card terminates plot requests
BLANK card terminates EMTP solution-mode
```

Figure 9.12: EMTP input data for energization of a 120 mile frequency dependent line connecting bus 1 and bus 2 using frequency dependent network equivalent.

The results of simultaneous and sequential energization with both models are shown in Figure 9.13 and 9.14.

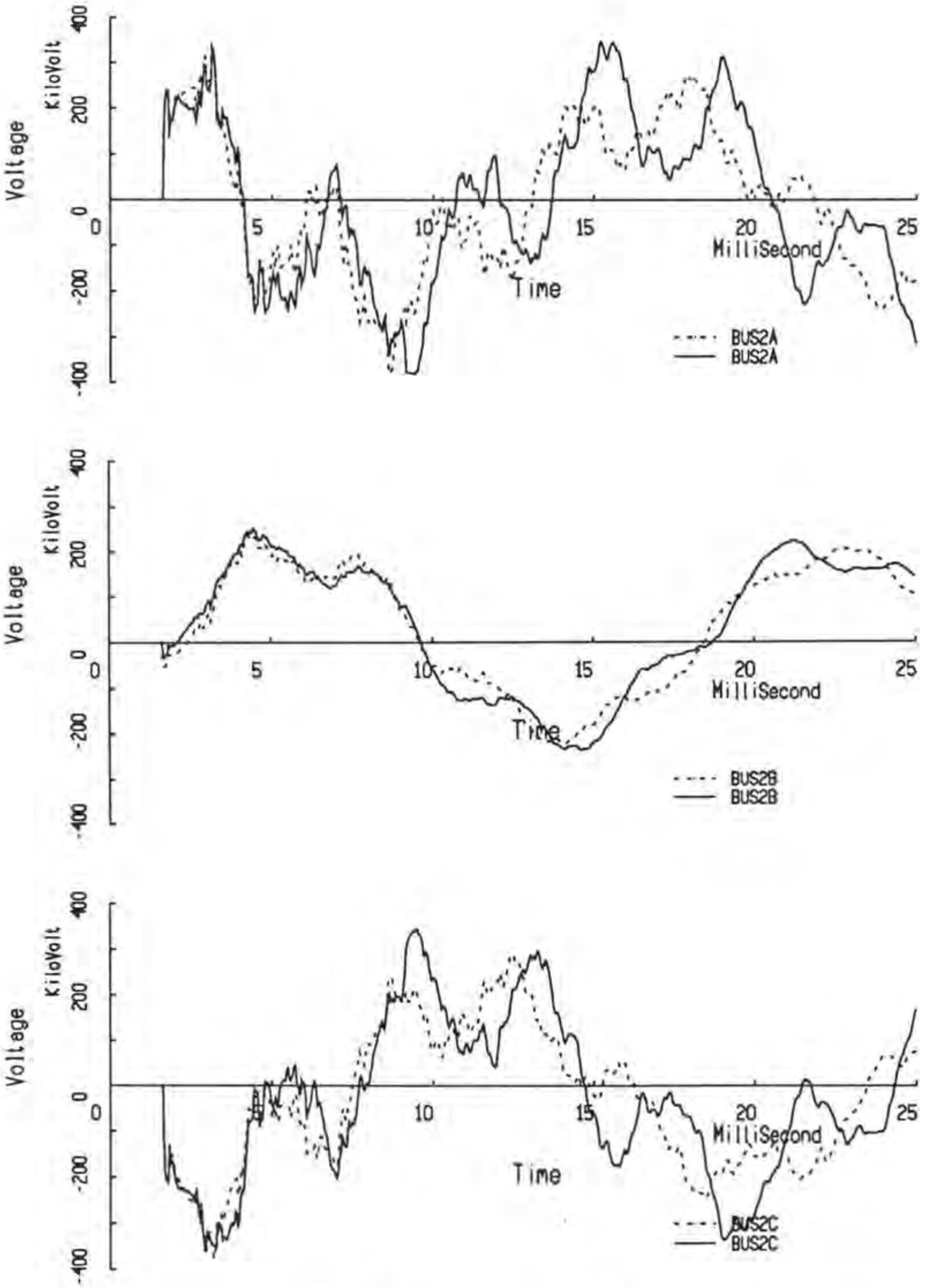


Figure 9.13: Voltages at bus 2 for simultaneous energization of line 1-2. Solid lines represent the results of simulation using FDNA and dotted lines represents output of the reference case using Matri line models.

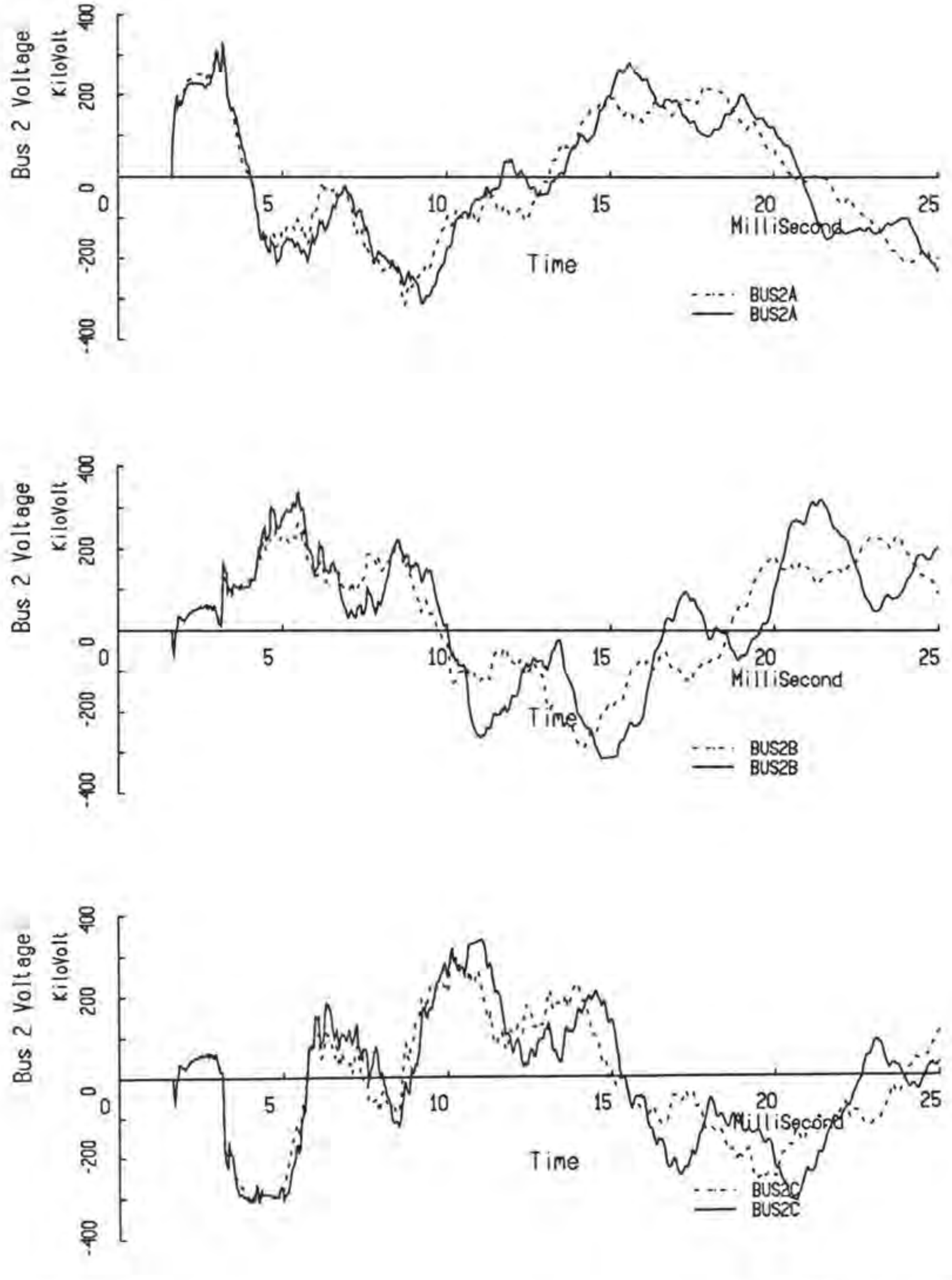


Figure 9.14: Voltages at bus 2 for sequential energization of line 1-2. Solid lines represent the results of simulation using FDNA and dotted lines represents output of the reference case using Matri line models.

9.4. References

[1] A. S. Morched and V. Brandwajn, "Transmission Network Equivalents for Electromagnetic Transient Studies," IEEE Transactions on Power Apparatus and Systems, pp. 2984-2994, September 1983.

[2] F. L. Alvarado, "Formation of Y-Node using the Primitive Y-node Concept," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, pp. 4563-4572, December 1983.

SECTION 10

CORONA MODELING IN THE EMTP

The representation of corona represents an important new area in EMTP applications. At the time of the preparation of this workbook, no definitive studies that are both accurate and efficient in implementation for the representation of corona within the EMTP exist. To supplement this section refer to [1, 2, 3]. These papers describe the details of a reasonably accurate model for corona based on physical considerations and recent work on the implementation of corona models in the EMTP. The main difficulties with these models at this time appears to be computational and lack of sufficient field test comparisons. It will become availble in version 2.0 of the EMTP. In addition to these papers, the remainder of this chapter describes simple mathematics of certain models that may be suitable for some types of corona studies, and provides a qualitative description of the effect of corona in transient studies.

10.1. Corona is a Nonlinear Phenomena

Corona is a nonlinear phenomena which occurs when the strength of the electric field on the surface of a conductor becomes sufficient to ionize the surrounding air. The electric field intensity at the onset of corona in dry air is according to Peek's formula:

$$E_{CR} = 30\, d\, m \left(1 + \frac{0.3}{\sqrt{d\, r}} \right) \text{kV/cm}$$

where:

d = relative air density = $3.92\, b/T$
T = Temperature in Degrees Kelvin
b = atmospheric pressure in cm Hg
m = stranding factor (1: smooth, 0.9: ACSR)
r = conductor radius, cm

The field strength can be calculated based on the voltage of the line.

10.2. A Simple Classic Model of Corona

The main effect that is traditionally considered when discussing corona is its effect on system losses. The following empirical formula gives an approximate expression for the losses due to corona in fair weather [5]:

$$P = \frac{3.37\times10^{-5}\, f\, V^2\, F}{\left(\log_{10} \frac{2s}{d} \right)^2} \text{ kW/phase/mile}$$

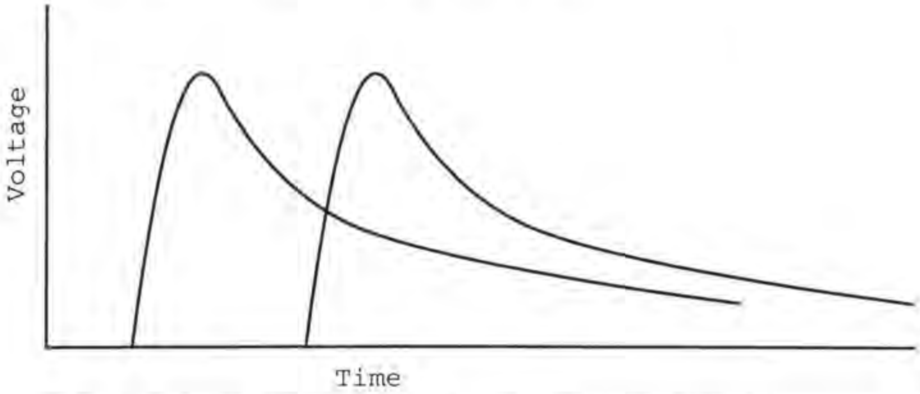
where

V = rms line to neutral voltage
f = frequency in Hz
F = empirical corona factor
s = phase spacing
d = conductor diameter

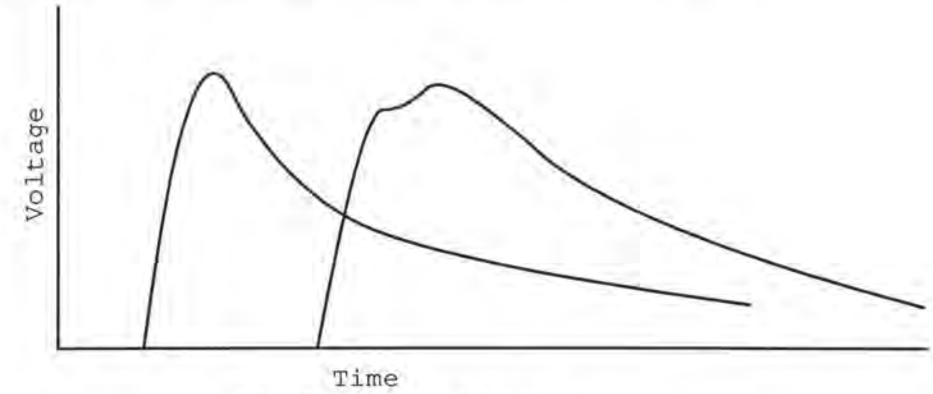
Losses are not the entire story, however. Corona has a significant effect on overvoltage and on the manner in which waves propagate throughout the system due to several effects:

- Corona changes the propagation velocity of the line.
- The losses due to corona attenuate travelling waves.

Of these, the most important effect is the effect of corona on travelling speeds. A number of experimental and theoretical papers have attempted to quantify this effect. We describe only one of many possible models, a model that is based on the idea that the effect of corona is to expand the effective radius of the conductor, thereby changing the parameters of the line. Since the effect is voltage-dependent, the result is often a distortion of waveforms only after certain voltage peaks are reached. Figure 10.1 illustrates a common effect of corona on waveforms.



(a) Original waveform propagation without losses or corona.



(b) The Effect of Corona.

Figure 10.1: The effect of corona on impulse waveform propagation.

10.3. Corona Models and the EMTP

The simplest corona representations allow for the larger effective diameter of conductors undergoing corona. An off-line computation of the line parameters with a larger effective diameter of conductors to be used instead of or in conjunction with an ordinary line is sufficient to capture the slower propagation velocities associated with corona.

All the corona models considered require breaking up the line into several smaller segments, which is not desirable from the viewpoint of efficiency of computation or numerical behavior of the models.

A more detailed but still relatively simple corona model valid for fast transients can be implemented to some degree by allowing the presense of shunt nonlinear capacitances at various points throughout a line. The instant at which the surface field strength of the conductor exceeds a critical field strength E_{CR}, the effective conductive radius of the conductor increases to a diameter necessary to bring the field strength to E_{CR}. The models proposed by Semlyen and Huang [1] are in this category.

A second attempt at efficient representation of corona (to be implemented in version 2.0 of the EMTP) is the model proposed by Hamadanizadeh [2, 3], based on earlier models by Suliciu [4]. These models are dynamic.

Figure 10.2 illustrates (from [3]) the effect that neglecting corona can have on transients above certain voltage levels.

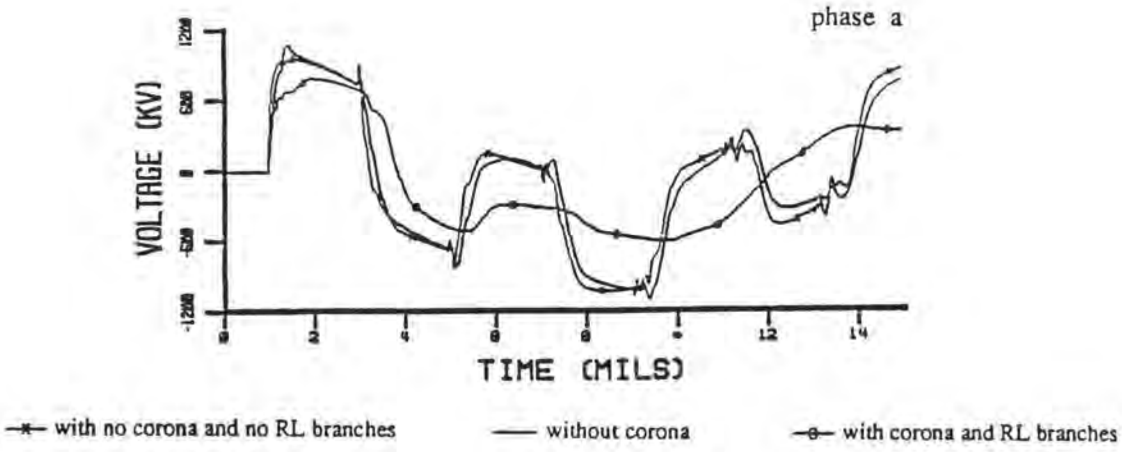


Figure 10.2: Voltage at the receiving end of the transmission line with and without corona models (from [3]).

10.4. References

[1] A. Semlyen and H. Wei-Gang, "Corona Modelling for the Calculation of Transients on Transmission Lines," IEEE Transactions on Power Delivery, Vol. PWRD-1, No. 3, pp. 228-239, July 1986.

[2] H. Hamadanizadeh, "Dynamic Corona Model and Frequency-Dependent Line Model for the EMTP," IREQ Report, October 1986.

[3] H. Hamadanizadeh, "Implementation of a Transmission Line Model Representing Frequency Dependence and Corona Effects in the EMTP," IREQ Report, March 14, 1986.

[4] M. M. Suliciu, I. Suliciu, "A Rate Constitutive Equation for the Description of the Corona Effect," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 8, pp. 3681-3685, August 1981.

[5] F. W. Peek, "Law of Corona and Dielectric Strength of Air," AIEE Transaction, Vol. 30, pp. 1889-1965, June 1911.

SECTION 11

INSULATION COORDINATION STUDIES

Insulation coordination refers to the art of selecting appropriate insulation levels for equipment and the corresponding overvoltage protection system (arresters). The steady-state effect of the arresters should be minimal. The arresters should act fast enough to keep the fastest expected overvoltages reaching the equipment below their permissible values. They should also be able to dissipate the necessary energy during the longest lasting overvoltages to maintain their integrity.

The objective of this chapter is to bring together all studies and ideas relating to the EMTP into a comprehensive overview of how to use the EMTP for insulation coordination studies. No new simulations are performed. Rather, we review how to use previously described material for the purpose of insulation level selection and arrester specification. This chapter starts with a generic description of lightning insulation coordination methodologies, based largely on [29] and [30].

11.1. Voltage Stresses within the System

Power equipment must be able to tolerate two kinds of voltages: the ordinary system operating voltage (simply called the system voltage), and overvoltages. Overvoltages are of interest in system insulation level design and coordination. There are three types of overvoltages, any one of which can determine a choice of insulation level or a choice or location of an arrester, and all of which are amenable to EMTP studies to some degree. These are:

- Temporary overvoltages. These are generally regarded as power frequency overvoltages of relatively long duration. Many of these overvoltages can be sustained indefinitely or for long periods, while others decay after several cycles. A partial list of conditions that lead alone or in combination to temporary overvoltages includes:
    - Faults, particularly single line to ground.
    - Sudden changes in load, such as load rejection.
    - Unloaded long lines (Ferranti effect).
    - Ferroresonance.
    - Linear resonance.
    - Negative sequence resulting from the interaction of line to line faults and generators.
    - Electromagnetic induction.
    - Open conductors.

Some of these effects are purely linear, and amenable in principle to analytic studies, while other effects are nonlinear. The EMTP can perform both types of studies, but very different techniques are needed for each.

- Switching transients. These are conditions that result from the operation of breakers and other switching-type phenomena in the system, either during normal conditions or as the result of faults. Switching transients represent transition phenomena from one steady-state condition to another. The natural frequencies of oscillation within the network and the travelling waves on lines interact with the applied voltages to produce transitory voltage conditions that ultimate decay and lead to a new steady state. The duration and time constants of these transients are generally from tenths of microseconds to a couple of cycles. The main types of switching transient phenomena are:

    - Line energization.
    - Line reclosing, particularly after a charge is trapped on the line.
    - The occurrence of a fault. In addition to temporary over–voltages, the occurrence of faults causes additional switching type transients.
    - Breaker opening. In three phase systems, all three poles must be studied.
    - Capacitor switching, both energization and de-energization. Partial breaker failure during capacitor switching can result on extremely severe transients.
    - Switching of inductors, particularly de-energization. Too rapid arc quenching results in "current chopping" overvoltages.

  Most switching transients can be study analytically. In practice, however, only Transient Network Analizers or a program such as the EMTP are used. The overvoltages induced by these transients depend on a number of factors, such as the exact configuration and state of the system at the time of the initiation of the transient, the exact timing of the transient, the exact sequence of events that follow the transient and the location of the phenomena (such as a fault) that may have caused the transient. The calculation of the overvoltages resulting from a specific switching transient may be of interest (1) to reproduce a specific observed event, (2) to understand a given type of transient phenomena, or (3) to attempt to identify the worst credible overvoltages from a given type of transient. However, it is often of greater interest to characterize these overvoltages statistically.

- Lightning transients. These transients are the result of lightning phenomena interacting with the system. Transient phenomena are extremely fast, in the order of microseconds. Contrary to what one may expect, most overvoltages due to lightning phenomena are not the result of direct strokes onto a line conductor but the result of secondary effects. The following mechanisms for overvoltages as a result of lightning can be recognized:

    - Direct lightning strokes to a conductor
    - Electromagnetic induction of overvoltages from a ground conductor to the phase conductors

- Back-flashover as a result of lightning striking the ground conductor, reaching a tower, and being reflected from the ground due to a relatively high grounding resistance, with an overvoltage between the tower and the phase conductor becoming sufficiently high to produce a flashover.

The most severe but least common of these mechanisms is a direct stroke to a tower, the next in severity (and the most common) is the backflashover. Electromagnetic induction, while always present, is usually not the limiting criteria. Lightning transients can be studied using the EMTP.

The most frequently considered switching surges on transmission lines with rated voltages above 300 to 500 kV are those generated by closing into a line, or reclosing into a line with trapped charge. These switching surges are significant because they determine the required air clearances and insulator string lengths. Line insulation has always been selected based on probable switching surges to be expected, even at the lower voltage levels. It is generally not possible by insulation alone to tolerate a direct lightning stroke of appreciable magnitude. Lines are not normally insulated against lightning strokes, but rather protected with shielding. If shielding fails and flashover occurs, a surge will travel into the substation, where equipment is protected against this surge with surge arresters.

At EHV and UHV voltages the large safety margins of the lower voltage levels become too costly. A better understanding of the statistical distribution of switching overvoltages and the economic incentives for smaller towers have led to reduced surge levels of 2.0 to 2.5 p.u. and even lower at 500 kV levels.

In a study concerned with switching surges, it is worthwhile to pay attention to other types of transients. For example, a single phase to ground fault initiated by lightning will only cause a minor, temporary outage of 1s duration or less if the line is properly designed for three phase or single pole reclosing. The same fault will turn into a permanent outage, however, if reclosing is unsuccessful, for instance because the secondary arc current could not be extinguished. Analyzing the magnitude of the secondary arc current and the recovery voltage at the fault location, and schemes for its reduction may be more important in such cases than the analysis of closing and reclosing surges alone. Experience at the Bonneville Power Administrations (BPA) shows that 90% of all lightning-caused tripouts are successfully reclosed [12].

In what follows, an attempt will be made to summarize the various types of switching transients and to discuss the factors which influence their severity. For additional detail on switching surges see one of many recent reports and papers on the subject. A list of references is included at the end of this chapter. The next few sections provide an overview of the main classes of transients of probable interest in an insulation design study. This chapter concludes with an overview of how to select appropriate studies to perform in connection with insulation coordination.

11.2. Closing and Reclosing Surges

Energization and reclosing transients are among the most important in the determination of insulation levels.

Since power circuit breakers can never close the line from both ends exactly simultaneously, there is always a short period during which the line is closed or reclosed from one end, with the other end still open. Travelling waves are then reflected at the open end with the well-known doubling effect, and transient overvoltages of 2.0 p.u. at the receiving end are therefore to be expected.

Reality is more complicated than this simple explanation. The line is three phase rather than single phase; the network on the source side of the circuit breaker may be fairly complicated and therefore create rather complicated reflections of travelling waves; the line capacitance may be charged up in case of a reclosing operation ("trapped charge"); the magnitude of the overvoltage depends on the instant of closing; etc.

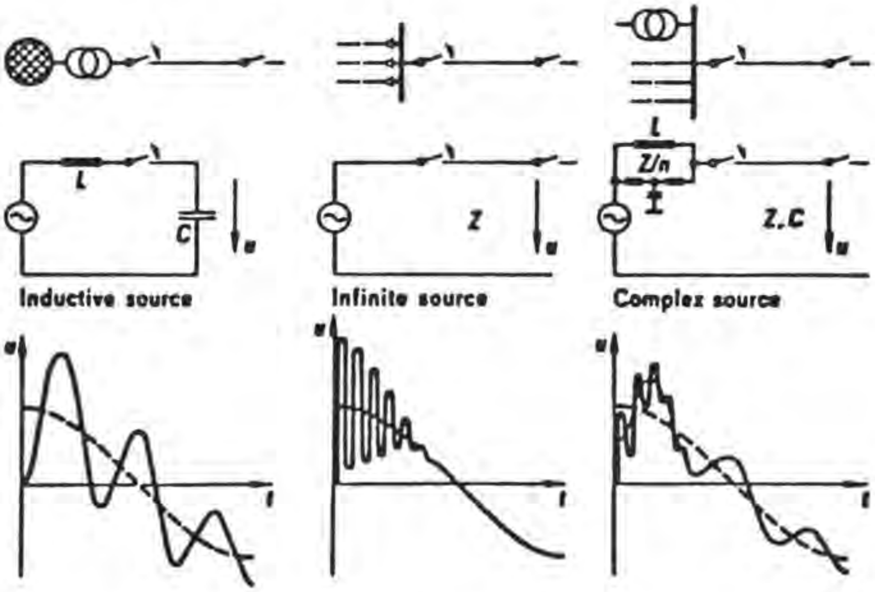


Figure 11.1: Types of closing surges. From [2] by permission.

M. Erche has attempted to classify closing surges as shown in Figure 11.1 [2, p. 67]. The left-hand case in this figure shows energization of an unloaded line through a transformer, where the feeding network can basically be represented by the leakage inductance of the transformer and the short circuit inductance of the network behind the transformer. Since these inductances filter out high-frequency transients, the line can be represented by its shunt capacitance as a first low frequency approximation. The transient surge consists of a single frequency in this case, with a peak overvoltage of 2.0 p.u.. Transients caused by closing into lines from an inductive source have been thoroughly studied by CIGRE Working Group 13.05 [3].

Again, reality is more complicated, as shown in Figure 11.2 (from [3]), which indicates that overvoltages of approximately 2.8 p.u. or higher can be expected in 1% of the closing operations on a 202.8 km line fed from a source of 630 MVA short circuit power if no closing resistors are used. Figure 11.2 illustrates that it makes little sense to calculate the maximum possible overvoltage, because the line insulation could not be economically designed for that one high value. Instead, the probability of occurrence and their distribution is calculated, in order to find a compromise between costs and possible damages. The curves in Figure 11.2 were obtained from the simulation of 100 closing operation, with a statistical distribution of closing times in the three phases.

The middle case in Figure 11.1 shows a line energization from a "strong" bus with many feeders, which can be represented as an infinite bus or as a bus with very low internal impedance as a first approximation. Here, the switching surges are travelling waves occurring at a frequency of $f = 1/4\tau$, where τ is the travel time of waves on the line (example: $\tau = 1\text{ms}$ for a line of 300 km length, or $f = 250$ Hz).

The right-hand case in Figure 11.1 shows a complex source, where lines of the same voltage level as the switched line, as well as lines of other voltage levels, terminate in the substation. This is probably the most typical case in practice. Requirements for simulating this case with sufficient accuracy have been summarized by CIGRE Working Group 13.05 [4]. Figure 11.3 (from this reference) compares results of field tests with the TNA results for switching surges in the Sao Paulo 440 kV power system CESP in Brazil. While not stated in [4], one has to assume that the circuit breakers were equipped with closing resistors, since only 2% of the operations produce overvoltages of 1.8 p.u. or above.

The most important factors which influence the magnitude of closing and reclosing surges are the presence of trapped charges in case of reclosing operations, and the use or lack of closing resistors in the circuit breakers. This is shown in Figure 11.4 from [2, p. 69] for one particular transmission line. An alternative to the use of closing resistors is the use of "controlled closing," which BPA has successfully tested on a 500 kV line [5].

CIGRE Working Group 13.02 evaluated numerous measurements and calculations of closing and reclosing surges [6]. The results redrawn in [2, p. 87] are summarized in Figure 11.5. It shows the overvoltages which one would expect in 2% of the switching operations, with average values as well as maximum and minimum values from all available data entered into the bar charts. From these results it can be seen that closing and reclosing surges can be limited to below 2.0 p.u. by equipping circuit breakers with closing resistors. In Figure 11.5, one-step closing resistors were assumed.

For ultra-high voltage systems in the 1100 to 1200 kV range, suitable measures are being studied to limit switching surges to 1.3, 1.5 or 1.8 p.u. [7], with the most effective measure being two-step closing resistors in the circuit breaker. Such circuit breakers are already in operation on 500 kV systems, and BPA is using them to reduce switching surges to 1.7 p.u. (2% value), with allowance for up to 1 flashover per 10 switching operations, on their new 500 kV lines [12]. Two-step closing resistors are obviously more complicated than one-step closing resistors, and may themselves create an increased risk of failure. If closing and reclosing surges are limited to below 1.8 p.u. or 1.5 p.u., then more attention must be paid to overvoltages on the unfaulted phases in case of single-phase-to-ground faults, which can be around 1.7 p.u. in effectively grounded systems, and to overvoltages caused by clearing of faults, which can be around 2.0 p.u. and as high as 2.4 p.u. [7].

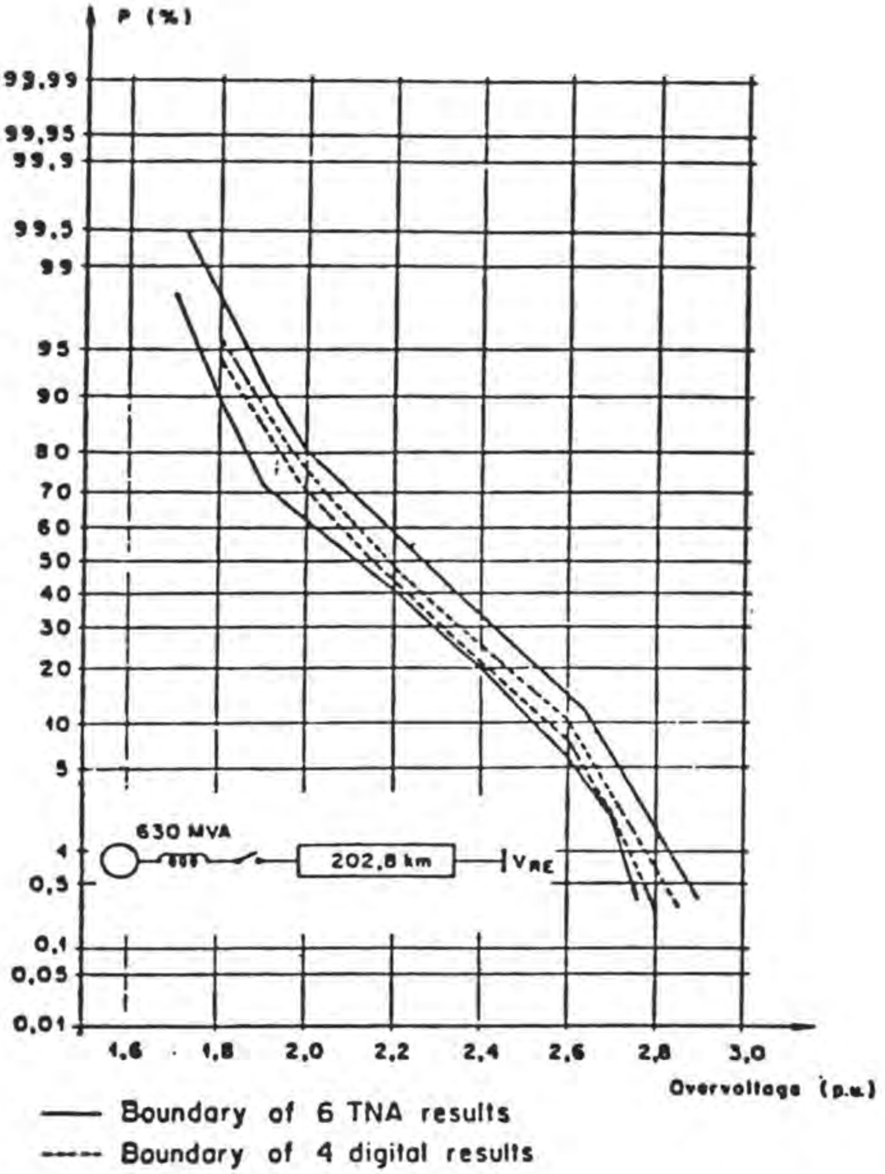


Figure 11.2: Comparison of cumulative distribution of receiving end overvoltages obtained by digital computer and TNA; no closing resistors in circuit breakers. From [3] by permission.

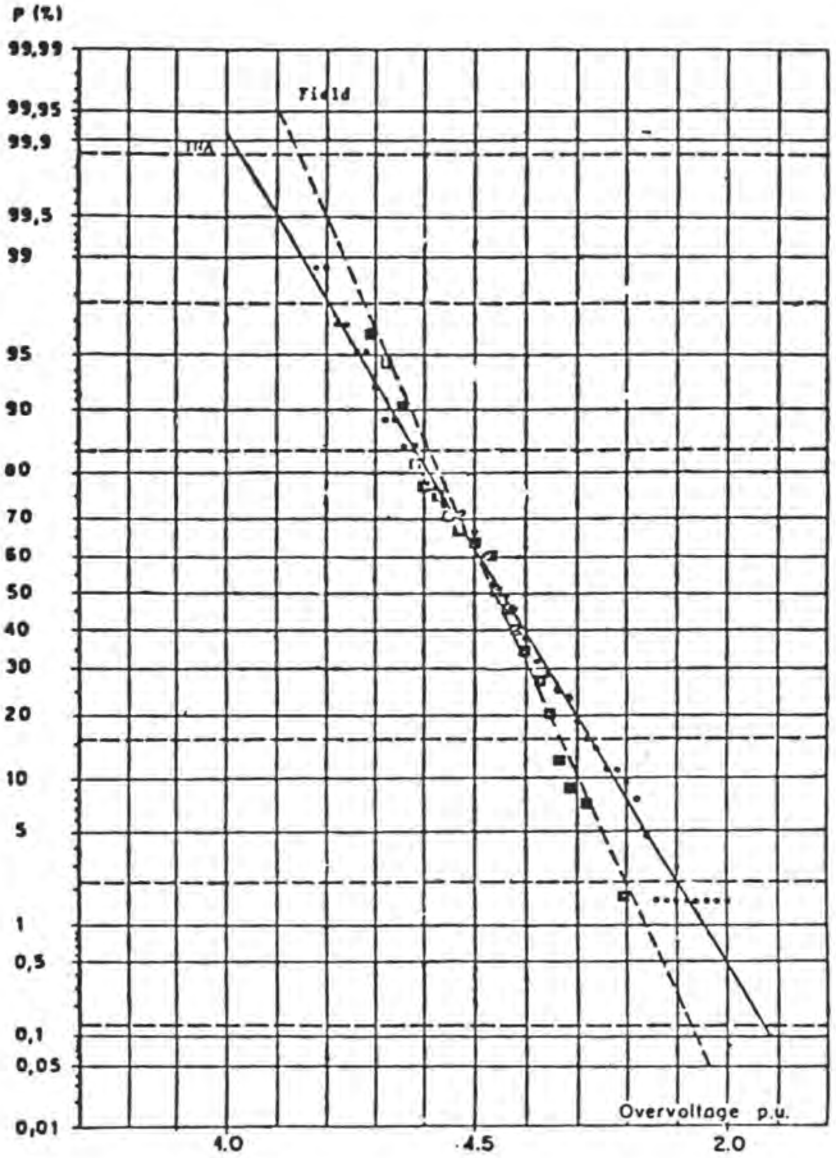


Figure 11.3: Comparison of switching surges between field tests and TNA studies in CESP System in Brazil [4].

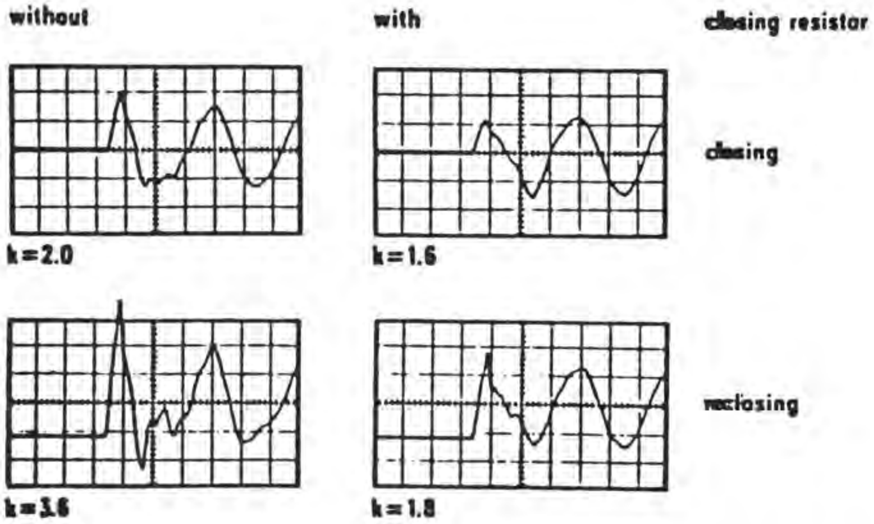


Figure 11.4: Overvoltages in p.u. on a 420 kV line of length 400 km. From [2] by permission.

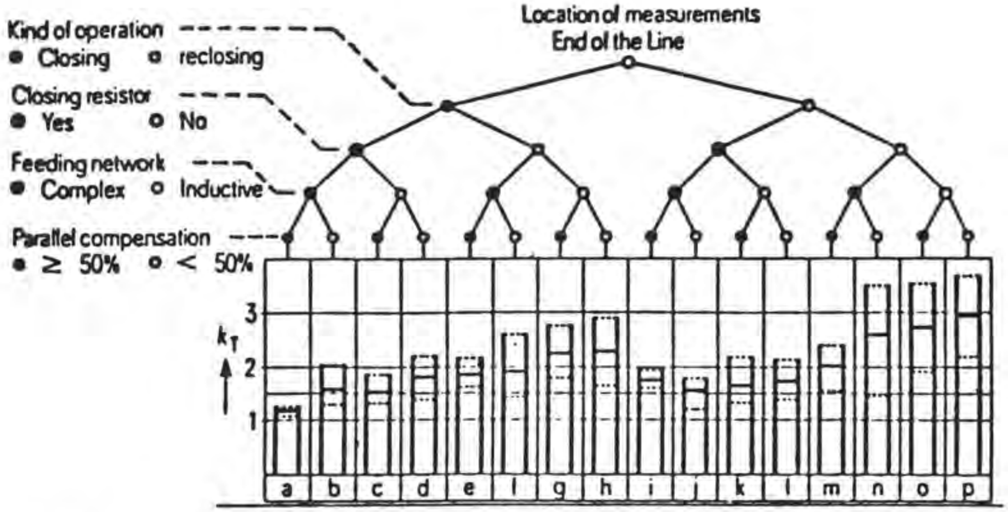


Figure 11.5: 2% overvoltage factors in extra-high voltage systems. From [2] by permission.

11.3. Capacitor Switching Transients

Capacitor switching can result in severe transients upon either energization (currents) or de-energization (voltages and the possibility of re-strike). Capacitor switching transients also apply with slight modification to short lines and cables.

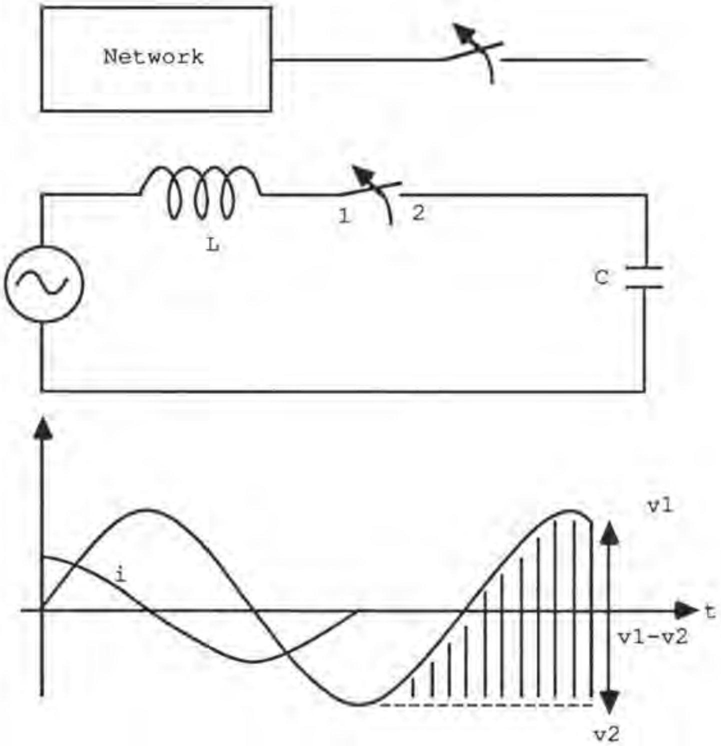


Figure 11.6: Transient recovery voltage after interruption of capacitive current.

Appendix D contains a detailed description of specific capacitor switching transients. Of importance in capacitor switching transients is the selection and determination of adequate transient recovery voltage (TRV) characteristics, as a re-strike during a capacitor switching operation can result in extremely high overvoltages. The recovery voltage in a single phase capacitor results in a 2.0 p.u. voltage across the contacts, and up to 2.5 p.u. in three phase systems.

In Figure 11.6 it can be seen that this overvoltage is caused by the capacitance remaining charged at -1.0 p.u. voltage, the voltage at current interruption, while the source side voltage changes to +1.0 p.u. half a cycle later. In older types of circuit breakers (particularly in oil type breakers) this relatively high voltage accross the contacts can lead to re-striking, which in turn produces high overvoltages in the system.

Modern circuit breakers are usually claimed to be free of restrikes. Therefore, switching off unloaded lines or capacitor banks should no longer be the problem which it once was.

Of some additional concern is energization of capacitor banks and the large inrush currents that may result, especially if another bank in parallel is already in operation. Energizing shunt capacitor banks produces inrush transients which have been the topic of numerous technical publications and are also covered in ANSI Standards. They are highest if switching occurs at an instant when the voltage difference between the source and the capacitor is a maximum, and they can also affect the duty of other circuit breakers in the substation [10]. Figure 11.7 shows the equivalent circuit used for such an inrush current study, and Figure 11.8 the results, similar to those of [9] (note that Figures 2 and 3 in [9] are in error). Since the voltage across the capacitor cannot change instantaneously, the bus voltage collapses very rapidly to zero if the capacitor had zero voltage before closing. The severity of the transients is related to the magnitude and slope of the steep voltage dip, to the peak magnitude of the overvoltage, and to the peak magnitude of the inrush current. The voltage transients are more severe during single bank switching, while the inrush currents are highest during back-to-back switching (energization of a capacitor bank, with another adjacent bank already energized). These transients can be significantly reduced by controlling the closing to occur around the instant where the voltage is zero across the switch. BPA has succesfully tested this scheme on a 230 kV shunt capacitor bank with minor modifications to a 230 kV vacuum interrupter consisting of 9 series contacts per pole [9]. Not only were the inrush currents significantly reduced, but transient potential rises on the substation fence were reduced as well, as indicated in Table 11.1.

Table 11.1: Transient Potential Rise (from [9]).

Circuit Configuration	Energized near	Fence to Neutral Potential	Fence to Earth Potential
Single Bank	crest voltage	6.2 kV	364 0 V
Single Bank	zero voltage	1.2 kV	0 0 V
Back to back	crest voltage	13.5 kV	912 0 V
Back to back	zero voltage	0.8 kV	6 0 V

The analysis of switching surges in series capacitor stations is usually concerned with the proper functioning of protective gaps and with the development of new protection schemes [11]. One of the contributors was involved in the analysis of very high frequency transients (in the MHz range) in a 500 kV series capacitor station, which occurred during energization of the capacitor platform from one end, and endangered the current transformer which was used as power supply to control equipment on the platform (Figure 11.9). Similar overvoltages can occur in current transformers during shunt capacitor energization [10].

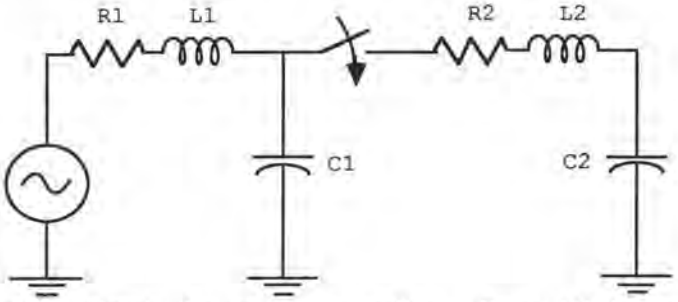
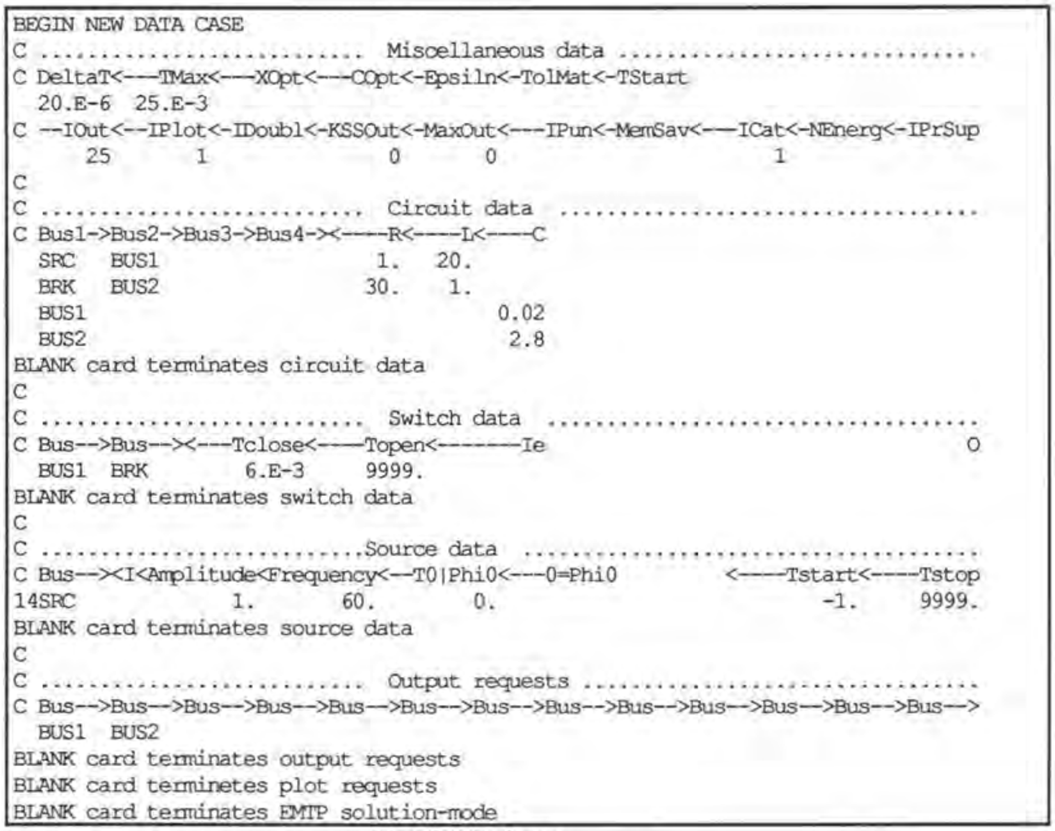


Figure 11.7: Equivalent circuit for computer studies. From [9] by permission. Notice,, however, that the corresponding Figure in [9] is in error, the one above is the correct one [31].



```
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  20.E-6  25.E-3
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      25       1               0       0                       1
C
C ............................ Circuit data ....................................
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  SRC   BUS1                1.   20.
  BRK   BUS2               30.    1.
  BUS1                              0.02
  BUS2                               2.8
BLANK card terminates circuit data
C
C ............................ Switch data .....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                     O
  BUS1  BRK         6.E-3     9999.
BLANK card terminates switch data
C
C ...........................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop
14SRC             1.       60.        0.                            -1.      9999.
BLANK card terminates source data
C
C ............................ Output requests .................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BUS1  BUS2
BLANK card terminates output requests
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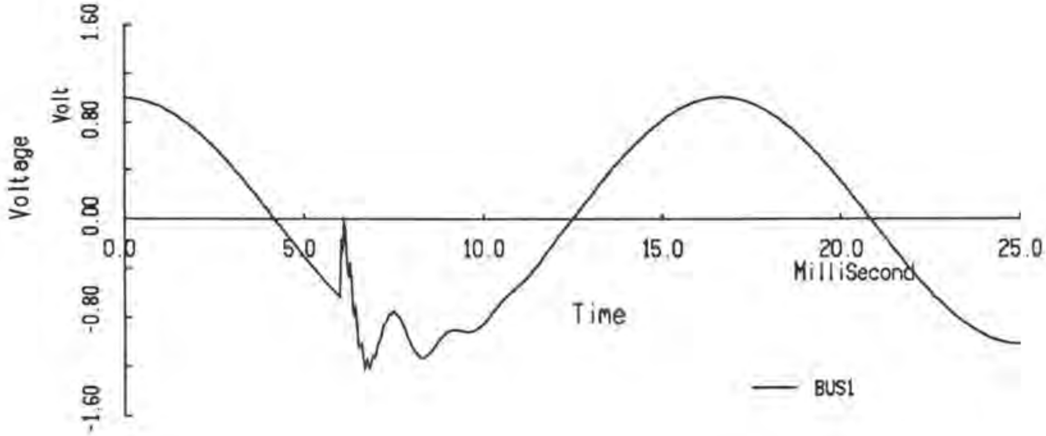
(a) EMTP input.



(b) Voltage at bus 1.

Figure 11.8: Computer simulation of bus voltage for capacitor energization near crest voltage. From [9].

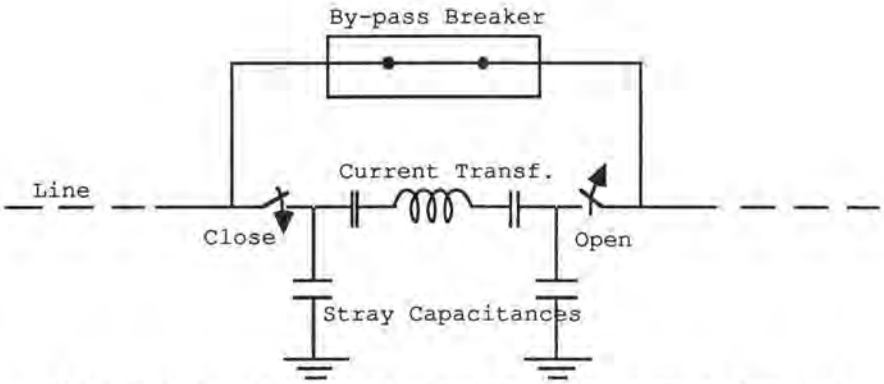


Figure 11.9: Transients in series-capacitor station during closing from left.

11.4. Interruption of Small Inductive Currents

Circuit breakers are designed to interrupt high short-circuit currents with powerful arc quenching processes. If asked to interrupt very small inductive currents, e.g., when switching off an unloaded transformer, this arc quenching process may be strong enough to "chop" the small current before its natural zero (Figure 11.10). The magnetic energy $L_m i^2/2$ left in the magnetizing inductance is transferred into electric energy $C_{stray}v^2/2$ in the stray capacitance, with an oscillation frequency of $1/(2\pi\sqrt{L_m C_{stray}})$ and with accompanying overvoltages. Reality is more complicated because of possible saturation effects in L_m. Figure 11.11 shows the overvoltage for modern HV transformers as a function of system voltage.

The situation is worse for switching off shunt reactors, or transformers loaded with shunt reactors, as seen in the field test results of Figure 11.12 [2, p. 72]. There is a high probability that the switching surge levels exceed the insulation strength, and surge arrester protection is therefore needed. These problems are avoided if the shunt reactors are directly connected to the transmission line, and switched with the line, but resonance overvoltages may then occur if the reactor goes into saturation.

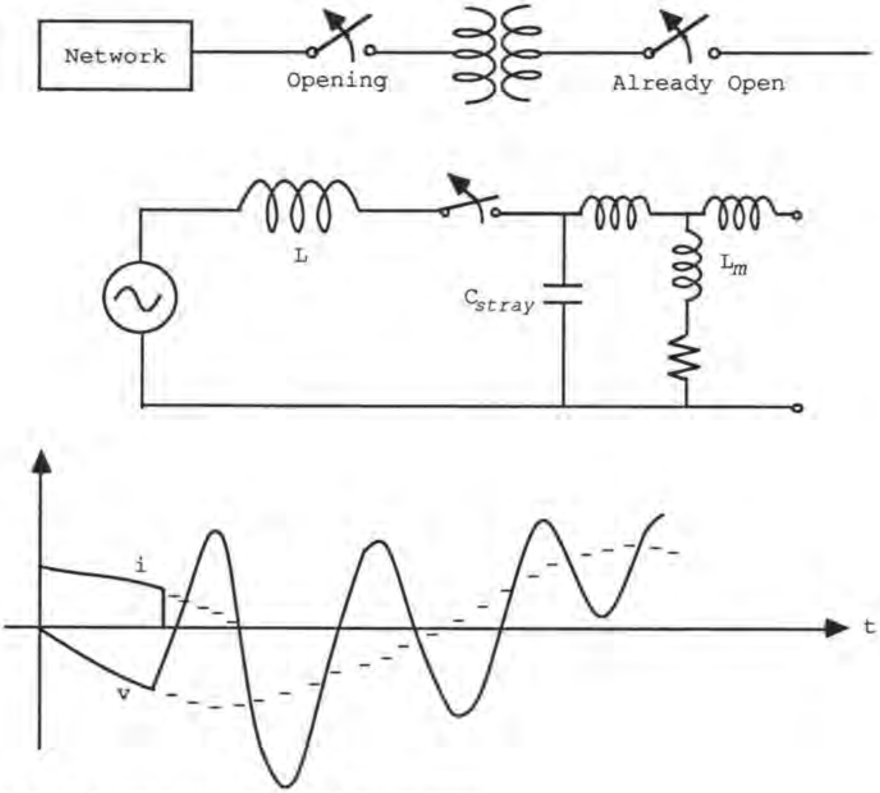


Figure 11.10: Interruption of exciting current.

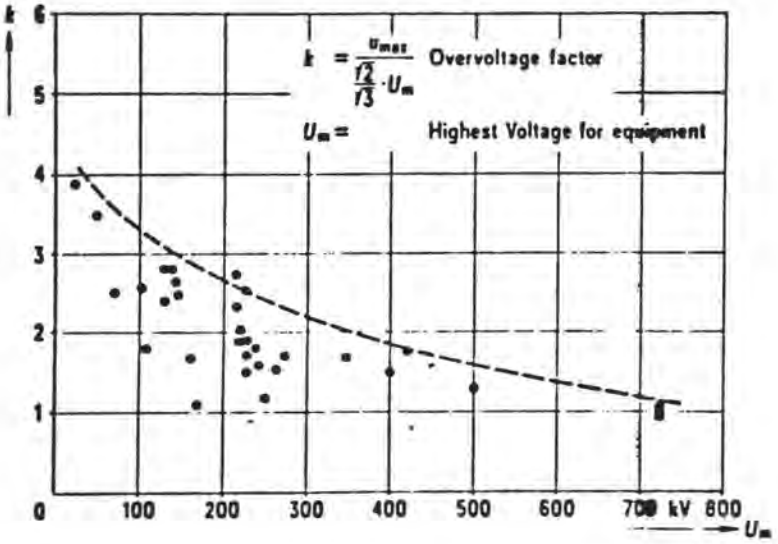


Figure 11.11: Maximum overvoltages when interrupting exciting currents of HV transformers [6].

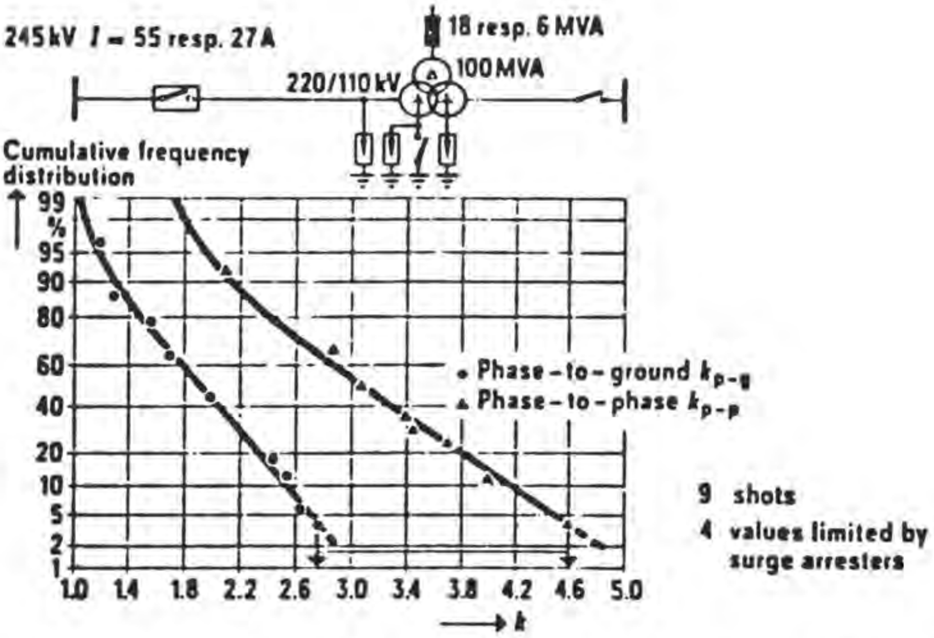


Figure 11.12: Cumulative frequency distribution of overvoltages when switching off a reactor-loaded transformer.

11.5. Transformer Inrush Currents

Since modern circuit breakers close with very high speed, closing at voltage zero is as probable as closing at maximum voltage (with low speed contacts, prestrikes are likely to happen around maximum voltage, thereby increasing the probability of closing at maximum voltage). When an unloaded transformer is energized, the inrush current is determined by the flux-current curve $\psi = f(i)$. If resistance and the source inductance are ignored, then closing at voltage zero will produce 100% offset in the flux, since $\psi = \int v\,dt$ (Figure 11.13), which in turn will lead to very high inrush currents. Figure 11.14 [2, p. 75] shows a typical oscillogram. These currents are lightly damped and last for seconds. They usually contain strong second, third and fourth harmonics, which flow into the connected network, where they often create resonant overvoltages, since power systems typically resonate at frequencies between 100 and 200 Hz. In studying these cases, the frequency response of the system may be of more interest than the time-domain response. The EMTP provides an option for obtaining frequency responses as well as time-domain solutions. Figure 11.15 shows an example of a resonant case. Since the voltages persist for a long time, they are classified as "temporary overvoltages" rather than as "transient overvoltages."

Resonance phenomena can also occur during closing into lines which are terminated with unloaded transformers or shunt reactors. One example from field tests in a 765 kV system is shown in Figure 11.16 [2, p. 77].

In this connection it may be worth mentioning that nonlinear reactors (Figure 11.17(a)) do not necessarily keep the peak voltages down. If the ψ-i curve is idealized to a horizontal slope in the saturated region (Figure 11.17(b)), then it becomes clear that the flux cannot become larger than ψ_{knee}. As soon as this knee point is reached, the voltage must collapse to zero to keep $\int v\,dt$ (the increase in flux) to zero

(Figure 11.17(c)). The RMS value is therefore kept down by cutting out pieces of the sine wave at the zero crossing, and not by reducing the peak magnitudes.

A special type of high frequency overvoltages can occur during energization of three phase transformer banks if the differences among the closing times of the three poles exceed 5 ms. Such overvoltages have caused damages to transformers [2, p. 75].

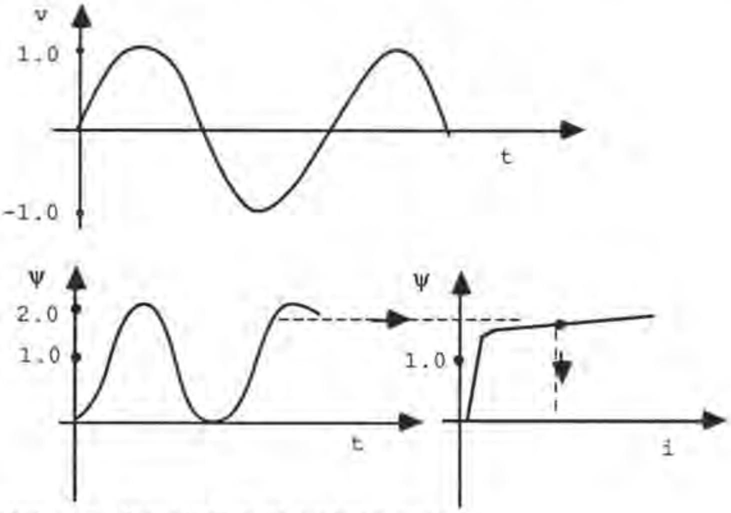


Figure 11.13: Offset flux for closing at voltage zero.

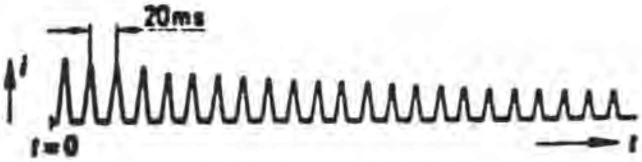


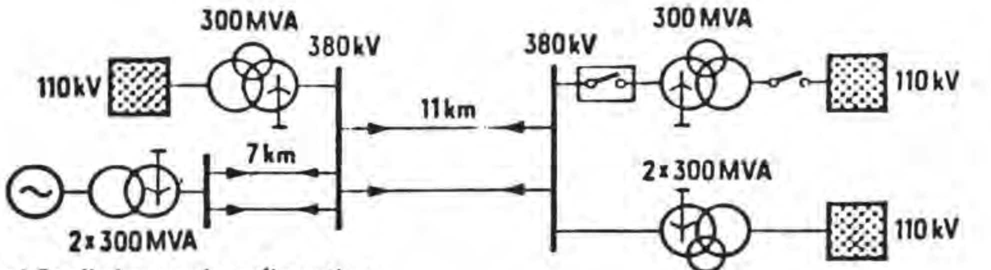
Figure 11.14: Typical inrush current [2].

11.6. Fault Initiation and Clearing Transients

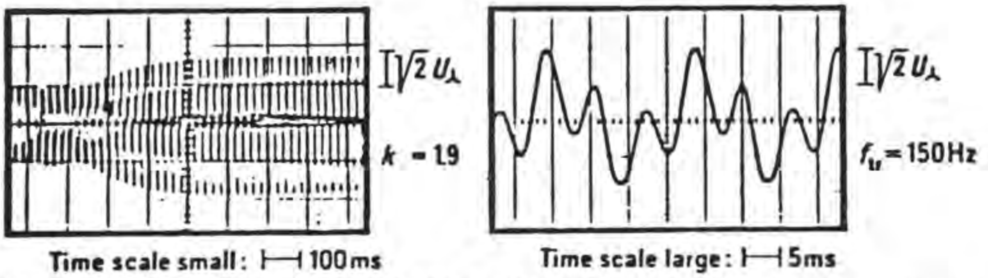
Very little can be done to reduce the overvoltages which result from the occurrence of faults. They can be as high as 2.7 p.u. in the unfaulted phases in case of a single-phase-to-ground fault in resonance-grounded or floating neutral systems [2, p. 79]. Most high voltage networks are effectively grounded, and fault initiated overvoltages should typically be no higher than 1.7 p.u., depending on the magnitude and angle of the Z_0/Z_1 ratio [2, p. 81]. Values of 1.7 p.u. are of no concern if the lines are insulated for 2.0 p.u. switching surges, but they may warrant more careful investigation in line designs with insulation levels reduced to 1.7 p.u. [12].

Fault clearing produces transient recovery voltages across the circuit breaker contacts, as well as phase-to-ground overvoltages. Both can be reduced with opening resistors in the circuit breaker. In a joint U.S.A./U.S.S.R. study of 1200 kV lines [7], which may or may not be representative of lower voltage levels, maximum overvoltages of 1.85 p.u.

were reported for clearing symmetrical faults (that is, no dc offset component) without opening resistors. When clearing asymmetrical faults, the overvoltages could reach 2.0 p.u. with opening resistors and 2.4 p.u. without for high load angles of 90°. For more realistic load angles of 30°, clearing with opening resistors produced overvoltages of 1.6 p.u. or below in case of single-phase-to-ground faults, and of 1.8 p.u. or below for three phase faults with asymmetrical fault current in one phase. Fault clearing can also create harmonic resonant overvoltages, as mentioned next.



a) Studied network configuration



b) Phase-to-ground voltage due to closing of a transformer

TNA results

Figure 11.15: Temporary overvoltages in a 50 Hz 380 kV cable network with resonance at 150 Hz.

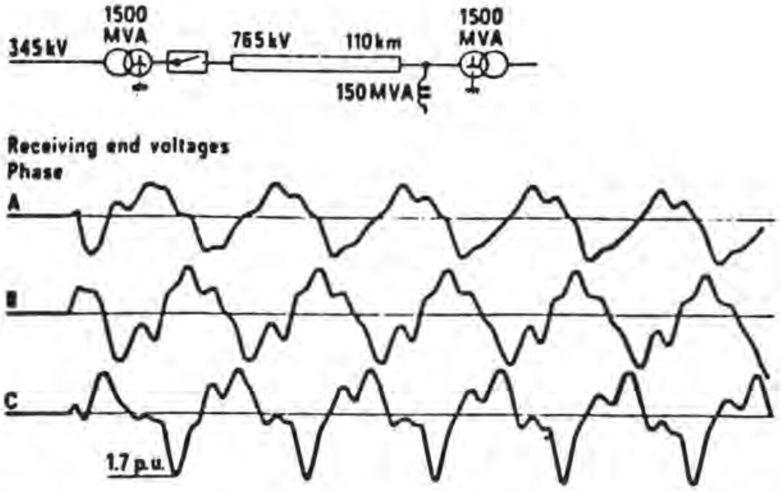


Figure 11.16: Temporary overvoltages during energization of a transformer-terminated line [2, p. 77].

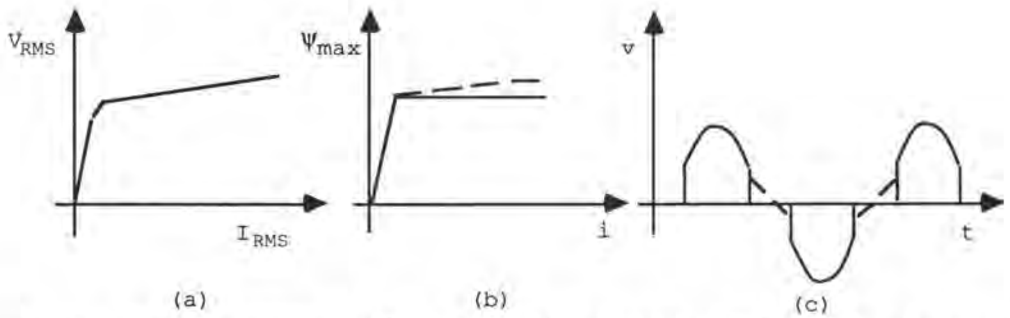


Figure 11.17: Saturable reactor (solid line in (b) and (c) is idealized, dotted line is more realistic).

11.7. Linear Resonance and Ferroresonance

Sometimes switching or lines of the occurrence of faults can create unexpected resonance conditions at fundamental frequency or at one of the harmonic frequencies. These resonance phenomena are steady state in nature, and are usually investigated by using steady-state solution techniques. The EMTP is well suited to these studies, because it has an option for steady-state solutions, either at one frequency or over a frequency range.

Typical is resonance between shunt reactors or unloaded transformers connected to a switched-off line, and the coupling capacitances to an energized line on the same right-of-way. Figure 11.18 shows such an example. The capacitive coupling depends very much on the particular transposition scheme (not shown in Figure 11.18). A detailed line representation for capacitive coupling is therefore needed in such studies (the series impedance representation is usually unimportant). The case of Figure 11.18 was analyzed by representing the two circuits as a cascade connection of six-phase Π circuits, with one six-phase Π circuit used for each section between transposition towers. Figure 11.19 shows the results of a study in which the rated inductance of 6.09 H (or 120 MVar at 525 kV) was varied. Phases A and B are clearly close to resonance, and a small deviation of only -2% from rated inductance values would produce currents in excess of the rated current of 132 A. This happens in spite of the line being switched off. Similar examples are analyzed in [13] with steady-state solution methods and with transient studies on a transient network analyzer.

Resonance can also occur at one of the harmonics, rather than at fundamental frequency. The harmonics are usually generated by transformer saturation. The resonance is still basically linear in nature, with the nonlinear magnetizing inductance acting as the harmonic generator. Such harmonic resonant overvoltages are discussed in [14] for the case of line dropping and fault clearing of transformer-terminated lines. The authors of [14] use steady-state solution techniques with frequency variation to show the resonance conditions in the frequency response, and also compare field test measurements with transient network analyzer results.

Of a different nature are oscillations between a nonlinear inductance and a capacitance. These phenomena are called ferroresonance. A good review of ferroresonance problems is given in [15], and comparisons of simulation results with field tests are shown in [16]. A case of ferroresonance in a situation very similar to that of Figure 11.18 occurred in the BPA system some years ago, except that an unloaded transformer switched on the 230 kV side (Figure 11.20) went into ferroresonance, rather than a linear reactor going into linear resonance. This particular case is discussed in more detail in [17].

11.8. Subsynchronous Resonance

Switching operations on series compensated lines produce electrical transients with resonance frequencies below 60 Hz ("subsynchronous resonance"). These can coincide with the resonance frequencies of the mechanical turbine-generator shaft system of large thermal units, and lead to torsional vibrations and possibly shaft failures. After two such incidents at the Mohave power plant in the U.S.A. in the early 1970's, much attention has been paid to this problem of subsynchronous resonance. While basically associated with series-compensated lines, the phenomenon can also happen in power plants connected to HVDC lines [18]. The study tools developed for subsynchronous resonance are now also being used to re-evaluate the high shaft torques which can occur in any turbine-generator during out-of-phase synchronization. Figure 11.21 shows a comparison between computer simulations with the EMTP and field tests for such a study. It is important to realize that stability programs cannot be used for these studies, since frequencies other than 60 Hz as well as phase unbalances must be represented properly.

A great deal has been written on the subject. For more details, the reader is referred to two IEEE Symposia [20, 21] and to the two IEEE Benchmark Model for subsynchronous resonance studies [22, 8]. Countermeasures to subsynchronous resonance problems have been summarized by an IEEE Working Group in [23].

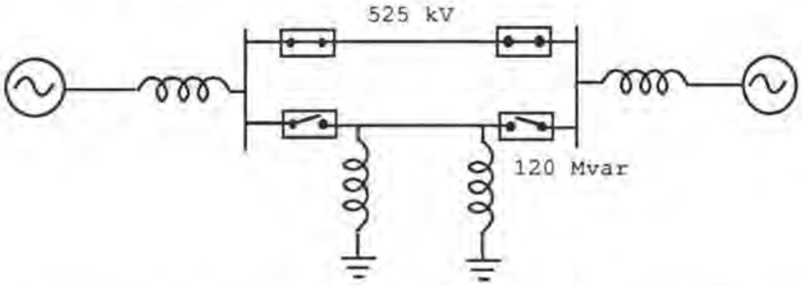


Figure 11.18: Resonance on switched-off line with parallel, energized line.

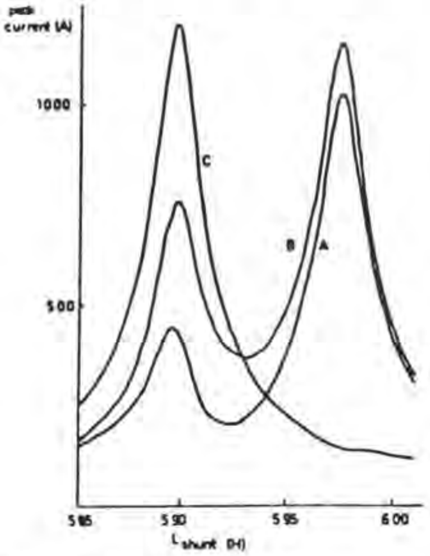


Figure 11.19: Resonance with shunt reactors.

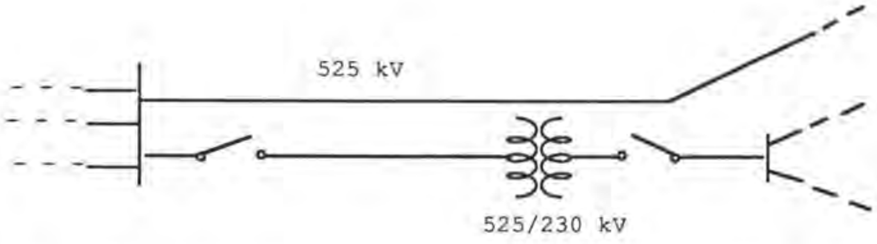


Figure 11.20: Ferroresonance between transformer magnetizing inductance and coupling capacitance.

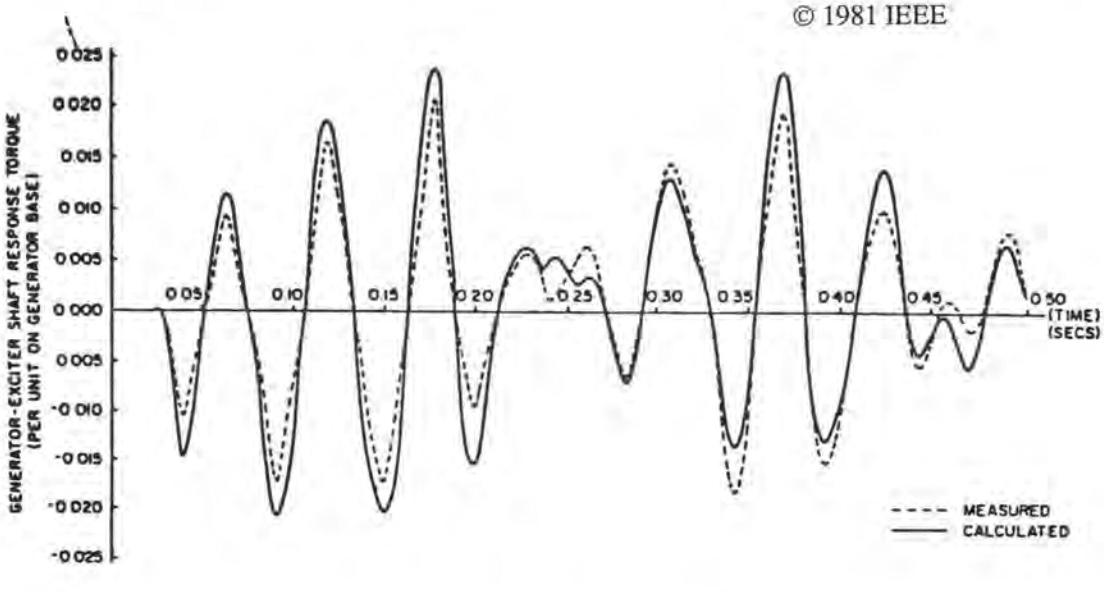


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Figure 11.21: Shaft torque comparison of calculated results to actual test measurements for out-of-phase synchronization.

11.9. Single Pole Reclosing

More than 70% of the faults on transmission lines are single-phase-to ground faults [2, p. 89]. In BPA's 500 kV system, the figure is 93% [24]. Stability of the power system is much easier to maintain if only the faulted phase is opened and reclosed ("single pole reclosing") in these cases, since the power system remains connected through the two unfaulted phases. Single pole reclosing has been used more extensively in Europe than in North America, probably because lines are typically shorter in Europe.

On long lines (longer than 80 km at 500 kV [24]), the secondary arc current (the current that continues to flow through the arc after the primary fault current has been interrupted) cannot be extinguished by single pole opening alone anymore, because the capacitive coupling to the unfaulted phases becomes strong enough to sustain the arc. A practical method of successful extinction of the secondary arc on long lines is compensation of the capacitive coupling with neutral reactors X_N (Figure 11.22), assuming that the long line is equipped with shunt reactors X_1 anyhow, which is normally the case. An easy way for understanding the compensation effect is to convert the star circuit with X_1, X_1, X_1, X_N (left side of Figure 11.22) into an equivalent circuit (right side of Figure 11.22), in which the neutral node N has been eliminated (e.g., by using a system of nodal equations for A, B, C, N and eliminating V_N). The mutual reactances X_m in this equivalent circuit will then be a function of X_1 and X_N. The value of X_1 is chosen in the normal way for shunt compensation purposes. By choosing X_N such that X_m becomes equal to $1/\omega C_{coupling}$ of the line, the total admittance $j\omega C_{coupling} - j\frac{1}{X_m}$ between phases will become zero, thereby compensating the capacitive coupling effect. This scheme has been implemented on many 500 kV lines and AEP has modified and successfully tested it on their untransposed 765 kV lines [25].

Single pole reclosing and neutral reactor compensation is usually studied with steady-state equations assuming zero arc resistance. The two significant quantities are the magnitude of the secondary arc current, which must be below 20 to 40 A for successful arc extinction, and the recovery voltage at the fault location after arc extinction, which must be below the flashover voltage to prevent re-ignition.

An alternative to neutral reactor compensation for lines without shunt reactors is temporary grounding of the faulted phase. It has been tested successfully [24], but is not yet used in practice.

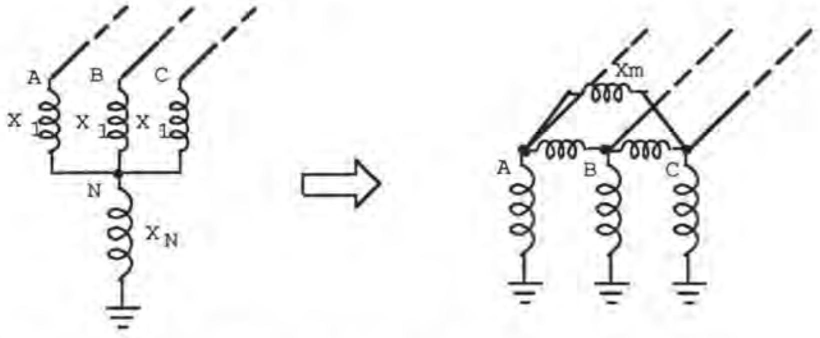

Figure 11.22: Neutral reactor (four reactor scheme).

11.10. Various Other Transients

Transients occur in so many situations that it becomes difficult to describe them all. Some transients not included in this overview include:

- Load rejection transients. Normally these overvoltages are below 1.5 p.u., unless accompanied by resonance phenomena on transformer terminated lines. A case study is described in Appendix B.
- Transients in HVDC systems. This is a specialized topic, and the reader is referred to the specialized literature, such as [26], or Workbook IV.
- TRV across circuit breakers. These transients are quite important in selecting and rating the switching duties of a circuit breaker.

- Transients in SF_6 insulated substations. Protection of these substations against lightning and switching phenomena differs from the protection of conventional substations, inasmuch as the entire equipment assembly (bus enclosures, circuit breakers, disconnect and grounding switches, etc.) must be protected because the entire system is vulnerable to non-self-restoring and fatal overvoltage damage. Again, the reader is referred to the specialized literature, e.g., [27].

11.11. Insulation Coordination in Perspective

Insulation coordination means the selection and specification of insulation levels for the various pieces of equipment in the system such as transmission lines, transformers and generators. For transmission lines, this means the design of the conductor to conductor and tower clearances, the selection and specification of insulator strings, the placement of ground (and in some cases shield and counterpoise) conductors and the specification of towers and tower footing resistances. For equipment such as transformers this means the specification of both BIL (basic lightning impulse insulation level) and BSL (basic switching impulse insulation level). Both conventional and statistical ways of specifying these insulation levels are recognized in the standards. For equipment such as breakers, additional specification parameters include the TRV (transient recovery voltage) characteristics.

Selection of insulation levels for equipment and selection and location of overvoltage protection equipment are interrelated: the insulation level of a piece of equipment or line depends on the type of overvoltage protective equipment installed. Recent practice has been to attempt to reduce insulation levels by more liberal use of arresters, particularly zinc oxide arresters, and also the limiting of overvoltages by means of closing resistors.

A fundamental distinction must be made in the design process between self-restoring and non-self-restoring insulation. With solid insulation, such as in many cables systems and transformers, once it fails it must be replaced: this is non-self-restoring insulation. Open air insulator strings, on the other hand, will usually fail by arcing around the string. Once the initial arc is extinguished, the insulation capability is restored. Statistical specification of a BIL or a BSL is not appropriate to a non-self-restoring insulation, but is quite appropriate to the specification of self-restoring insulation.

It is of importance to understand the meaning of BSL and BIL specifications. These specifications are intended to measure the ability of equipment to withstand representative overvoltages, intended to capture the general ability of the device with respect to a general kind of overvoltage condition. The BIL is specified with reference to a specific waveform: 1.2 microseconds rise time, 50 microseconds time to decay to half value. The BSL waveform has a 250 microseconds to peak, 2500 microseconds to half value. The implication (not necessarily correct) is that typical lightning and switching waveforms have the same general characteristics and shape. While the expected characteristics of the overvoltage resulting from switching can usually be determined with good accuracy using the EMTP (and consequently the designer can verify to what extent the standard test waveform is applicable), actual lightning waveforms can differ considerable from the assumed ones.

Insulation coordination also means the selection, specification and location of equipment intended to reduce overvoltages, such as lightning arresters and to some extent breakers, pre-insertion resistors and other such items.

There are five parameters of interest in the selection of a lightning arrester:

- The lightning current discharge capability and its corresponding voltage. Generally a current of about 10 kA is considered in the design process. Lightning overvoltage considerations also often constrain the location of the arrester. Gapped arresters often have difficulty meeting tight lightning overvoltage discharge requirements because of the slower action induced by the gap.
- The switching current discharge and corresponding voltage. Switching considerations usually influence the energy dissipated in the arresters.
- The energy dissipation characteristics of the arrester, or temporary overvoltage capability. This parameter is associated with the duration as well as the magnitude of the overvoltage. This information is generally available in the form of voltage versus time curves for each arrester.
- The arrester rated voltage (generally the maximum temporary overvoltage expected during operation before the arrester has a significant effect on the system).
- The continuous operating voltage. This determines the steady-state losses in the arrester. If we restrict our attention to gapless ZnO arresters this value is generally quite small.

Arrester location is always an important subject. In general, arresters should be located as close to equipment as is practical, with as short leads as possible. However, there are many reasons why sometimes arresters must be located at some distance from the protected equipment. For example, in Gas Insulated Substations (GIS) arresters are often located outside the substation for economic reasons, but encapsulated arresters may also be required.

Thus, we see that insulation coordination is, as has been said of many other aspects of engineering design, as much an art as it is an exact discipline, where the designer attempts to weigh and consider many diverse factors and come up with a single answer. Insulation coordination methodologies are likely to vary with individual companies and individuals.

11.12. Insulation Coordination Methodologies

Methods for insulation coordination can be classified into four general categories:

- Rule of thumb methods.
- Precalculated deterministic studies.
- Deterministic methods and semi-statistical methods.
- Statistical methods.

Rule of thumb methods and precalculated studies are mostly outside the scope of this workbook. They are, nevertheless, practical ways of designing insulation levels for most standard substations with simple configurations. We illustrate below a simple table giving maximum expected overvoltages under several common events. Designs based on these values will generally be too conservative:

Table 11.2: Typical Maximum Overvoltage Magnitudes

Nature of overvoltage	Maximum p.u. overvoltage
Energization of line (no closing resistors)	3.5
Energization, one step closing resistors	2.1
Energization, multi-stage closing resistors	1.5
Reclosing into trapped charge, one step resistors	2.2
Fault initiation overvoltage, SLG fault, unfaulted phase	2.1
Temporary SLG fault overvoltage, ungrounded system	1.73
Temporary SLG fault overvoltage, properly grounded system	1.3-1.4
Fault clearing	1.9
Capacitor bank energization	2.0
Capacitor bank re-strike	3.0

We offer here the steps for a representative insulation coordination study methodology:

- Insulation coordination can be done from three (perhaps more) different perspectives: (1) assuming that the equipment and transmission lines installed are known, where the objective is to select and size arrester(s); (2) assuming that the arresters and their probable location, and all transmission line parameters are known, where the objective is to specify the BSL and BIL for new equipment; (3) assuming that a transmission line is being built and/or upgraded and the objective is to select the insulation level for the new line. The first step in insulation coordination is to determine which of these three categories of studies the intended study falls under.

Once the desired study has been classified, three slightly different methodologies can be adopted. If the study is to be done to select, size and place arresters, then follow the following steps:

- Select an initial arrester operating voltage and rated voltage based on the system voltage class and expected temporary overvoltages.
- Define all important service configurations (equipment in and out of service possibilities).
- Locate the arrester at the entrance of the substation. For all important service configurations, verify that all equipment will be adequately protected by simulating a number of 1.2/50 μs standard lightning impulse strokes at various locations within the nearest few spans of the incoming lines. We recommend representing lightning strokes as current surges of a peak amplitude of at least 20 kA, but other waveforms and impulse currents levels may be selected according to different standards or study requirements.
- Identify all probable switching operations that may lead to arrester operation. Include trapped charge conditions.

- Identify any possible load rejection conditions. Determine load rejection overvoltages. These can be done analytically or using the steady-state solution capability within the EMTP. Temporary overvoltages are comparatively more important than for line insulation design because of limits on energy dissipation capability.

- Identify other possible credible temporary overvoltages induced by single line to ground faults.

For deterministic design, the service configuration in effect, the stroke location, the time to crest, the peak magnitude of stroke current, the time to half value, the stroke polarity and the phase angle of the service voltage at the time of stroke are preselected. For statistical design these values are allowed to vary randomly within known distributions (including the probability of each service configuration). In addition, we consider the frequency of lightning strokes at the substation location. In the end we obtain an overall indication of the probable failure rate measured in failures per year.

If the objective of the study is to select BIL or BSL levels for specific pieces of equipment, proceed as follows:

- Define all important service configurations (equipment in and out of service possibilities).

- Using simple EMTP simulations, determine the waveforms of overvoltages produced by all switching and lightning transients. Use these to specify equipment.

- If the resulting peak voltage values and voltage waveforms on equipment are within tolerable limits for all cases tested, the design is satisfactory. Otherwise consider different arrester location, a different arrester rating, the possible use of multiple arresters, and the possibility of increasing insulation levels and repeat the process.

- For all important service configurations, verify that all equipment will be adequately protected by simulating a number of 1.2/50 µs standard lightning impulse strokes (IEEE Std 4-1978) at various locations within the nearest few spans of the incoming lines. We recommend representing lightning strokes as current surges of a peak amplitude of at least 20 kA. Corona representation would be helpful. Results without it are likely to be more conservative.

- Identify any possible load rejection conditions. Consider possible ferroresonance and harmonic resonance conditions.

- For low insulation levels, identify the worst credible fault conditions, with particular attention to single line to ground faults in the vicinity of the equipment.

- Consider the possibility of equipment-specific transients. For example, generators near series capacitors or near HVDC lines should be studied for possible subsynchronous resonance.

- SF_6 insulated equipment requires more careful design and tighter tolerances. Detailed modeling of the transients within the substation buses, not just at the equipment points, may be required.

If the objective is to design a line and to size and specify insulator strings, proceed as follows:

- Define all important service configurations (equipment in and out of service possibilities). Configurations with open ended lines or transformers can result in higher overvoltages. Certain configurations may only occur briefly (such as during non-simultaneous energization of phases or of both ends of the line).
- Identify the worst credible switching transients within these configurations (including any trapped charge conditions). Consider the effect of arresters, if any.
- Using statistical EMTP simulations, determine the overvoltages produced by all switching and lightning transients.
- If attempting to specify low insulation levels (<2.0 p.u.), identify any possible load rejection conditions. Consider Ferranti effect.
- If attempting to specify low insulation levels (<2.0 p.u.), identify the worst credible fault conditions, with particular attention to single line to ground faults.
- If the line is short, consider the possibility of the line behaving like a capacitor (see "capacitor switching"). Consider the effect of restrikes.
- If single pole switching is called for, perform studies to determine the ability of the line to clear the arc.

11.13. Using the EMTP Appropriately

The EMTP provides the ability of performing better insulation design. The questions that a designer faces when attempting to use the EMTP for insulation coordination are:

- What runs should I perform and what outputs do I request?
- How do I interpret and use the results?
- What models do I use within the EMTP?

We see throughout this workbook how to perform a variety of specific studies. This chapter has described criteria to use to select which studies to perform. This section summarizes the EMTP models to be used in the main two types of transients.

- Switching transients. Switching transient studies require generally a full three phase representation of transmission lines. Frequency dependence is of some importance to determine accurate waveforms for events involving the zero sequence, such as single line to ground faults or breaker opening action, but is strictly speaking not required for many design studies.
- Lightning transients. Detailed modeling of a few spans is required, as well as a detailed knowledge of the exact substation layout and arrester location. All equipment capacitances must be considered. Frequency dependence in the phase conductors can be considered, although good results can be obtained without it. Back-flashover studies are probably more important than electromagnetic induction studies.

11.14. Concluding Remarks

The EMTP represents an evolving and quite powerful tool. It can do many things quite well. It gives users the ability to obtain numeric and graphic solutions from both simple and sophisticated models of power systems with ease. However, it is no substitute for good engineering judgement. Sophisticated models can be misused. Wrong or simply irrelevant questions may be asked of it. It is better to obtain correct representations to simplified situations where the assumptions are well understood, limitations clearly stated and where an intuitive feel for expected answers is possible than to obtain results of sophisticated simulations where the assumptions are poorly understood and where the results may be questionable. The EMTP can do many things well, but it cannot do all things. Furthermore, there are situations where no simulation tool can give a better understanding of the phenomena. Simulation is not the key to all of engineering: it has its place. Simulation programs like the EMTP must be put into the broader perpective of electric power system analysis tools.

Good luck!

11.15. References

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APPENDIX A

TEMPLATES

A.1 Type of Templates

This appendix contains templates useful for the preparation of input data and understanding the organization of data for most of the EMTP capabilities described in this workbook. In most cases both a short and a long version of each template are provided. The long templates provide extensive information, and in most cases eliminate the need for the User's Guide. The short templates are more practical and concise. You must first select the desired template from the following list, then locate and use this template.

A.2. Short Templates

The following templates are included in this section:

- `CABLE CONSTANTS` data input for single core coaxial cables without metallic enclosure (a pipe). Use this template to generate EMTP data for systems of one or more coaxial conductors directly buried, on the surface of the earth, or above ground.
- `CABLE CONSTANTS` data input for single core coaxial cables with metallic enclosure (a pipe). Use this template to generate EMTP data for systems of coaxial conductors within a metallic enclosure, whether below or above ground.
- `CABLE CONSTANTS` data input for automatic generation of crossbonding π sections. The use of this template is optional, as you can generate the same data yourself by renaming the terminal nodes of the cable, but this capability simplifies the preparation of data for cable systems crossbonded at regular intervals.
- `LINE CONSTANTS` data input for overhead lines. You can also use the `CABLE CONSTANTS` routines for overhead lines, but templates are not provided. One capability available through the `CABLE CONSTANTS` routines is the ability to specify a stratified ground.
- Template for use of the `JMARTI SETUP` in conjunction with the `CABLE CONSTANTS` routine on regular cable without pipe. The `JMARTI SETUP` routine is used for preparation of frequency dependent line models. Since pipe type cable is less frequency dependent, a template is not provided.
- Template for use of the `JMARTI SETUP` in conjunction with the `CABLE CONSTANTS` routine on crossbonded cable. The `JMARTI SETUP` routine is used for preparation of frequency dependent line models.

- Template for use of the `JMARTI SETUP` in conjunction with the `LINE CONSTANTS` routine.
- Template for performing `SYSTEMATIC` study.
- Template for performing `STATISTICAL` study.
- Template for performing Frequency Dependent Network Equivalent (FDNA).
- Template for general EMTP case study.

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

> *Notice: There is an error in the CABLE CONSTANTS portion of Volume 2 of the Rule Book associated with Version 1 of the EMTP. The additional "grounding conditions" card that is required if NGND=4 to request different grounding patterns for different cables should be placed* ***right before the frequency cards*** *instead of right after the miscellaneous data card.*

```
C Template for CABLE CONSTANTS data input (Class A: SC coaxial cable, no pipe)
BEGIN NEW DATA CASE
C Cable constants card------------------------------------><N<--------------->
CABLE CONSTANTS
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C Number of conducting layers in each SC cable  N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C Geometrical and physical data for each SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ------rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ------rhoA<------muA<-----muI3<epsilonI3

C Repeat this card for 2nd, 3rd, ... cable.
C
C Horizontal and vertical coordinates of the center of each SC cable
C -----vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C Grounding conditions card
C 123456789...

C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C Repeat the frequency card and the complex earth model parameters card for
C    other frequencies of interest.
C
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

```
C Template for CABLE CONSTANTS data input (Class B: SC coaxial cable, with pipe)
BEGIN NEW DATA CASE
C Cable constants card--------------------------------------><N<--------------->
CABLE CONSTANTS
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    3
C Parameters of the conducting pipe
C -----RP1<------RP2<------RP3<------rho<-------mu<-epsilon1<-epsilon2

C Location of each SC cable within the conducting pipe
C ---Dist1<---Theta1<----Dist2<---Theta2<----Dist3<---Theta3<----Dist4<---Theta4

C Number of conducting layers for each cable     N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C Geometrical and physical data for each SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C Repeat this card for 2nd, 3rd, ... cable.
C
C Vertical distance between center of the conducting pipe and the earth surface
C --center

C Grounding conditions
C 123456789...

C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C
C Repeat the frequency card and the complex earth model parameter cards for
C    other frequencies of interest.
C
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

```
C Template for CABLE CONSTANTS with crossbonding data input (Class A:
C    SC coaxial cable, no pipe)
BEGIN NEW DATA CASE
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS
PUNCH
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C                       X
C   N    N    I         m          C
C   P    c    R         a          n
C   A    r    s         j         Ra
C   I    o    e         o         Sm
C --S<---s<---p<--------r<--------Ge

C Number of conducting layers for each SC cable  N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1

C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C Repeat this card for 2nd, 3rd, ... cable.
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C Grounding conditions
C 123456789...

C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C Repeat the frequency card and the complex earth model parameter cards for
C    other frequencies of interest.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
```

```
C Template for LINE CONSTANTS input
BEGIN NEW DATA CASE
LINE CONSTANTS
C Branch cards
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C Select system of units
METRIC
ENGLISH
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

C Repeat the conductor card for each conductor or bundle.
BLANK card terminates conductor cards
C Frequency Cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C Repeat the frequency card for other frequencies of interest.
BLANK card terminates frequency cards
C Change Case Card
CHANGE
C Repeat the conductor card for the conductors or bundles need changes.
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

BLANK card terminates CHANGE data case
C Repeat the frequency cards for the frequencies of interest.
C                                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK terminates EMTP solution-mode
```

```
C Short Template for Frequency Dependent Cable (no pipe) using MARTI model
BEGIN NEW DATA CASE
JMARTI SETUP
C Branch Cards
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C Cable constants card--------------------------------------><N<--------------->
CABLE CONSTANTS
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y              N
C   y    s         a    m    f    f              g
C   p    y    N    r    o    l    l    N         r
C   e    s    P    t    d    a    a    p         n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C Number of conducting layers in each SC cable   N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----RhoC<------MuC<-----MuI1<EpsilonI1<-----RhoS<------MuS<-----MuI2<EpsilonI2

C ----RhoA<------MuA<-----MuI3<EpsilonI3

C Repeat the three cards above for 2nd, 3rd cables ... etc.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---Vert1<---Horiz1<----Vert2<---Horiz2<----Vert3<---Horiz3<----Vert4<---Horiz4

C Grounding conditions
C 123456789...

C Frequency cards.
C   Either supply the following three data cards or the alternative frequency
C   data cards.  The three frequency cards required are:
C     1. Frequency at which the modal transformation matrix is calculated.
C        Default is 5000 Hz.
C     2. Steady state power frequency.
C     3. Logarithmic looping frequency, usually covers 8 or 9 decades beginning
C        from 0.01 Hz with 10 points per decade.
C If the Nakagawa earth model is begin used, each frequency card must be
C followed by the two cards specify the earth model.
C ----------Rho<----------Freq<IDec<IPnt<---Dist<-----IPun

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---Dep12<----Dep23<-----rho2<-----rho3

C -----Mu1<------Mu2<------Mu3<-Epsilon1<-Epsilon2<-Epsilon3

C Alternative frequency data cards
C ---KPh<-IModal<-MetriK<---Dist

C ----------FMin<-----------FMax<-----------Root

C Include the following cards if IModal > 0.
C ---------Omega<--------------G<--------------B<--------------R<--------------X

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)
```

```
C Repeat the last two cards for each frequency point.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
C
C Fitting parameters:
C   DEFAULT   - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C               data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

BLANK card terminates JMARTI SETUP
BLANK card terminates EMTP solution-mode
```

```
C Template for Frequency Dependent cross-bonded Cable using MARTI model
C with embedded CABLE CONSTANTS routine.
BEGIN NEW DATA CASE
JMARTI SETUP
C Branch Cards
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C Cable constants card---------------------------------------><N<-------------->
CABLE CONSTANTS
PUNCH
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C                       X
C   N    N    I         m          C
C   P    c    R         a          n
C   A    r    s         j         Ra
C   I    o    e         o         Sm
C --S<---s<---p<--------r<--------Ge

C Number of conducting layers for each SC cable  N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C Geometrical and physical data for EACH SC cable
C -------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C -----rhoC<-------muC<------muI1<epsilonI1<------rhoS<-------muS<------muI2<epsilonI2

C -----rhoA<-------muA<------muI3<epsilonI3

C Repeat this card for 2nd, 3rd, ... cable.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C Grounding conditions
C 123456789...

C Frequency cards.
C   Either supply the following three data cards or the alternative frequency
C   data cards.  The three frequency cards required are:
C      1. Frequency at which the modal transformation matrix is calculated.
C         Default is 5000 Hz.
C      2. Steady state power frequency.
C      3. Logarithmic looping frequency, usually covers 8 or 9 decades beginning
C         from 0.01 Hz with 10 points per decade.
C If the Nakagawa earth model is begin used, each frequency card must be
C followed by the two cards specify the earth model.
C ----------Rho<----------Freq<IDec<IPnt<---Dist<-----IPun

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---Dep12<----Dep23<------rho2<------rho3

C ------Mu1<-------Mu2<-------Mu3<-Epsilon1<-Epsilon2<-Epsilon3
```

```
C Alternative frequency data cards
C ---KPh<-IModal<-MetriK<---Dist

C ----------FMin<-----------FMax<-----------Root

C Include the following cards if IModal > 0.
C ---------Omega<--------------G<--------------B<--------------R<--------------X

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)

C Repeat the last two cards for each frequency point.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
C
C Fitting parameters:
C   DEFAULT   - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C               data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

BLANK card terminates JMARTI SETUP
BLANK card terminates EMTP solution-mode
```

```
C Frequency Dependent Line using MARTI model with LINE CONSTANTS
BEGIN NEW DATA CASE
JMARTI SETUP
C Branch Cards
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
LINE CONSTANTS
C Select System of Units
METRIC
ENGLISH
C Conductor Cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

C Repeat conductor card for each conductor (or bundle).
BLANK card terminates conductor (or change case) cards
C
C Frequency Cards.
C   Either supply the frequency cards for Transposed and Untransposed Lines or
C   use the alternative frequency cards.
C     Transposed   - Requires 2 frequency cards:
C                      1. Steady state power frequency.
C                      2. Logarithmic looping frequency, usually covers 8 or 9
C                         decades beginning from 0.01 Hz with 10 points per decade.
C     Untransposed - Requires 3 frequency cards:
C                      1. Frequency at which the modal transformation matrix is
C                         calculated.  Default is 5000 Hz.
C                      2. Steady state power frequency.
C                      3. Logarithmic looping frequency, same as transposed line.
C                                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C Alternative frequency cards.
C ---KPh<-IModal<-MetriK<---Dist

C ----------FMin<-----------FMax<-----------Root

C Include the following cards if IModal > 0.
C ---------Omega<--------------G<--------------B<--------------R<--------------X

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)

C Repeat the last two cards for each frequency point.
BLANK card terminates frequency cards
BLANK card terminates LINE CONSTANTS study
C
C Fitting parameters:
C   DEFAULT   - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C               data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

BLANK card terminates JMARTI SETUP
BLANK card terminates EMTP solution-mode
```

```
C Template for SYSTEMATIC study.
BEGIN NEW DATA CASE
C ...........................  Miscellaneous data .............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart

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

C ---ISw<--ITest<-------><--AIncr<-XMaxMx

C
C ...........................  Circuit data  ..................................
C Untransposd distributed parameter line.
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<------------------->0

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)

C RLC branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C

BLANK card terminates circuit data
C
C ...........................  Switch data  ...................................
C Independent switches.
C Bus1->Bus2-><TcMid|Beg<----TStep<----NStep<--------><-------->Targe>
                                                     SYSTEMATIC
C Dependent switches.
C Bus1->Bus2-><Tdel|Toff<----------------------------><-------->Bus5->Bus6->
                                                     SYSTEMATIC
BLANK card terminates switch data
C
C ...........................  Source data  ...................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop

BLANK card terminates source data
C
C ...........................  Output Request Data  ...........................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->

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

```
C Template for STATISTICS study.
BEGIN NEW DATA CASE
C ............................ Miscellaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart

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

C ---ISw<--ITest<--IDist<--AIncr<-XMaxMx<-DegMin<-DegMax<-StatFr<-SigMax<--NSeed

C
C ............................ Circuit data ...................................
C Untroposed distributed parameter line.
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<------------------>0

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)

C RLC branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C

BLANK card terminates circuit data
C
C ............................ Switch data ....................................
C Independent switches.
C Bus1->Bus2-><--Tc mean<--Std Dev<--------I<--------><-------->Targe>
                                                        STATISTICS
C Dependent switches.
C Bus1->Bus2-><Tb random<--Std Dev<--------I<--------><-------->Bus5->Bus6->
                                                        STATISTICS
BLANK card terminates switch data
C
C ............................ Source data ....................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0          <----Tstart<----Tstop

BLANK card terminates source data
C
C ............................ Output Request Data ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->

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

```
C FDNA input data.
C   Notice: The current version of FDNA program does not accept comments in
C   the input data.  So, this template serves only as a guide line.
C   All comment lines must be removed before actual run, and all BLANKs have
C   to be replaced by a blank line.
C Study identifications.
C Label------------------------------------------------------------------------>


C -FileId

C Maxima and minima selection.
C ---REjct<-----RMxd<-----RMxi<-----RMnd<----RMni1<----RMni2

C Output options specification.
C Prt<Plot<Scal<-Old<Resu<-Cap<Prt2<Prt3<Icom

C Reference bus data.
C RfNam><------RefKV

C Frequency range over which the network admittance is approximated.
C --StrFeq<NDec<DPrt<---RefFrq

C Right-of-Way Cards.
C R/W Name--->< --Len<-NCCT<-Data<-IPrt

C From->To---><BasKV

C Conductor Cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

BLANK card terminates conductor cards
C Frequency Cards                                         M            I
C                                                       I u          M T
C               F         F      I      I I       D    PIt  I  I  I o r
C     R         r         C      C      Z C       i    iSu  D  P  P d n
C     h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C Repeat from Conductor Cards for each set of conductors.
C Reapeat from Right-of-Way Cards for each Right-of-Way.
BLANK card terminates Right-of-Way cards
C
C Linear series branches.
C From->To--->RFrom>RTo--><---R0<---X0<---B0<---R1<---X1<---B1<-Base

BLANK card terminates linear series branches.
C Shunt branches.
C From-><---------------><---R0<---X0<---B0<---R1<---X1<---B1<-Base

BLANK card terminates shunt branches and FDNA data case.  (Don't forget!)
```

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

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

C
C ............................ Circuit data ....................................
C Untransposed distributed parameters line.
C Bus1->Bus2->Bus3->Bus4-><---R'<----A<----B<--len 0 0 0<--------------------->O

C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)

C Transposed distributed parameters line.
C Bus1->Bus2->Bus3->Bus4-><---R'<----A<----B<--len 0 0 0<--------------------->O
                                                       0
C Series RLC branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C

C Pi-equivalent branch.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C<----R<----L<----C<----R<----L<----C

C Mutually-coupled RL branch.
C Bus1->Bus2->            <----R<----------L<----R<----------L<----R<----------L
51
C Circuit data includes transformers and other circuit components.
BLANK card terminates circuit data
C
C ............................ Switch data .....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O

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

C Source data also includes machines, etc.
BLANK card terminates source data
C
C ............................ Output Request Data ..............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->

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

A.3. Detailed Templates

The following templates are included in this section:

- `CABLE CONSTANTS` data input for single core coaxial cables without metallic enclosure (a pipe). Use this template to generate EMTP data for systems of one or more coaxial conductors directly buried, on the surface of the earth, or above ground.
- `CABLE CONSTANTS` data input for single core coaxial cables with metallic enclosure (a pipe). Use this template to generate EMTP data for systems of coaxial conductors within a metallic enclosure, whether below or above ground.
- `CABLE CONSTANTS` data input for automatic generation of crossbonding π sections. The use of this template is optional, as you can generate the same data yourself by renaming the terminal nodes of the cable, but this capability simplifies the preparation of data for cable systems crossbonded at regular intervals.
- `LINE CONSTANTS` data input for overhead lines. You can also use the `CABLE CONSTANTS` routines for overhead lines, but templates are not provided. One capability available through the `CABLE CONSTANTS` routines is the ability to specify a stratified ground.
- Template for use of the `JMARTI SETUP` in conjunction with the `CABLE CONSTANTS` routine on regular cable without pipe. The `JMARTI SETUP` routine is used for preparation of frequency dependent line models. Since pipe type cable is less frequency dependent, a template is not provided.
- Template for use of the `JMARTI SETUP` in conjunction with the `CABLE CONSTANTS` routine on crossbonded cable. The `JMARTI SETUP` routine is used for preparation of frequency dependent line models.
- Template for use of the `JMARTI SETUP` in conjunction with the `LINE CONSTANTS` routine.
- Template to help interpret the output of the `JMARTI SETUP` routine and incorporate the frequency dependent models into the EMTP data.

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

> *Notice: There is an error in the CABLE CONSTANTS portion of Volume 2 of the Rule Book associated with Version 1 of the EMTP. The additional "grounding conditions" card that is required if NGND=4 to request different grounding patterns for different cables should be placed* ***right before the frequency cards*** *instead of right after the miscellaneous data card.*

```
C Template for CABLE CONSTANTS data input (Class A: SC coaxial cable, no pipe)
BEGIN NEW DATA CASE
C
C Cable constants card--------------------------------------><N<--------------->
CABLE CONSTANTS
C                                                              |___select
C  transmission lines or cables: 0 (majority of the cables have 2 or less
C  conductors not including pipe), 1 (majority of the cables have 2 or more
C  conductors not including pipe)
C
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C   |    |    |    |    |    |    |    |    |___grounding condition: 0 or 1 (
C   |    |    |    |    |    |    |    |          none of the cond is gnd),
C   |    |    |    |    |    |    |    |          2 (all armors are gnd), 3 (
C   |    |    |    |    |    |    |    |          all sheathes and armors are
C   |    |    |    |    |    |    |    |          gnd), 4 (see grounding card)
C   |    |    |    |    |    |    |    |___BLANK (unused)
C   |    |    |    |    |    |    |___shunt-admittance matrices output: 0 )print
C   |    |    |    |    |    |         [G] & [C]), 1 (print [G] & w[C]),
C   |    |    |    |    |    |         2 (print both of the above)
C   |    |    |    |    |    |___series-impedance matrices output: 0 (print [R]
C   |    |    |    |    |          & [L]), 1 (print [R] & w[L]), 2 (print both
C   |    |    |    |    |          of the above)
C   |    |    |    |    |___modal quantities calculation: 0 (no calculation or
C   |    |    |    |          output), 1 (calculate and print)
C   |    |    |    |___earth model: 0 (homogeneous), 99 (3-layer stratified,
C   |    |    |          only for overhead systems, ISYST = 0 or 1)
C   |    |    |___number of SC coaxial cables which makes up the system
C   |    |___input specification: -1 (underground), 0 (on earth surface),
C   |          1 (in the air)
C   |___input classification: 2 (class A - SC coaxial, no pipe)
C
C Number of conducting layers in each SC cable   N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C   |___number of conducting layers in the kth cable: 1 (one conductor: core
C          only), 2 (two conductors: core and sheath), 3 (three conductors: core
C          sheath & armor)
C IMPORTANT: NCPPk MUST be non-increasing, so ALL 3-conductor cables MUST
C    precede 2-conductor cables and ALL 2-conductor cables MUST precede core
C    only cables.  This ordering, once established, is applied throughout the
C    rest of the data case.
C Remark: If NPC > 16, insert a new data card with the same format.
C
C Geometrical and physical data for EACH SC cable
C -------R1<--------R2<--------R3<--------R4<--------R5<--------R6<--------R7

C         |         |         |         |         |         |       |___outer
C         |         |         |         |         |         |   radius of 3rd
C         |         |         |         |         |         |   insulation layer
C         |         |         |         |         |         |___outer radius of
C         |         |         |         |         |              armor
```

```
C         |         |         |         |         |___inner radius of armor
C         |         |         |         |___outer radius of sheath
C         |         |         |___inner radius of sheath
C         |         |___outer radius of tubular core
C         |___inner radius of tubular core
C
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C         |         |         |         |         |         |         |        |
C         |         |         |         |         |         |         |relative
C         |         |         |         |         |         |         |permittiv-
C         |         |         |         |         |         |         |ity of 2nd
C         |         |         |         |         |         |         |insulation
C         |         |         |         |         |         |         |layer
C         |         |         |         |         |         |         |___relat-
C         |         |         |         |         |         |ive permeability of
C         |         |         |         |         |         |2nd insulation layer
C         |         |         |         |         |         |___relative
C         |         |         |         |         |               permeability
C         |         |         |         |         |               of  sheath
C         |         |         |         |         |___resistivity of sheath
C         |         |         |         |___relative permittivity of 1st
C         |         |         |               insulation layer
C         |         |         |___relative permeability of 1st insulation layer
C         |         |___relative permeability of core
C         |___resistivity of core
C
C ----rhoA<------muA<-----muI3<epsilonI3

C         |         |         |         |___relative permittivity of 3rd
C         |         |         |               insulation layer
C         |         |         |___relative permeability of 3rd insulation layer
C         |         |___relative permeability of armor
C         |___resistivity of armor
C
C Repeat the following card for 2nd, 3rd, ... cable.
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C Remarks: These cards must be stacked in the order established by the cards
C    that define NCPPk.  All rho's are in ohm-meters.  All mu's & epsilon's a
C    All radii are in meters.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C         |         |___horizk is the distance from the center of the kth cable
C         |               to an arbitrary reference line located to the left of
C         |               the cable
C         |___vertk is the vertical distance from the center of the kth cable to
C               the earth surface.  This number is always positive.
C Remarks: All units are in meters.  Repeat this card if there are more than 4
C    cables.  Ordering of the cable is established in the cards define NCPPk.
C
C Grounding conditions
C 123456789...

C |___cable grounding code: 0 (none of the conductors in the cable is gnd),
C        1 (core is gnd), 2 (sheath is gnd), 3 (armor is gnd), 4 (sheath & armor
C        are gnd), 5 (core & sheath are gnd), 6 (core & armor are gnd), 7 (core,
C        sheath & armor are gnd)
```

```
C Remarks: This card is used when grounding conditions are different for diff-
C    erent cables, or not all outer conductors are grounded.  Each column
C    represents a cable where the ordering is established by the card follows.
C
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C             |              |    |    |       |         |___BLANK for indep-
C             |              |    |    |       |             endent data case
C             |              |    |    |       |___length of transmission
C             |              |    |    |             system: BLANK (usually),
C             |              |    |    |             required only in "SEMLYEN
C             |              |    |    |             SETUP".
C             |              |    |    |___number of points per decade for R, L
C             |              |    |            & C to be calculated for log freq
C             |              |    |            scan BLANK for single frequency.
C             |              |    |___frequency span in number of decades, BLANK
C             |              |          for single frequency.
C             |              |___frequency used in calculation: 0 or BLANK (
C             |                    default power frequency), non-BLANK (freq
C             |                    used in single frequency calculation, or
C             |                    beginning frequency in log frequency scan
C             |                    IDEC <> BLANK)
C             |___resistivity of top layer of the earth (resistivity of the
C                    entire uniform earth in homogeneous case).
C Remarks: Units of rho in ohm-meters, frequency in hertz.
C
C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C        |         |         |         |___resistivity of layer 3 of the earth
C        |         |         |___resistivity of layer 2 of the earth
C        |         |___distance from the surface of the earth to where layer 2 &
C        |                3 meets
C        |___distance from the surface of the earth to where layer 1 & 2 meets
C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C        |         |         |         |         |         |___relative permit-
C        |         |         |         |         |             tivity of layer 3
C        |         |         |         |         |___relative permittivity of
C        |         |         |         |               layer 2
C        |         |         |         |___relative permittivity of layer 1
C        |         |         |___relative permeability of layer 3
C        |         |___relative permeability of layer 2
C        |___relative permeability of layer 1
C Remarks: All distances are in meters.  All rho's are in ohm-meters.  All mu's
C    & epsilon's are dimensionless.  Resistivity of layer 1 is specified in the
C    frequency card.  Remove these cards if homogeneous earth model is chosen.
C
C Repeat the frequency card and the complex earth model parameter cards for
C    other frequencies of interest.  Remove these cards for single frequency
C    study.
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
C Remarks: EMTP interprets BLANK lines as BLANK cards.  Delete all blank lines
C   before running the data case.
```

```
C Template for CABLE CONSTANTS data input (Class B: SC coaxial cable, with pipe)
BEGIN NEW DATA CASE
C Cable constants card--------------------------------------><N<------------->
CABLE CONSTANTS
C                                                               |___select
C  transmission lines or cables: 0 (majority of the cables have 2 or less
C  conductors not including pipe), 1 (majority of the cables have 2or more
C  conductors not including pipe)
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    3
C   |    |    |    |    |    |    |    |    |___grounding condition: 0 (none
C   |    |    |    |    |    |    |    |           of the cond is gnd), 1 (the
C   |    |    |    |    |    |    |    |           pipe is gnd), 2 (armors &
C   |    |    |    |    |    |    |    |           pipe are gnd), 3 (armors,
C   |    |    |    |    |    |    |    |           sheathes & pipe are gnd),
C   |    |    |    |    |    |    |    |           4 (see grounding card)
C   |    |    |    |    |    |    |    |___pipe thickness: 1 (pipe of finite
C   |    |    |    |    |    |    |           thickness), 2 (pipe of infinite
C   |    |    |    |    |    |    |           thickness, ISYST = 0)
C   |    |    |    |    |    |    |___shunt-admittance output matrices: 0 (print
C   |    |    |    |    |    |           [G] & [C]), 1 (print [G] & w[C]), 2 (
C   |    |    |    |    |    |           print both of the above)
C   |    |    |    |    |    |___series-impedance matrices output: 0 (print [R]
C   |    |    |    |    |           & [L]), 1 (print [R] & w[L]), 2 (print both
C   |    |    |    |    |           of the above)
C   |    |    |    |    |___modal quantities calculation: 0 (no calculation
C   |    |    |    |           or output), 1 (calculate and print)
C   |    |    |    |___earth model: 0 (homogeneous), 99 (3-layer stratified,
C   |    |    |           only for overhead systems, ISYST = 0 or 1)
C   |    |    |___number of SC coaxial cables which makes up the system
C   |    |___system specification: -1 (underground), 0 (on earth surface), 1 (in
C   |           the air)
C   |___input classification: 3 (class B - SC coaxial, with pipe)
C
C Parameters of the conducting pipe
C -----RP1<------RP2<------RP3<------rho<-------mu<-epsilon1<-epsilon2

C        |         |         |         |         |         |         |___relat-
C        |         |         |         |         |         |ive permittivity of
C        |         |         |         |         |         |insulating tube
C        |         |         |         |         |         |surrounds pipe
C        |         |         |         |         |         |___relative permit-
C        |         |         |         |         |        tivity of insulating
C        |         |         |         |         |        medium inside the pipe
C        |         |         |         |         |___relative permeability of
C        |         |         |         |                the pipe
C        |         |         |         |___resistivity of the pipe
C        |         |         |___outer radius of insulator surrounds the pipe
C        |         |___outer radius of the pipe
C        |___inner radius of the pipe
C Remarks: All epsilon's and mu's are dimensionless.  Rho is in ohm-meters and
C    RP's in meters.
C
C Location of each SC cable within the conducting pipe
C ---Dist1<---Theta1<----Dist2<---Theta2<----Dist3<---Theta3<----Dist4<---Theta4

C        |         |___thetak is the angular position of the kth cable measured
C        |                from the positive x-axis where the x-y axes intercepts
```

```
C        |                the center of the conducting pipe
C        |___distk is the distance from center of the pipe to the center of the cable
C Remarks: All distances are measured in meters and angles in degrees.  If the
C    number of cable > 4 then use a second data card with the same format.
C
C Number of conducting layers for each cable     N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C   |___number of conducting layers for the kth cable: 1 (one conductor: core
C          only), 2 (two conductors: core and sheath), 3 (three conductors: core
C          sheath & armor)
C IMPORTANT: NCPPk MUST be non-increasing, so ALL 3-conductor cables MUST
C    precede 2-conductor cables and ALL 2-conductor cables MUST precede core
C    only cables.  This ordering, once established, is applied throughout the
C    rest of the data case.
C Remark: If NPC > 16, insert a new data card with the same format.
C
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C        |         |         |         |         |         |         |___outer
C        |         |         |         |         |         |    radius of 3rd
C        |         |         |         |         |         |    insulation layer
C        |         |         |         |         |         |___outer radius of
C        |         |         |         |         |                armor
C        |         |         |         |         |___inner radius of armor
C        |         |         |         |___outer radius of sheath
C        |         |         |___inner radius of sheath
C        |         |___outer radius of tubular core
C        |___inner radius of tubular core
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C        |         |         |         |         |         |         |         |
C        |         |         |         |         |         |         |relative
C        |         |         |         |         |         |         |permittiv-
C        |         |         |         |         |         |         |ity of 2nd
C        |         |         |         |         |         |         |insulation
C        |         |         |         |         |         |         |layer
C        |         |         |         |         |         |         |___relat-
C        |         |         |         |         |         |ive permeability of
C        |         |         |         |         |         |2nd insulation layer
C        |         |         |         |         |         |___relative permea-
C        |         |         |         |         |             bility of sheath
C        |         |         |         |         |___resistivity of sheath
C        |         |         |         |___relative permittivity of 1st
C        |         |         |                insulation layer
C        |         |         |___relative permeability of 1st insulation layer
C        |         |___relative permeability of core
C        |___resistivity of core
C ----rhoA<------muA<-----muI3<epsilonI3

C        |         |         |         |___relative permittivity of 3rd
C        |         |         |                insulation layer
C        |         |         |___relative permeability of 3rd insulation layer
C        |         |___relative permeability of armor
C        |___resistivity of armor
C
C Repeat the following card for 2nd, 3rd, ... cable.
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7
```

```
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C Remarks: These cards must be stacked in the order established by the cards
C    that define NCPPk.  All rho's are in ohm-meters, all mu's & epsilon's are
C    dimensionless.  All radii are in meters.
C
C Vertical distance between center of the conducting pipe and the earth surface
C --center

C        |___distance from center of pipe to the earth surface
C Remarks: Input is always positive.  Units is in meters.
C
C Grounding conditions
C 123456789...

C |___cable grounding code: 0 (none of the conductors in the cable is gnd),
C        1 (core is gnd), 2 (sheath is gnd), 3 (armor is gnd), 4 (sheath & armor
C        are gnd), 5 (core & sheath are gnd), 6 (core & armor are gnd), 7 (core,
C        sheath & armor are gnd)
C Remarks: This card is used when grounding conditions are different for diff-
C    erent cables, or not all outer conductors are grounded.  Each column
C    represents a cable where the ordering is established by the card follows.
C
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C             |              |    |    |       |         |___BLANK for indep-
C             |              |    |    |       |             endent case study.
C             |              |    |    |       |___length of transmission
C             |              |    |    |              system: BLANK (usually),
C             |              |    |    |              required only in "SEMLYEN
C             |              |    |    |              SETUP".
C             |              |    |    |___number of points per decade for R, L
C             |              |    |           & C to be calculated for log freq.
C             |              |    |           scan BLANK for single frequency.
C             |              |    |___frequency span in number of decades, BLANK
C             |              |           for single frequency.
C             |              |___frequency used in calculation: 0 or BLANK (
C             |                     default power frequency), non-BLANK (freq
C             |                     used in single frequency calculation, or
C             |                     beginning frequency in log frequency scan
C             |                     IDEC <> BLANK).
C             |___resistivity of top layer of the earth (resistivity of the
C                    entire uniform earth in homogeneous case).
C Remarks: Units of rho in ohm-meters, frequency in hertz.
C
C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C        |         |         |         |___resistivity of layer 3 of the earth
C        |         |         |___resistivity of layer 2 of the earth
C        |         |___distance from the surface of the earth to where layer 2 &
C        |                3 meets
C        |___distance from the surface of the earth to where layer 1 & 2 meets
C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C        |         |         |         |         |         |___relative permit-
C        |         |         |         |         |             tivity of layer 3
C        |         |         |         |         |___relative permittivity of
C        |         |         |         |                layer 2
C        |         |         |         |___relative permittivity of layer 1
C        |         |         |___relative permeability of layer 3
```

```
C         |          |___relative permeability of layer 2
C         |___relative permeability of layer 1
C Remarks: All distances are in meters.  All rho's are in ohm-meters.  All mu's
C    & epsilon's are dimensionless.  Resistivity of layer 1 is specified in the
C    frequency card.  Remove these cards if homogeneous earth model is chosen.
C
C Repeat the frequency card and the complex earth model parameter card for
C    other frequencies of interest.  Remove these cards for single frequency
C    study.
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
C Remarks: EMTP interprets BLANK lines as BLANK cards.  Delete all blank lines
C    before running the data case.
```

```
C Template for CABLE CONSTANTS with crossbonding data input (Class A:
C SC coaxial cable, no pipe) Long form
BEGIN NEW DATA CASE
C Cable constants card------------------------------------><N<------------->
CABLE CONSTANTS
C                                                              |___select
C  transmission lines or cables: 0 (majority of the cables have 2 or less
C  conductors not including pipe), 1 (majority of the cables have 2 or more
C  conductors not including pipe)
C
C Accept crossbonding cable input
PUNCH
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C   |    |    |    |    |    |    |    |    |___grounding condition: 0 or 1 (
C   |    |    |    |    |    |    |    |          none of the cond is gnd),
C   |    |    |    |    |    |    |    |          2 (all armors are gnd), 3 (
C   |    |    |    |    |    |    |    |          all sheathes and armors are
C   |    |    |    |    |    |    |    |          gnd), 4 (see grounding card)
C   |    |    |    |    |    |    |    |___BLANK (unused)
C   |    |    |    |    |    |    |___shunt-admittance matrices output: 0 (print
C   |    |    |    |    |    |           [G] & [C]), 1 (print [G] & w[C]),
C   |    |    |    |    |    |           2 (print both)
C   |    |    |    |    |    |___series-impedance matrices output: 0 (print [R]
C   |    |    |    |    |           & [L]), 1 (print [R] & w[L]), 2 (print both)
C   |    |    |    |    |___modal quantities calculation: 0 (no calculation or
C   |    |    |    |           output), 1 (calculate and print)
C   |    |    |    |___earth model: 0 (homogeneous), 99 (3-layer stratified,
C   |    |    |           only for overhead systems, ISYST = 0 or 1)
C   |    |    |___number of SC coaxial cables which make up the system
C   |    |___input specification: -1 (underground), 0 (on earth surface),
C   |          1 (in the air)
C   |___input class: 2 (class A - SC coaxial, no pipe)
C
C                        X
C   N    N    I         m          C
C   P    c    R         a          n
C   A    r    s         j         Ra
C   I    o    e         o         Sm
C --S<---s<---p<--------r<--------Ge

C   |    |    |         |         ||___define a one letter node name for the
C   |    |    |         |         |       pi-circuit model.  BLANK (NPAIS = 0)
C   |    |    |         |         |___sheath grounding resistance at the end of
C   |    |    |         |                a major section of a cable.
C   |    |    |         |___length of a major section.  In discrete pi-circuit
C   |    |    |                modeling (NPAIS < 0), a major section corresponds
C   |    |    |                to 3 minor sections.  Each minor section forms a
C   |    |    |                6-phase pi-circuit. In uniform pi-circuit model-
C   |    |    |                ing (NPAIS > 0), one major section equals a 4-
C   |    |    |                phase pi-circuit.
C   |    |    |___sheath connections for discrete pi-circuit model: 0 or BLANK
C   |    |           (all sheaths are short-circuited and grounded through RSG
C   |    |           at the end of each major section), non-ZERO (each sheath
C   |    |           is grounded separately from each other through RSG at the
C   |    |           end of each major section).  BLANK (NPAIS >= 0).
C   |    |___cable selection: 0 or BLANK (non-crossbonded cable), non-ZERO (
C   |           crossbonded cable)
```

```
C  |__number of pi-sections in uniform and discrete pi-circuit models.  If
C         NPAIS = 0 or BLANK, no data card of a cable will be punched out.  If
C         NPAIS <> 0, then data cards of a cable will be punched out.  NPAIS >
C         0 refers to uniform pi-circuit modeling and NPAIS < 0 use discrete
C         pi-circuit modeling.  In both cases NPAIS = total length of a cable/Xmajor
C
C Input guidelines for different combinations of NPAIS and Ncros:
C   [1] NPAIS > 0 and Ncros = 0 or BLANK
C       Uniform pi-circuit modeling of a non-crossbonded cable.  This is a
C       cascaded pi-circuit model in which each major section is represented
C       by a 4-phase pi-circuit.  There is no grounding resistance and no con-
C       nection other than the cascade connection between two pi-sections.
C   [2] NPAIS > 0 and Ncros <> 0
C       Uniform pi-circuit modeling of a crossbonded cable.  One major section
C       of the cable corresponds to a 4-phase pi-circuit.  It has only one
C       sheath and there is grounding resistance.
C   [3] NPAIS < 0 and Ncros = 0 or BLANK
C       Discrete pi-circuit modeling of a non-crossbonded cable.  One major
C       section of the cable corresponds to a 6-phase pi-circuit.  There is a
C       grounding resistance RSG.  In most practical cases IRsep = 0, the
C       sheathes are short-circuited to ground.
C   [4] NPAIS < 0 and Ncros <> 0
C       Discrete pi-circuit modeling of a crossbonded cable.  One major sect-
C       tion consists of three pi-circuits.  One pi-circuit corresponds to
C       one minor section.  Within one major section, crossbonding of 3-phase
C       sheathes are carried out.
C   [5] NPAIS = Ncros = 0 or BLANK
C       This mode operates like the previous version of CABLE CONSTANTS without
C       crossbonding feature.
C   [6] NPAIS = 0 or BLANK and Ncros <> 0
C       Crossbonded cable with no data punch out.
C
C Summary to the crossbonding input:
C    NPAIS < 0, Ncros = 0 : needs IRsep, Xmajor, RSG, Cname.
C    NPAIS < 0, Ncros <> 0: needs IRsep, Xmajor, RSG, Cname.
C    NPAIS = 0, Ncros = 0 : leave blank.
C    NPAIS = 0, Ncros <> 0: needs Xmajor.
C    NPAIS > 0, Ncros = 0 : needs Xmajor, Cname.
C    NPAIS > 0, Ncros <> 0: needs Xmajor, RSG, Cname.
C
C Remarks: For case 2, 3 & 4, parallel resistances should be added to the output
C    data of the punch file for the RSG at the sending and receiving-ends.
C    Units for length is in meters, resistance in ohms.  RSG is usually 1 to 10 ohms.
C
C Number of conducting layers in each SC cable   N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C   |__number of conducting layers in the kth cable: 1 (one conductor: core
C         only), 2 (two conductors: core and sheath), 3 (three conductors: core
C         sheath & armor)
C IMPORTANT: NCPPk MUST be non-increasing, so ALL 3-conductor cables MUST
C    precede 2-conductor cables and ALL 2-conductor cables MUST precede core
C    only cables.  This ordering, once established, is applied throughout the
C    rest of the data case.
C Remark: If NPC > 16, insert a new data card with the same format.
C
C Geometrical and physical data for EACH SC cable
C -------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C        |         |         |         |         |         |         |__outer
```

```
C        |         |         |         |         |         |    radius of 3rd
C        |         |         |         |         |         |    insulation layer
C        |         |         |         |         |         |___outer radius of
C        |         |         |         |         |                armor
C        |         |         |         |         |___inner radius of armor
C        |         |         |         |___outer radius of sheath
C        |         |         |___inner radius of sheath
C        |         |___outer radius of tubular core
C        |___inner radius of tubular core
C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C        |         |         |         |         |         |         |         |
C        |         |         |         |         |         |         |relative
C        |         |         |         |         |         |         |permittiv-
C        |         |         |         |         |         |         |ity of 2nd
C        |         |         |         |         |         |         |insulation
C        |         |         |         |         |         |         |layer
C        |         |         |         |         |         |         |___relat-
C        |         |         |         |         |         |ive permeability of
C        |         |         |         |         |         |2nd insulation layer
C        |         |         |         |         |         |___relative
C        |         |         |         |         |                permeability
C        |         |         |         |         |                of  sheath
C        |         |         |         |         |___resistivity of sheath
C        |         |         |         |___relative permittivity of 1st
C        |         |         |                insulation layer
C        |         |         |___relative permeability of 1st insulation layer
C        |         |___relative permeability of core
C        |___resistivity of core
C ----rhoA<------muA<-----muI3<epsilonI3

C        |         |         |         |___relative permittivity of 3rd
C        |         |         |                insulation layer
C        |         |         |___relative permeability of 3rd insulation layer
C        |         |___relative permeability of armor
C        |___resistivity of armor
C
C Repeat the following card for 2nd, 3rd, ... cable.
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C Remarks: These cards must be stacked in the order established by the cards
C    that define NCPPk.  All rho's are in ohm-meters.  All mu's & epsilon's a
C    All radii are in meters.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C        |         |___horizk is the distance from the center of the kth cable
C        |                  to an arbitrary reference line located to the left of
C        |                  the cable
C        |___vertk is the vertical distance from the center of the kth cable to
C                the earth surface.  This number is always positive.
C Remarks: All units are in meters.  Repeat this card if there are more than 4
C    cables.  Ordering of the cable is established in the cards define NCPPk.
C
C Grounding conditions
C 123456789...

C |___cable grounding code: 0 (none of the conductors in the cable is gnd),
C        1 (core is gnd), 2 (sheath is gnd), 3 (armor is gnd), 4 (sheath & armor
```

```
C       are gnd), 5 (core & sheath are gnd), 6 (core & armor are gnd), 7 (core,
C       sheath & armor are gnd)
C Remarks: This card is used when grounding conditions are different for diff-
C    erent cables, or not all outer conductors are grounded.  Each column
C    represents one cable.  The numbering is established by the following data.
C
C Frequency card
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C             |              |    |    |       |         |__BLANK for indep-
C             |              |    |    |       |            endent data case
C             |              |    |    |       |__length of transmission
C             |              |    |    |              system: BLANK (usually),
C             |              |    |    |              required only in "SEMLYEN
C             |              |    |    |              SETUP".
C             |              |    |    |__number of points per decade for R, L
C             |              |    |         & C to be calculated for log freq
C             |              |    |           scan BLANK for single frequency.
C             |              |    |__frequency span in number of decades, BLANK
C             |              |           for single frequency.
C             |              |__frequency used in calculation: 0 or BLANK (
C             |                     default power frequency), non-BLANK (freq
C             |                     used in single frequency calculation, or
C             |                     beginning frequency in log frequency scan
C             |                     IDEC <> BLANK)
C             |__resistivity of top layer of the earth (resistivity of the
C                  entire uniform earth in homogeneous case).
C Remarks: Units of rho in ohm-meters, frequency in hertz.
C
C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---DEP12<----DEP23<-----rho2<-----rho3

C        |         |         |         |__resistivity of layer 3 of the earth
C        |         |         |__resistivity of layer 2 of the earth
C        |         |__distance from the surface of the earth to where layer 2 &
C        |                 3 meets
C        |__distance from the surface of the earth to where layer 1 & 2 meets
C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

C        |         |         |         |         |         |__relative permit-
C        |         |         |         |         |            tivity of layer 3
C        |         |         |         |         |__relative permittivity of
C        |         |         |         |               layer 2
C        |         |         |         |__relative permittivity of layer 1
C        |         |         |__relative permeability of layer 3
C        |         |__relative permeability of layer 2
C        |__relative permeability of layer 1
C Remarks: All distances are in meters.  All rho's are in ohm-meters.  All mu's
C    & epsilon's are dimensionless.  Resistivity of layer 1 is specified in the
C    frequency card.  Remove these cards if homogeneous earth model is chosen.
C
C Repeat the frequency card and the complex earth model parameter cards for
C    other frequencies of interest.  Remove these cards for single frequency study.
C ----------rho<----------freq<IDEC<IPNT<---DIST<-----IPUN

C ---DEP12<----DEP23<-----rho2<-----rho3

C -----mu1<------mu2<------mu3<-epsilon1<-epsilon2<-epsilon3

BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS study
BLANK card terminates EMTP solution-mode
C Remarks: EMTP interprets BLANK lines as BLANK cards.  Delete all blank lines
C   before running the data case.
```

```
C Template for LINE CONSTANTS input
BEGIN NEW DATA CASE
LINE CONSTANTS
C Branch cards
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C ___Used only when IPun = 44, remove it otherwise.  The odd number buses are
C    nodes at the sending ends of a branch.  The even number buses are those at
C    the receiving ends.  Each pair of buses represents the nodes of a phase
C    (i.e Bus1, Bus2 belongs to phase 1, Bus3, Bus4 belongs to phase 2 and etc).
C    If there are more than 6 phases, repeat this branch card.
C
C Select system of units
METRIC
ENGLISH
C ___Select either metric or English system of units and remove the unwanted
C    line.
C
C Conductor cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h  S         e T       e       D       o       o       V       e     l     N B
C a  k         s y       a       i       r       w       M       p     p     a u
C s  i         i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

C |    |       | |       |       |       |       |       |       |     |     | |
C |    |       | |       |       |       |       |       |       |     | ref.| 4
C |    |       | |       |       |       |       |       |       |     |ref. 3
C |    |       | |       |       |       |       |       |       |     |__ref. 2
C |    |       | |       |       |       |       |       |       |___ref. 1
C |    |       | |       |       |       |       |       |___vertical height of
C |    |       | |       |       |       |       |           the center of the
C |    |       | |       |       |       |       |           conductor or bundle
C |    |       | |       |       |       |       |           above the ground at
C |    |       | |       |       |       |       |           mid-span.
C |    |       | |       |       |       |       |___vertical height of the
C |    |       | |       |       |       |           center of the conductor or
C |    |       | |       |       |       |           bundle above the ground at
C |    |       | |       |       |       |           the towers.
C |    |       | |       |       |       |___horizontal separation of the center
C |    |       | |       |       |           of the conductor or bundle from the
C |    |       | |       |       |           reference line.  See remarks.
C |    |       | |       |       |___outside diameter of the tubular conductor.
C |    |       | |       |___see IXType.
C |    |       | |___alternative self-inductance calculations: 0 (React =
C |    |       |       reactance for unit spacing (1 meter or 1 foot) assumed to
C |    |       |       be valid for all frequencies appears in the freq cards),
C |    |       |       1 (React = reactance for unit spacing at 60 Hz.  At
C |    |       |       other frequencies, reactances are scaled proportionally),
C |    |       |       2 (React = GMR of the conductor), 3 ( React = GMR/r of
C |    |       |       the conductor, where r is the outer radius of the con-
C |    |       |       ductor.  GMR/r = 0.7788 for solid conductors), 4 (Used
C |    |       |       normally.  React = relative permeability of the conduct-
C |    |       |       or.  Default is 1.0.  Internal inductance is corrected
C |    |       |       for skin effect), IXType >= 6 (IXType equals to the total
C |    |       |       number of outer strands.  React = relative permeativity
C |    |       |       of outer strands.  Default is 1.0.  Skin = -1.0).
C |    |       |___dc resistance of the conductor.  If Skin = 0.0, specify ac
C |    |             resistance.  In this case, internal inductance is not
C |    |             corrected for skin effect when IXType = 4.  If Skin = -1.0,
C |    |             specify per unit length resistance of one outer strand.
C |    |___skin effect correction: T/D ratio (0.5 for a solid conductor), 0.0 or
C |          BLANK (bypass skin effect correction), -1.0 (use Galloway's formula
```

```
C |           with stranded conductors).  See remarks.
C |___conductor phase number: 0 (ground wire), 1,2,... (the phase number to
C       which the conductor or bundle belongs.  Numbering must be consecutive
C       without missing numbers.  If there are more than one conductor carry
C       the same phase number, all those that have the same phase number are
C       consider as a bundle), -1,-2,... (branch to be ignored).
C
C <ref. 1> separation between two adjacent conductors in a bundle.  BLANK for
C             single conductor.
C <ref. 2> angular position of the first, or any, conductor of the bundle.  The
C             angle is measured counter clockwise from the x-axis to the first,
C             or any, conductor in the bundle.  BLANK for single conductor.
C <ref. 3> conductor name for change case option, normally BLANK.  Used only
C             when this branch is referenced by a case immediately follows the
C             current case study using the CHANGE case feature within the LINE
C             CONSTANTS routine.  The conductor names in both cases must be
C             identical.  Those names that are not referenced do not have to
C             be unique.
C <ref. 4>    number of conductors which make up the bundle.  BLANK for single
C             conductor.
C
C Repeat the conductor card for each conductor or bundle.
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

C Remarks: 1. Units for resistance and reactance are in ohms/km or ohms/mile.
C              Diameter, separation of conductors within a bundle and geometric
C              mean radius (GMR) are in centimeters or inches.  Horizontal
C              location of the conductor or bundle and height are in meters or feet.
C           2. The values of the first 6 variables are based on a single
C              conductor, no matter the card is used for a conductor or a bundle.
C           3. If any of the first 6 variables on the conductor card is left
C              BLANK, the variables will be assumed to carry the same values as
C              it is on the previous card (0 <> BLANK for these input).
C           4. T/D ratio stands for (thickness of tubular conductor) / (outside
C              diameter of tubular conductor).
C           5. To enter average height instead of tower height and mid-span
C              height, leave either of the VTower or VMid BLANK and set the
C              other one to the average height.  This is the same as setting
C              both heights to the same value.
C           6. A regular bundle is defined as a bundle consists of identical
C              conductors which are uniformly spaced on the circumference of a
C              circle.
C           7. Location of the reference line is arbitrary, distances to the
C              right if it are positive.
C           8. The ordering of the conductors is arbitrary.
BLANK card terminates conductor cards
C
C Frequency Cards                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C      |         |         |      |      | |       |    |||  |  |  | | |__ref. 8
C      |         |         |      |      | |       |    |||  |  |  | |___ref. 7
C      |         |         |      |      | |       |    |||  |  |  |___ref. 6
C      |         |         |      |      | |       |    |||  |  |___ref. 5
C      |         |         |      |      | |       |    |||  |___# of decades
```

```
C      |         |         |      |      | |       |    ||| to be spanned in
C      |         |         |      |      | |       |    ||| log freq scan. BLANK
C      |         |         |      |      | |       |    ||| for single freq.
C      |         |         |      |      | |       |    |||__existence of a
C      |         |         |      |      | |       |    || communication circuit
C      |         |         |      |      | |       |    || parallel to the power
C      |         |         |      |      | |       |    || circuit: 1 (exists,
C      |         |         |      |      | |       |    || number the commun-
C      |         |         |      |      | |       |    || ication line as cond-
C      |         |         |      |      | |       |    || uctor 4), 0 (other-
C      |         |         |      |      | |       |    || wise).
C      |         |         |      |      | |       |    ||___treatment of ground
C      |         |         |      |      | |       |    | wire (if any): 0 (
C      |         |         |      |      | |       |    | continuous, normally),
C      |         |         |      |      | |       |    | 1, (segmented).  See
C      |         |         |      |      | |       |    | remarks.
C      |         |         |      |      | |       |    |__equivalent-pi
C      |         |         |      |      | |       | matrices of a long line: 1
C      |         |         |      |      | |       | (print corresponding matrix
C      |         |         |      |      | |       | ), 0 or BLANK (otherwise).
C      |         |         |      |      | |       | The columns correspond to
C      |         |         |      |      | |       | Y, Ys, Z, Zs.  See remarks.
C      |         |         |      |      | |       |___line length for the
C      |         |         |      |      | | development of pi-equivalent
C      |         |         |      |      | | circuits using long line formula.
C      |         |         |      |      | | See IPiPr.
C      |         |         |      |      | |___capacitance/susceptance select-
C      |         |         |      |      |       ion for ICPr: 0 (susceptance),
C      |         |         |      |      |       1 (capacitance).
C      |         |         |      |      |___series impedance matrices output:
C      |         |         |      |            1 (print corresponding matrix),
C      |         |         |      |            0 or BLANK (otherwise).  The
C      |         |         |      |            columns of IZPr correspond to
C      |         |         |      |            {Z, Ze, Zs, 1/Z, 1/Ze, 1/Zs}.
C      |         |         |      |            See remarks.
C      |         |         |      |___capacitance/susceptance matrices output:
C      |         |         |            1 (print corresponding matrix), 0 or
C      |         |         |            BLANK (otherwise).  The columns of ICPr
C      |         |         |            correspond to {1/C, 1/Ce, 1/Cs, C, Ce,
C      |         |         |            Cs} or {1/wC, 1/wCe, 1/wCs, wC, wCe,
C      |         |         |            wCs}.  Selection is controlled by ICap.
C      |         |         |            See remarks.
C      |         |         |___earth return correction: 1 in column 28 or BLANK
C      |         |               (used normally, give full precision), 0 (no
C      |         |               correction term added, amounts to zero earth
C      |         |               resistivity, Resis = 0), FCar >= 1.0 (add as
C      |         |               many correction terms as specified by FCar
C      |         |               rounded to the nearest integer, but not more
C      |         |               than 31 if a <= 5.  For a > 5, use finite
C      |         |               series), FCar < 1.0 (add as many correction
C      |         |               terms as necessary to get two successive cor-
C      |         |               rection terms smaller in magnitude than FCar
C      |         |               if a <= 5.  For a > 5, use finite series).
C      |         |             Note: the precision and correction terms refer
C      |         |             to that of the Carson's earth return formula
C      |         |             for impedance.
C      |         |___frequency used in single frequency calculation or beginning
C      |               frequency of log frequency scan, IDec > 0.
C      |___resisitivity of the homogeneous Carson earth.
C
C <ref. 5>  number of points per decade at which line constants are to be
C             calculated in log frequency scan.  BLANK for single frequency.
C <ref. 6>  punch output for pi-circuit representation: 44 (automatic punching,
C             requires the BRANCH card input), 0 or BLANK (usually).
```

```
C <ref. 7>  transposition: 0 or BLANK (continuously transposed), 1 (untrans-
C             posed, modal parameters and transformation matrix will be cal-
C             culate and punched as branch data).
C <ref. 8>  full complex or real modal transformation matrix:  -2, 0, BLANK (
C             output only the real part of the modal transformation matrix
C             calculated for untransposed line.  Use this in general), 9 (output
C             full complex transformation matrix).
C
C Repeat the frequency card for other frequencies of interest.
C                                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C Remarks: 9.  Units of rho is in ohm-meters, frequency in hertz, distances in
C              kilometers or miles.
C          10. 1/C, 1/Z, 1/wC, ... etc are symbols for inverse of C, Z, wC, ...
C              matrices correspondingly.
C          11. The subscripts of the C and Z matrices in ICPr and IZPr have the
C              following meanings:
C                No subscript - Represents an unreduced system (every physical
C                               conductor and ground wire has a row and a
C                               column in the matrix).
C                "e"          - Corresponds to the equivalent phase conductors
C                               (Conductors are bundled and ground wires are
C                               removed).
C                "s"          - Corresponds to symmetrical components of the
C                               equivalent phase conductors.  Three phase
C                               circuits are assumed.  The first three phases
C                               make up the first circuit, second three phases
C                               make up a second circuit and etc.  The remaining
C                               phases which do not make up a circuit are
C                               ignored.
C          12. The admittance and impedance matrices in IPiPr are the shunt
C              admittance (impedance) matrix and transfer admittance (impedance)
C              matrix of the equivalent multiphase pi-circuit for untransposed
C              line.
C          13. Since segmented ground wire cannot carry current of wave length
C              much larger than the length of a segment interval.  Series
C              impedance matrices are computed by ignoring the ground wire.
C              But shunt admittance matrices are calculated by taking the ground
C              wire into account.  This approach may not be valid for higher
C              frequencies.
BLANK card terminates frequency cards
C
C Change Case Card
CHANGE
C ___Change case permits the access of the conductor data cards of the case
C    preceding this one.  If this option is not used, remove all data cards
C    before the BLANK cards that terminates LINE CONSTANTS. The following rules
C    have to be observed:
C      1. Conductor cards do not need to be in order.
C      2. The three options available are:
C           a. Addition - A complete conductor card with the Name different
C                         form those in the previous case study.
C           b. Deletion - A conductor card with an identical Name in the
C                         previous case study and a phase number < 0.
C           c. Change   - A conductor card with an identical Name in the
C                         previous case study.  Changes are allowed in the
C                         first 6 fields.  Changing other fields requires
C                         deletion and addition.  Of the first 6 fields, only
C                         those are punched will be changed.  Leaving BLANK
```

```
C                         a field will keep the variable unchanged.  Multiple
C                         cards operate on the same conductor card is allowed.
C      3. These definitions will override those of the conductor cards.
C Repeat the conductor card for the conductors or bundles need changes.
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

BLANK card terminates CHANGE data case
C Repeat the frequency card for the frequencies of interest.
C                                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C ------o<---------q<---------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

BLANK card terminates frequency card
BLANK card terminates LINE CONSTANTS study
BLANK terminates EMTP solution-mode
```

```
C Template for Frequency Dependent Cable (no pipe) using MARTI model
BEGIN NEW DATA CASE
JMARTI SETUP
C
C Branch Cards (Optional)
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C ___The odd number buses are nodes at the sending ends of a branch.  The
C    even number buses are those at the receiving ends.  Each pair of buses
C    represents the nodes of a phase (i.e Bus1, Bus2 belongs to phase 1, Bus3,
C    Bus4 belongs to phase 2 and etc).  If there are more than 6 phases, repeat
C    this branch card.
C
C Transfer Control to CABLE CONSTANTS Routine
C Cable constants card--------------------------------------><N<--------------->
CABLE CONSTANTS
C
C Miscellaneous data card
C   I              I         I    I
C   t    I         e    K    Z    Y         N
C   y    s         a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C
C Number of conducting layers in each SC cable   N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----RhoC<------MuC<-----MuI1<EpsilonI1<-----RhoS<------MuS<-----MuI2<EpsilonI2

C ----RhoA<------MuA<-----MuI3<EpsilonI3

C Repeat the three cards above for 2nd, 3rd cables ... etc.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---Vert1<---Horiz1<----Vert2<---Horiz2<----Vert3<---Horiz3<----Vert4<---Horiz4

C Grounding conditions
C 123456789...

C Frequency cards.
C   Either supply the following three data cards or the alternative frequency
C   data cards.  The three frequency cards required are:
C     1. Frequency at which the modal transformation matrix is calculated.
C        Default is 5000 Hz.
C     2. Steady state power frequency.
C     3. Logarithmic looping frequency, usually covers 8 or 9 decades beginning
C        from 0.01 Hz with 10 points per decade.
C If the Nakagawa earth model is begin used, each frequency card must be
C followed by the two cards specify the earth model.
C ----------Rho<----------Freq<IDec<IPnt<---Dist<-----IPun

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---Dep12<----Dep23<-----rho2<-----rho3
```

```
C -----Mu1<------Mu2<------Mu3<-Epsilon1<-Epsilon2<-Epsilon3

C Alternative frequency data cards
C ---KPh<-IModal<-MetriK<---Dist

C       |       |       |       |__ line length.
C       |       |       |__ system of measure: 0 (English), 1 (metric).
C       |       |__ transposition: 0 (transposed), KPh (untransposed).
C       |___ KPh: # of phases (or modes).
C
C ----------FMin<----------FMax<----------Root

C               |               |               |___ const. ratio between freq.
C               |               |                    Root = 10**(1/NPoint) where
C               |               |                    NPoint is the number of
C               |               |                    points per decade.
C               |               |___ maximum freq: FMax = FMin * 10**NDec, where
C               |                    NDec is the number of decades spanned.
C               |___ starting freq. for the loop over geometrically spaced freq.
C
C Include the following card if IModal > 0.
C ---------Omega<---------------G<--------------B<--------------R<--------------X

C               |               |               |               |               |
C               |               |               |               |   modal series
C               |               |               |               |   reactance.
C               |               |               |               |__ modal series
C               |               |               |                   resistance.
C               |               |               |__ modal susceptance.
C               |               |__ modal shunt conductance.
C               |__ angular frequency.
C
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)

C Note: This card specifies the current transformation matrix [Ti].  The
C       elements are complex, so each entry has two rows.  A row of real parts
C       precedes a row of imaginary values. This is a KPhxKPh matrix.
C
C Repeat the last two cards for each frequency point.
C
C Remarks: Units of length is kilometers; conductance, susceptance in mho per
C          unit length; resistance, reactance in ohm per unit length; angular
C          frequency in rad/sec.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS
C
C Fitting parameters:
C   DEFAULT   - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C               data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

C       |       |       |       |       |       |       |       |       |      |
C       |       |       |       |       |       |       |       |       | Ref. 1
C       |       |       |       |       |       |       |       |  punch output:
C       |       |       |       |       |       |       |       |   0 (punch),
C       |       |       |       |       |       |       |       |   1 (no punch).
C       |       |       |       |       |       |       |       |__ Diagnostic
C       |       |       |       |       |       |       |         output: 0 - 4,
C       |       |       |       |       |       |       |         default is 0.
C       |       |       |       |       |       |       |___ printer plot compare
C       |       |       |       |       |       |         input data function and
C       |       |       |       |       |       |         approx: 1 (plot), -1
```

```
C       |       |       |       |       |       |         (no plot).
C       |       |       |       |       |       |__ table compares magnitude and
C       |       |       |       |       |         phase angle of input data
C       |       |       |       |       |         function and approx: 0 (no
C       |       |       |       |       |         table), 1 (print table).
C       |       |       |       |       |___ CABLE CONSTANTS output: 0 (no
C       |       |       |       |         output), 1 (print output).
C       |       |       |       |__ maximum order (# of poles) of the rational
C       |       |       |         function approx. of the line functions Zc and
C       |       |       |         A1 for all modes: 0 - 30, default is 25.  A
C       |       |       |         larger number will produce a higher order fit.
C       |       |       |__ upper frequency range.
C       |       |__ lower frequency range.  FErr1 and FErr2 limit the frequency
C       |         range for error checking in the internal optimization loop.
C       |         Default is (1.0 - 1.0E5) Hz.
C       |__ conductors conductance to ground.  Overrides the value of GPhase in
C         CABLE CONSTANTS if <> 0.  Important in trapped charge decay.  Default
C         is (0.32E-9mhos/mile or 0.2E-9 mhos/km).  Units of length should be
C         the same as CABLE CONSTANTS data.
C
C Ref. <1> Punched output control: 0 - 2, default is 1.  Addition data is
C          outputted as "SKIP" on the branch card.
C
BLANK card terminates JMARTI SETUP
BLANK card terminates solution-mode
```

```
C Template for Frequency Dependent cross-bonded Cable using MARTI model
C with embedded CABLE CONSTANTS routine.
BEGIN NEW DATA CASE
JMARTI SETUP
C Branch Cards (Optional)
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C ___The odd number buses are nodes at the sending ends of a branch.  The
C    even number buses are those at the receiving ends.  Each pair of buses
C    represents the nodes of a phase (i.e Bus1, Bus2 belongs to phase 1, Bus3,
C    Bus4 belongs to phase 2 and etc).  If there are more than 6 phases, repeat
C    this branch card.
C
C Transfer Control to CABLE CONSTANTS Routine
C Cable constants card--------------------------------------><N<--------------->
CABLE CONSTANTS
PUNCH
C Miscellaneous data card
C   I         I         I    I
C   t    I    e    K    Z    Y         N
C   y    s    a    m    f    f         g
C   p    y    N    r    o    l    l    N    r
C   e    s    P    t    d    a    a    p    n
C --C<---t<---C<---h<---e<---g<---g<---p<---d
    2
C                       X
C   N    N    I         m          C
C   P    c    R         a          n
C   A    r    s         j         Ra
C   I    o    e         o         Sm
C --S<---s<---p<---------r<---------Ge

C
C Number of conducting layers for each SC cable  N    N    N    N    N    N    N
C   N    N    N    N    N    N    N    N    N    C    C    C    C    C    C    C
C   C    C    C    C    C    C    C    C    C    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    P    P    P    P    P    P    P
C   P    P    P    P    P    P    P    P    P    1    1    1    1    1    1    1
C --1<---2<---3<---4<---5<---6<---7<---8<---9<---0<---1<---2<---3<---4<---5<---6

C
C Geometrical and physical data for EACH SC cable
C ------R1<-------R2<-------R3<-------R4<-------R5<-------R6<-------R7

C ----rhoC<------muC<-----muI1<epsilonI1<-----rhoS<------muS<-----muI2<epsilonI2

C ----rhoA<------muA<-----muI3<epsilonI3

C
C Repeat this card for 2nd, 3rd, ... cable.
C
C Horizontal and vertical coordinates of the center of each SC cable
C ---vert1<---horiz1<----vert2<---horiz2<----vert3<---horiz3<----vert4<---horiz4

C
C Grounding conditions
C 123456789...

C Frequency cards.
C   Either supply the following three data cards or the alternative frequency
C   data cards.  The three frequency cards required are:
C     1. Frequency at which the modal transformation matrix is calculated.
C        Default is 5000 Hz.
C     2. Steady state power frequency.
```

```
C     3. Logarithmic looping frequency, usually covers 8 or 9 decades beginning
C        from 0.01 Hz with 10 points per decade.
C If the Nakagawa earth model is begin used, each frequency card must be
C followed by the two cards specify the earth model.
C ----------Rho<----------Freq<IDec<IPnt<---Dist<-----IPun

C Parameters for 3-layer stratified (Nakagawa) earth model for overhead cable
C ---Dep12<----Dep23<-----rho2<-----rho3

C -----Mu1<------Mu2<------Mu3<-Epsilon1<-Epsilon2<-Epsilon3

C Alternative frequency data cards
C ---KPh<-IModal<-MetriK<---Dist

C       |       |       |       |__ line length.
C       |       |       |__ system of measure: 0 (English), 1 (metric).
C       |       |__ transposition: 0 (transposed), KPh (untransposed).
C       |__ KPh: # of phases (or modes).
C
C ----------FMin<-----------FMax<-----------Root

C               |               |               |__ const. ratio between freq.
C               |               |                   Root = 10**(1/NPoint) where
C               |               |                   NPoint is the number of
C               |               |                   points per decade.
C               |               |__ maximum freq: FMax = FMin * 10**NDec, where
C               |                   NDec is the number of decades spanned.
C               |__ starting freq. for the loop over geometrically spaced freq.
C
C Include the following card if IModal > 0.
C ---------Omega<--------------G<--------------B<--------------R<--------------X

C               |               |               |               |               |
C               |               |               |               |    modal series
C               |               |               |               |    reactance.
C               |               |               |               |__ modal series
C               |               |               |                   resistance.
C               |               |               |__ modal susceptance.
C               |               |__ modal shunt conductance.
C               |__ angular frequency.
C
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)

C Note: This card specifies the current transformation matrix [Ti].  The
C       elements are complex, so each entry has two rows.  A row of real parts
C       precedes a row of imaginary values. This is a KPhxKPh matrix.
C
C Repeat the last two cards for each frequency point.
C
C Remarks: Units of length is kilometers; conductance, susceptance in mho per
C          unit length; resistance, reactance in ohm per unit length; angular
C          frequency in rad/sec.
BLANK card terminates conductor data case
BLANK card terminates CABLE CONSTANTS
C
C Fitting parameters:
C   DEFAULT   - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C               data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

C       |       |       |       |       |       |       |       |       |       |
C       |       |       |       |       |       |       |       |       |  Ref. 1
```

```
C       |       |       |       |       |       |       |       |   punch output:
C       |       |       |       |       |       |       |       |    0 (punch),
C       |       |       |       |       |       |       |       |    1 (no punch).
C       |       |       |       |       |       |       |       |__ Diagnostic
C       |       |       |       |       |       |       |         output: 0 - 4,
C       |       |       |       |       |       |       |         default is 0.
C       |       |       |       |       |       |       |___ printer plot compare
C       |       |       |       |       |       |         input data function and
C       |       |       |       |       |       |         approx: 1 (plot), -1
C       |       |       |       |       |       |         (no plot).
C       |       |       |       |       |       |__ table compares magnitude and
C       |       |       |       |       |         phase angle of input data
C       |       |       |       |       |         function and approx: 0 (no
C       |       |       |       |       |         table), 1 (print table).
C       |       |       |       |       |___ CABLE CONSTANTS output: 0 (no
C       |       |       |       |         output), 1 (print output).
C       |       |       |       |__ maximum order (# of poles) of the rational
C       |       |       |         function approx. of the line functions Zc and
C       |       |       |         A1 for all modes: 0 - 30, default is 25.  A
C       |       |       |         larger number will produce a higher order fit.
C       |       |       |__ upper frequency range.
C       |       |__ lower frequency range.  FErr1 and FErr2 limit the frequency
C       |         range for error checking in the internal optimization loop.
C       |         Default is (1.0 - 1.0E5) Hz.
C       |__ conductors conductance to ground.  Overrides the value of GPhase in
C         CABLE CONSTANTS if <> 0.  Important in trapped charge decay.  Default
C         is (0.32E-9mhos/mile or 0.2E-9 mhos/km).  Units of length should be
C         the same as CABLE CONSTANTS data.
C
C Ref. <1> Punched output control: 0 - 2, default is 1.  Addition data is
C          outputted as "SKIP" on the branch card.
C
BLANK card terminates JMARTI SETUP
BLANK card terminates EMTP solution-mode
```

```
C Frequency Dependent Line using MARTI model and LINE CONSTANTS
BEGIN NEW DATA CASE
JMARTI SETUP
C Branch Cards (Optional)
C ----->Bus1->Bus2->Bus3->Bus4->Bus5->Bus6->Bus7->Bus8->Bus9->Bus10>Bus11>Bus12>
BRANCH
C ___The odd number buses are nodes at the sending ends of a branch.  The
C    even number buses are those at the receiving ends.  Each pair of buses
C    represents the nodes of a phase (i.e Bus1, Bus2 belongs to phase 1, Bus3,
C    Bus4 belongs to phase 2 and etc).  If there are more than 6 phases, repeat
C    this branch card.
C
C Transfer Control to LINE CONSTANTS Routine
LINE CONSTANTS
C Select System of Units (Optional)
METRIC
ENGLISH
C ___Select either metric or English system of units and remove the unwanted
C    line.  Default uses English units.
C
C Conductor Cards
C I              I                               V
C P            R X       R               H       T               S     A       N
C h    S       e T       e       D       o       o       V       e     l     N B
C a    k       s y       a       i       r       w       M       p     p     a u
C s    i       i p       c       a       i       e       i       a     h     m n
C e<---n<------s<e<------t<------m<------z<------r<------d<------r<----a<----e<d

C Repeat conductor card for each conductor (or bundle).
BLANK card terminates conductor (or change case) cards
C
C Frequency Cards.
C   Either supply the frequency cards for Transposed and Untransposed Lines or
C   use the alternative frequency cards.
C     Transposed   - Requires 2 frequency cards:
C                      1. Steady state power frequency.
C                      2. Logarithmic looping frequency, usually covers 8 or 9
C                         decades beginning from 0.01 Hz with 10 points per
C                         decade.
C     Untransposed - Requires 3 frequency cards:
C                      1. Frequency at which the modal transformation matrix is
C                         calculated.  Default is 5000 Hz.
C                      2. Steady state power frequency.
C                      3. Logarithmic looping frequency, same as transposed line.
C                                                         M            I
C                                                       I u          M T
C                F         F      I      I I       D    PIt  I  I  I o r
C      R         r         C      C      Z C       i    iSu  D  P  P d n
C      h         e         a      P      P a       s    Pea  e  n  u a s
C -----o<--------q<--------r <----r <----r p<------t <--rgl<-c<-t<-n<l<f

C Alternative frequency cards.
C ---KPh<-IModal<-MetriK<---Dist

C      |       |       |       |__ line length.
C      |       |       |__ system of measure: 0 (English), 1 (metric).
C      |       |__ transposition: 0 (transposed), KPh (untransposed).
C      |___ KPh: # of phases (or modes).
C
C ----------FMin<-----------FMax<-----------Root

C             |               |               |___ const. ratio between freq.
C             |               |                    Root = 10**(1/NPoint) where
C             |               |                    NPoint is the number of
```

```
C              |                |                   points per decade.
C              |                |___ maximum freq: FMax = FMin * 10**NDec, where
C              |                     NDec is the number of decades spanned.
C              |___ starting freq. for the loop over geometrically spaced freq.
C
C Include the following cards if IModal > 0.
C --------Omega<----------------G<-------------B<--------------R<---------------X

C              |                |              |               |                |
C              |                |              |               |    modal series
C              |                |              |               |     reactance.
C              |                |              |               |__ modal series
C              |                |              |                   resistance.
C              |                |              |__ modal susceptance.
C              |                |__ modal shunt conductance.
C              |__ angular frequency.
C
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)<----Ti(x,5)<----Ti(x,6)

C Note: This card specifies the current transformation matrix [Ti].  The
C       elements are complex, so each entry has two rows.  A row of real parts
C       precedes a row of imaginary values. This is a KPhxKPh matrix.
C Remarks: Units of length is kilometers; conductance, susceptance in mho per
C          unit length; resistance, reactance in ohm per unit length; angular
C          frequency in rad/sec.
C Repeat the last two cards for each frequency point.
BLANK card terminates frequency cards
BLANK card terminates LINE CONSTANTS study
C
C Fitting parameters:
C   DEFAULT     - Use default JMARTI SETUP parameters.  Remove the miscellaneous
C                 data card that follows.
C   Otherwise - User supplied parameters.  Remove the DEFAULT card.
DEFAULT
C -GMode<--FErr1<--FErr2<-NorMax<-IFData<--IFWTA<-IFPlot<-IDebug<-IPunch<-KoutPr

C      |       |       |       |       |       |       |       |       |       |
C      |       |       |       |       |       |       |       |       |   Ref. 1
C      |       |       |       |       |       |       |       |   punch output:
C      |       |       |       |       |       |       |       |     0 (punch),
C      |       |       |       |       |       |       |       |     1 (no punch).
C      |       |       |       |       |       |       |       |__ Diagnostic
C      |       |       |       |       |       |       |         output: 0 - 4,
C      |       |       |       |       |       |       |         default is 0.
C      |       |       |       |       |       |       |___ printer plot compare
C      |       |       |       |       |       |         input data function and
C      |       |       |       |       |       |         approx: 1 (plot), -1
C      |       |       |       |       |       |         (no plot).
C      |       |       |       |       |       |__ table compares magnitude and
C      |       |       |       |       |         phase angle of input data
C      |       |       |       |       |         function and approx: 0 (no
C      |       |       |       |       |         table), 1 (print table).
C      |       |       |       |       |___ LINE CONSTANTS output: 0 (no output)
C      |       |       |       |         1 (print output).
C      |       |       |       |__ maximum order (# of poles) of the rational
C      |       |       |         function approx. of the line functions Zc and
C      |       |       |         A1 for all modes: 0 - 30, default is 25.  A
C      |       |       |         larger number will produce a higher order fit.
C      |       |       |__ upper frequency range.
C      |       |__ lower frequency range.  FErr1 and FErr2 limit the frequency
C      |         range for error checking in the internal optimization loop.
C      |         Default is (1.0 - 1.0E5) Hz.
C      |__ conductors conductance to ground.  Overrides the value of GPhase in
C        LINE CONSTANTS if <> 0.  Important in trapped charge decay.  Default
```

```
C        is (0.32E-9mhos/mile or 0.2E-9 mhos/km).  Units of length should be
C        the same as LINE CONSTANTS data.
C
C Ref. <1> Punched output control: 0 - 2, default is 1.  Addition data is
C          outputted as "SKIP" on the branch card.
C
BLANK card terminates JMARTI SETUP
BLANK card terminates EMTP solution-mode
```

```
C Template for JMARTI SETUP output
C   (This template contains all the information needed to interpret the punch
C   output of a JMARTI SETUP run.)
C
C Branch Card                                     I
C                                                 P I
C B     B     B     B     S                       u P
C u     u     u     u     k                       n o
C s     s     s     s     i                       c s
C 1---->2---->3---->4---->p---><---------------->h<e
-                                                -2
C |     |     |     |     |                       | |___Transposition:
C |     |     |     |     |                       |     0 or BLANK -
C |     |     |     |     |                       |        Transposed line.
C |     |     |     |     |                       |     IPose > 0 - # of
C |     |     |     |     |                       |        phases of the
C |     |     |     |     |                       |        untransposed line.
C |     |     |     |     |                       |___Select Model:
C |     |     |     |     |                             -2 - MARTI model.
C |     |     |     |     |___Output Control:
C |     |     |     |           0 - All input poles and residues of the
C |     |     |     |               characteristic impedance Zc and weighting
C |     |     |     |               function a1 of this branch will be printed.
C |     |     |     |           1 - The # of poles of Zc and a1, Zc at infinity
C |     |     |     |               and the travel time of this branch will be
C |     |     |     |               printed.
C |     |     |     |           2 - All input data of this branch will not be
C |     |     |     |               printed.
C |     |     |     |___Name of the bus at the receiving end of the reference
C |     |     |         branch.
C |     |     |___Name of the bus at the sending end of the reference branch.
C |     |___Name of the bus at the receiving end of this branch.
C |___Name of the bus at the sending end of this branch.
C ___IType in Column 1-2 (-1 to -N):
C       N <= 9 - The number of modes (branches or phases) in the transmission
C                system.  N has to be in ascending order.
C
C Characteristic Impedance (Zc) Data Cards
C ---NPZ<-------------------------AKOZc

C     |                              |___Value of Zc at infinite frequency.
C     |___The number of poles of Zc of this branch.
C
C -----------------VoltBC<-----------------VoltBC<-----------------VoltBC

C ___VoltBC's are the values of the residues of Zc of this branch.  There will
C    be NPZ values for VoltBC.
C
C -----------------VoltBC<-----------------VoltBC<-----------------VoltBC

C ___VoltBC's are the values of the poles of Zc of this branch.  There will be
C    NPZ values for VoltBC.
C Weighting Function (a1) Data Cards
C ---NPA<-------------------------Tau

C     |                              |___Travel time of this branch.
C     |___The number of poles of a1 of this branch.
C
C -----------------VoltBC<-----------------VoltBC<-----------------VoltBC

C ___VoltBC's are the values of the residues of a1 of this branch.  There will
C    be NPA values for VoltBC.
C
C -----------------VoltBC<-----------------VoltBC<-----------------VoltBC
```

```
C ___VoltBC's are the values of the poles of a1 of this branch.  There will be
C    NPA values for VoltBC.
C
C The branch card, characteristic impedance data cards and the weighting
C   function data cards (if any) will be repeated for each of the MARTI's
C   branches.
C
C Modal Transformation Matrix for Current (Ti) Data Cards
C ---Ti(j,k)<--Ti(j,k+1)<--Ti(j,k+2)<--Ti(j,k+3)<--Ti(j,k+4)<--Ti(j,k+5)

C Ti(j,k)'s are the elements of the current modal transformation matrix of the
C   transmission line.  The odd number rows contain the real parts of the
C   elements Ti(j,k), Ti(j,k+1), ... etc.  The even rows contain the imaginary
C   parts of the elements Ti(j,k), Ti(j,k+1), ... etc.  If there are more than
C   6 branches, the 3rd and 4th columns will contain elements of Ti(j,k+6),
C   Ti(j,k+7), ... etc.
C Note: Ti is read only when the transmission line is untransposed (IPose > 0).
```

APPENDIX B

DYNAMIC OVERVOLTAGES — CASE STUDY OF LOAD REJECTION

Vladimir Brandwajn

B.1. Introduction

The switching surges which are caused by operation of switching devices can be grouped as follows:

1. Switching Overvoltages (1 or 2 cycles of the fundamental frequency):
    a. energization of lines, cables, transformers, reactors and buses;
    b. re-energization by high speed reclosing of lines;
    c. re-striking recovery voltages due to line, cable or capacitor bank dropping.
2. Dynamic Overvoltages (many cycles of the fundamental frequency):
    a. switching of transformer terminated transmission lines;
    b. load rejection;
    c. ferroresonance.

To illustrate some of the problems related to dynamic overvoltages, consider a case of load rejection, with a stuck breaker, resulting in a generator being connected to an unloaded transmission line. The problem of load rejection normally arises in the system where generation supplies a load radially through one transmission line. This is most common on hydro systems as machine size is normally smaller and overspeed is greater than is normal for steam plants. But in some cases, steam units can be also exposed to severe radial load rejection overvoltages as will be shown in this study.

The initial overvoltage results from the switching surge caused by the change from the heavily loaded line conditions to those of an unloaded line. The Ferranti effect causes a higher voltage at the open end of the line and the line capacitance causes a considerable voltage rise through the generator step-up transformer.

The sudden change of loading conditions results also in instantaneous changes in the generator rotor currents to absorb Vars from the line. The amortisseur or rotor body currents, however, quickly decay (subtransient to transient) resulting in an additional voltage rise. Even further voltage rise will result when the field current returns to normal, and as a result of overspeed, but these phenomena are slow, and modern voltage regulators should be capable of negating their effects.

Harmonics in the current generated by the magnetic saturation in the transformers at the end of the line may also result in overvoltage on the system because of resonance conditions.

Load rejection overvoltages are generally not as severe in magnitude as those resulting from line energization but the long duration nature of the overvoltage can influence the lightning arrester application (choice of its rating). The purpose of this study was to determine the rating of a SiC arrester for the protection of the generator step-up transformer.

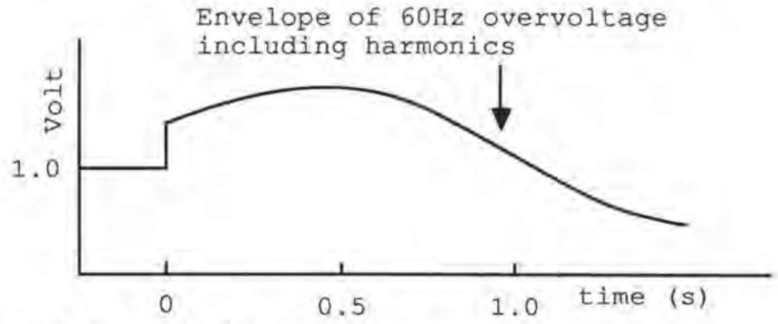


Figure B.1: Typical load rejection overvoltage

B.2. Modelling Requirements

a) Source Representation

The switching surge and the Ferranti effect can be adequately calculated using a sinusoidal voltage source behind the subtransient reactance of the generator. Normally, however, more than 1 or 2 (60 Hz) cycles are of interest and the transient time constant of the generator has to be represented. A synchronous machine model is, therefore, called for.

A conventional (sinusoidal) voltage source can be used behind the equivalent load impedance connected at the far end of the transmission line.

b) Transmission Line Representation

The distributed parameter representation should be used in the simulation. It may be even advisable to use a frequency dependent model.

c) Transformer Modelling

The generator step-up transformers are normally built from single-phase units. It is, therefore, possible to use any transformer model available in the EMTP.

If there is a three-limb core transformer at the remote end of the transmission line, only the RL^{-1} or RL models (BCTRAN or TRELEG) should be used. The model, provided for in the EMTP via the special request word TRANSFORMER THREE PHASE, is not entirely correct. Volume III of the Workbook gives additional details about transformer models.

It is also very important to represent the effects of magnetic saturation.

d) Initial Conditions

For a load rejection, the initial conditions have an important effect on the end result. Obviously the heavier the initial loading of the generator and line, the greater will be the resulting overvoltage. Care must be taken to ensure that the assumed initial conditions are realistic.

To establish the initial conditions it is advisable to run a conventional single-phase load flow program, thus establishing bus voltages and angles. In duplicating this load flow with the EMTP remember that your transformer models may now represent the 30° phase-shift of the wye-delta connected transformers, which the load-flow ignored. More complicated line representations, e.g., untransposed frequency dependent line models, may have different impedances, both because of an inaccurate fundamental frequency fit, and because a conventional load-flow program ignores positive sequence coupling between circuits, and line unbalances (lack of transposition). Minor adjustments may, therefore, be necessary to obtain the desired loading of the generator.

B.3. Study Conditions

A number of operating conditions should be considered. They should cover the possible range of Var generation at the generator terminals. Load rejection with and without faults should be investigated for all the selected sets of initial conditions. Each case should be simulated for a number of cycles of fundamental frequency after the last switching. This is to ensure that the system reaches its new steady-state (dynamic overvoltages subside).

It is also very important to decide on the type of the arrester (SiC or Zn0) to be used before starting the studies. If the arrester is of the Zn0 type without active gap, its model should be included in the studies.

B.4. Choice of an Arrester

a) SiC Type Arrester

These arresters are characterized by an ability to act as an open circuit for low level surges and normal voltage conditions while, for high level surges, they provide a low resistance path to ground. This is achieved by sparking over a series of gaps within the porcelain arrester housing. The arrester capabilities are defined by its rating, maximum switching and impulse overvoltage sparkover and protective level, reseal capabilities and lightning IR voltage drop. The rating of the arrester is a basic designation around which all its characteristics can be assigned.

The sparkover voltage determines the highest surge which can occur on the arrester prior to arrester sparkover and the IR voltage drop describes the magnitude of the arrester voltage following a sparkover of the gap. The IR voltage drop of the arrester is determined by the characteristics of the arrester and the surge current.

In simple words, the rating of the arrester is the level of the fundamental frequency voltage at which it will successfully reseal (extinguish arc in the gap) following a discharge. The standard duty cycle test demonstrates this capability for lightning overvoltage type impulses. Modern active gap arresters have a reseal capability at a voltage in excess of their rating for several cycles. This capability is obtained by the use of gaps capable of generating a back voltage in opposition to the power follow current (dynamic or current limiting gap). High reseal capability is particularly important in applications where long duration, temporary overvoltages resulting from transformer switching are encountered.

The choice of an arrester rating is based primarily on the maximum fundamental frequency voltage as well as temporary overvoltages. In general, one should examine the calculated prospective overvoltage trace (without arrester) and compare it with the allowable overvoltage capability. If in doubt, consult the manufacturer.

b) Zn0 Type Arresters

These arresters are characterized by their high energy dissipation capabilities and protective characteristics (IR voltage drop) superior to those of SiC units. They also do not have any significant power follow currents.

There are no clear standards specifying their parameters. It is, therefore, necessary to clarify the meaning of arrester characteristic with its manufacturer. In general, he will be able to answer the questions and provide guidance in the selection of arrester rating.

Important parameters of Zn0 arresters are as follows:

a) maximum allowable system voltage to which the arrester can be exposed without damage (maximum continuous operating voltage);

b) maximum allowable energy absorption (thermal stability);

c) maximum allowable current through it or more specifically maximum allowable rate of energy dissipation (thermal cracking);

It should also be pointed out that these arresters can be purchased with or without gaps. There are 3 basic types of gaps used with the Zn0 arresters:

1) series passive gaps;

2) series active (current limiting) gaps

3) shunt passive gaps.

The trend in the industry appears to be toward gapless Zn0 arresters. The use of passive gaps could be justified only for some special low current (low energy) applications. The use of active gaps does not appear to make much sense in view of their complexity and the inherent high energy dissipation capability of Zn0 blocks.

B.5. Example

The single-line diagram for a test system is shown in Figure B.2.

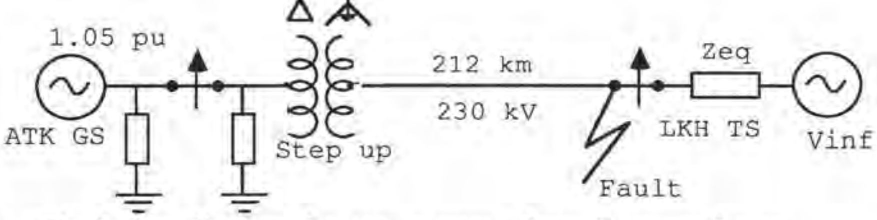


Figure B.2: Single-line diagram for test system, dynamic overvoltages.

Consider a case of single-phase to ground fault on the high side of the remote transformer station. It is assumed that the fault is present during the steady-state solution, and that the far side breakers begin to open almost immediately, but that the breakers at the generator end do not operate for several cycles. Figure B.3 illustrates the input data for this study. Figures B.4 shows the variation of voltages at the generator terminals (low side), Figure B.5 shows the voltages on the high side of the step-up transformer. Figure B.6 shows the remote end line voltage. Figure B.7 shows the simulated changes in the field current of the generator. Notice that the use of saturable transformers results in ferroresonant oscillations.

```
C Load rejection case, breaker stuck at ATK GS, L-G fault applied at the
C remote end of the line.
BEGIN NEW DATA CASE
C ............................ Miscelaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   .1E-3     .26     60.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      15       3       1       1       1                               1
C
C ............................ Circuit data  ..................................
C            Step-up xfmr at ATK (17.1/239 KV) saturation model.
C Saturable transformer components.
C ----------->Bus3-><---->-<----I<--PhiBusSt><-Rmag<--------------------------->O
  TRANSFORMER             64.78464.147TRANA 372.39                            0
C -------current<-----------flux
          64.784          64.147
         238.755          67.355
         465.840          70.562
        1106.083          73.789
        1479.039          75.053
        2178.307          78.977
        4700.627          81.018
        8129.549          87.826
       17119.653         107.165
            9999
C Bus1->Bus2-><----------><---Rk<---Lk<---Nk<------------------------------->O
 1LOWA  LOWB              5702-4.22413  17.1                                  0
 2HIGHA                   .3712914.594137.99                                  0
C <---------->Bus3-><--------------->BusSt>
  TRANSFORMER TRANA                   TRANB
C Bus1->Bus2->
 1LOWB  LOWC
 2HIGHB
  TRANSFORMER TRANA                   TRANC
 1LOWC  LOWA
 2HIGHC
C Distributed parameter line
C                    131.2 miles long transmission line data
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<-------------------->O
-1HIGHA LKHA              1.16223.40252.7463 131.2                            0
-2HIGHB LKHB              .09128.787585.4770 131.2                            0
-3HIGHC LKHC              .08182.886154.7963 131.2                            0
-4HIGHA OPENA                                                                 0
-5HIGHB OPENB                                                                 0
-6HIGHC OPENC                                                                 0
C                         System equivalent impedance
C Bus1->Bus2->Bus3->Bus4-><Code1<------Code2
51INFINASWITCA            1.3358    20.46352
52INFINBSWITCB            2.1780    22.72380
53INFINCSWITCC
C RLC branch
C                    Station service load equivalent (20 MW)
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  ATKA                    17.861
  ATKB                    17.861
  ATKC                    17.861
C                   Capacitors for delta windings of the step-up
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LOWA                                  5.
  LOWB                                  5.
  LOWC                                  5.
```

```
C                        Fault impedance 2 ohms.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LKHA  FAULTA                2.
BLANK card terminates circuit data
C
C ............................ Switch data ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   0
  ATKA  LOWA         -1.    .23666                                             0
  ATKB  LOWB         -1.    .23666                                             0
  ATKC  LOWC         -1.    .23666                                             0
  LKHA  SWITCA       -1.      .067                                             0
  LKHB  SWITCB       -1.      .067                                             0
  LKHC  SWITCC       -1.      .067                                             0
  FAULTA              0.        1.                                             0
BLANK card terminates switch data
C
C ...........................Source data .......................................
C                 Infinite bus (behind equivalent impedance)
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0        <----Tstart<----Tstop
14INFINA   198408.66      60.    -2.605                           -1.
14INFINB   198408.66      60.  -122.605                           -1.
14INFINC   198408.66      60.  -242.605                           -1.
C
C Dynamic synchronous machine.
C                      Synchronous generator at ATK GS
C Bus-->  <-----Volt<-----Freq<----Angle
59ATKA     15431.785      60.       -2.5
  ATKB
  ATKC
C --------------------><-----FM
PARAMETER FITTING            2.0
C <-<-<-NP<---SMoutP<---SMoutQ<-----RMVA<------RKV<---AGLine<-------S1<-------S2
 1 1     2        1.        1.      270.       18. -879.375     938.    1313.2
C -------><------AD1<------AD2<------AQ1<------AQ2<-----AGLQ<------S1Q<------S2Q
                                                          -1.
C ------Ra<-------X1<-------Xd<-------Xq<------X'd<------X'q<------X"d<------X"q
     .0035    .165        1.9       1.8       .27       .67       .19         .2
C ----T'd0<-----T'q0<-----T"d0<-----T"q0<-------X0<-------Rn<-------Xn<-------Xc
       6.2       1.5       .04        .4       .08    1500.
C <------><----Extrs<-----HiC0<------DSR<------DSM<------HSP<------DSD
 1               1.        .529
C print ctrl<----Angle<----Speed<--Torque
1 1                  1
  FINISH
BLANK card terminates source data
C
C ........................... Output Request Data ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  HIGHA HIGHB HIGHC LKHA  LKHB  LKHC  ATKA  ATKB  ATKC
BLANK card terminates output requests
BLANK card terminates plot request
BLANK card terminates EMTP solution-mode
```

Figure B.3: EMTP data case.

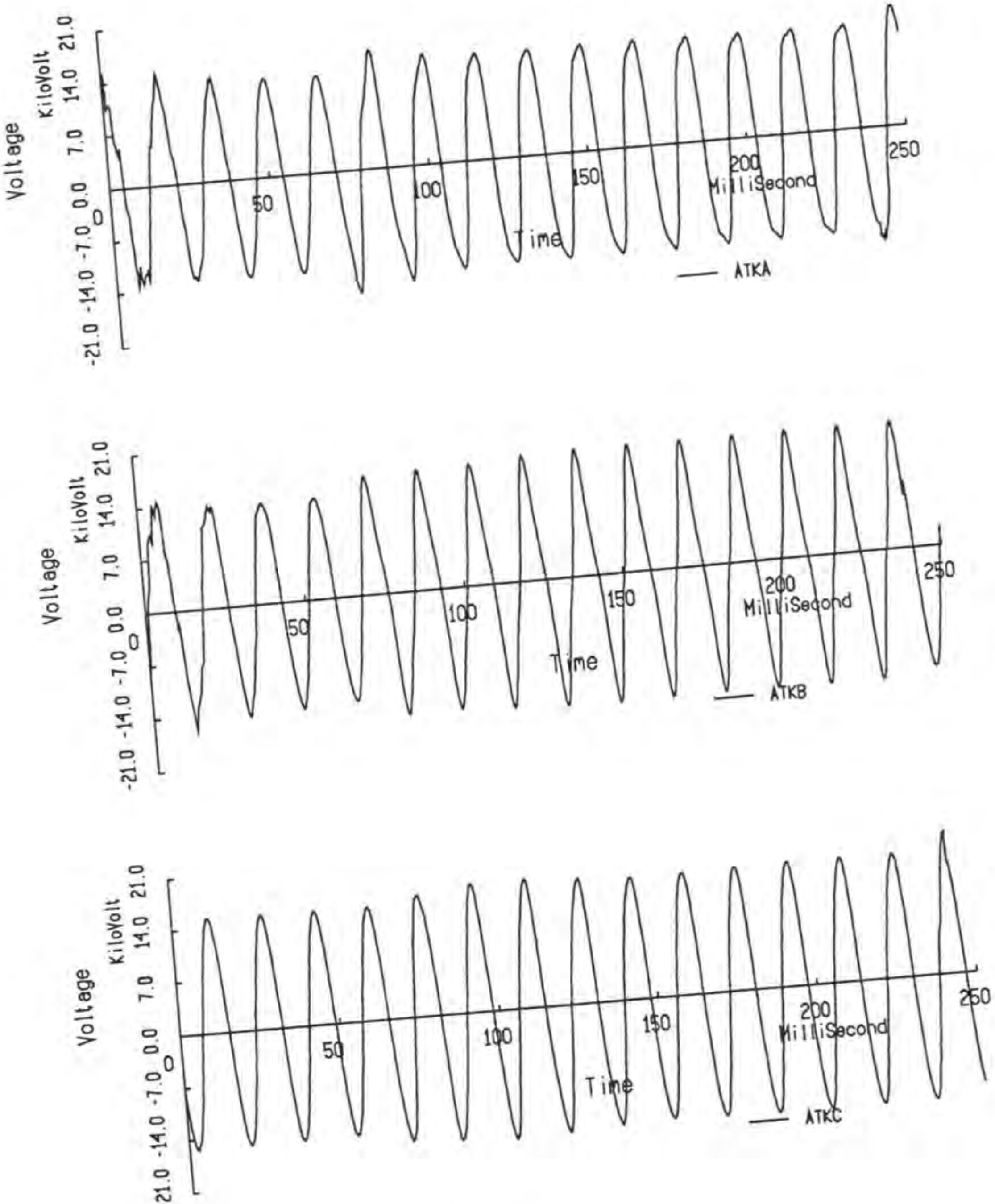


Figure B.4: Voltages at sending end low side.

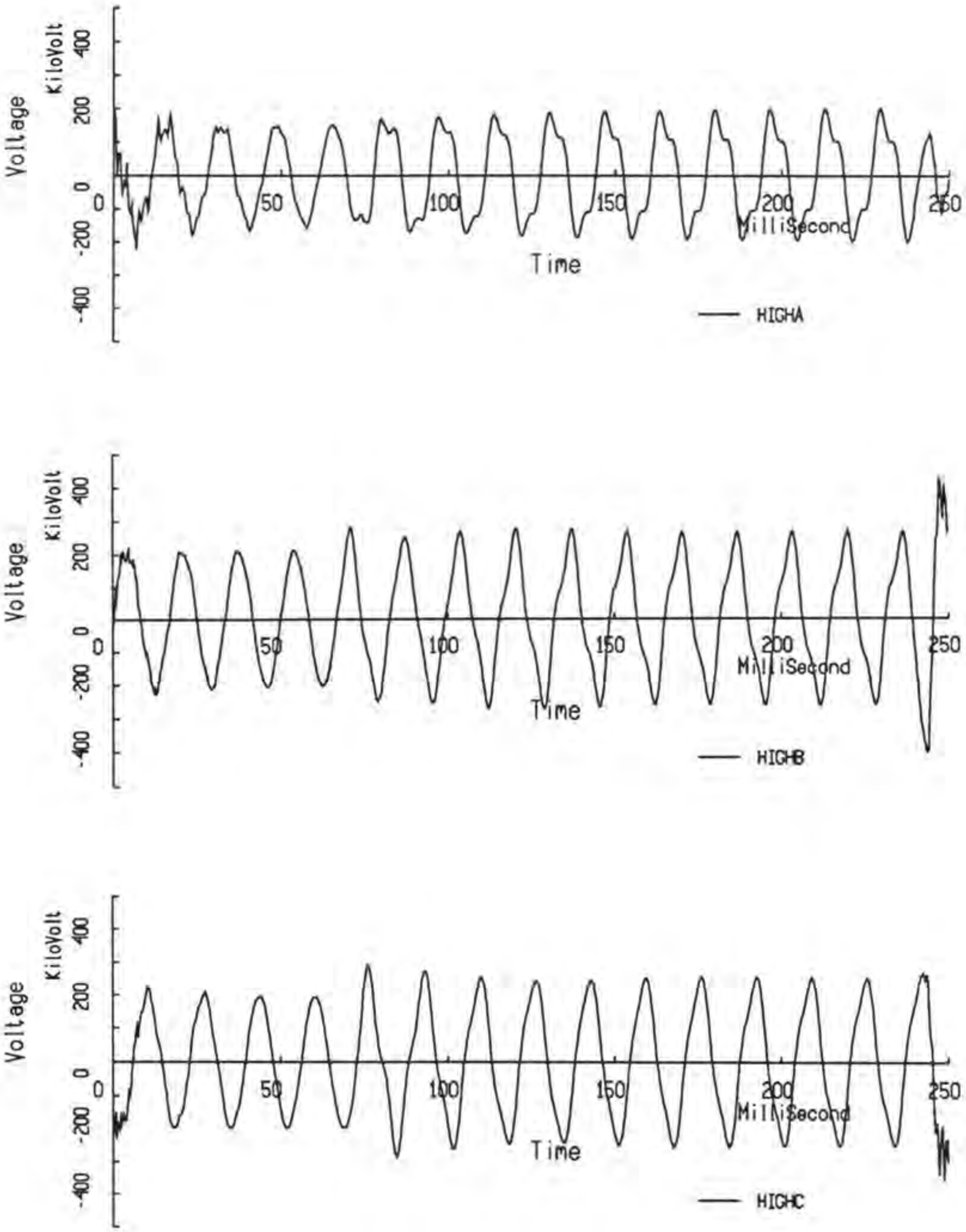


Figure B.5: Voltages at sending end high side.

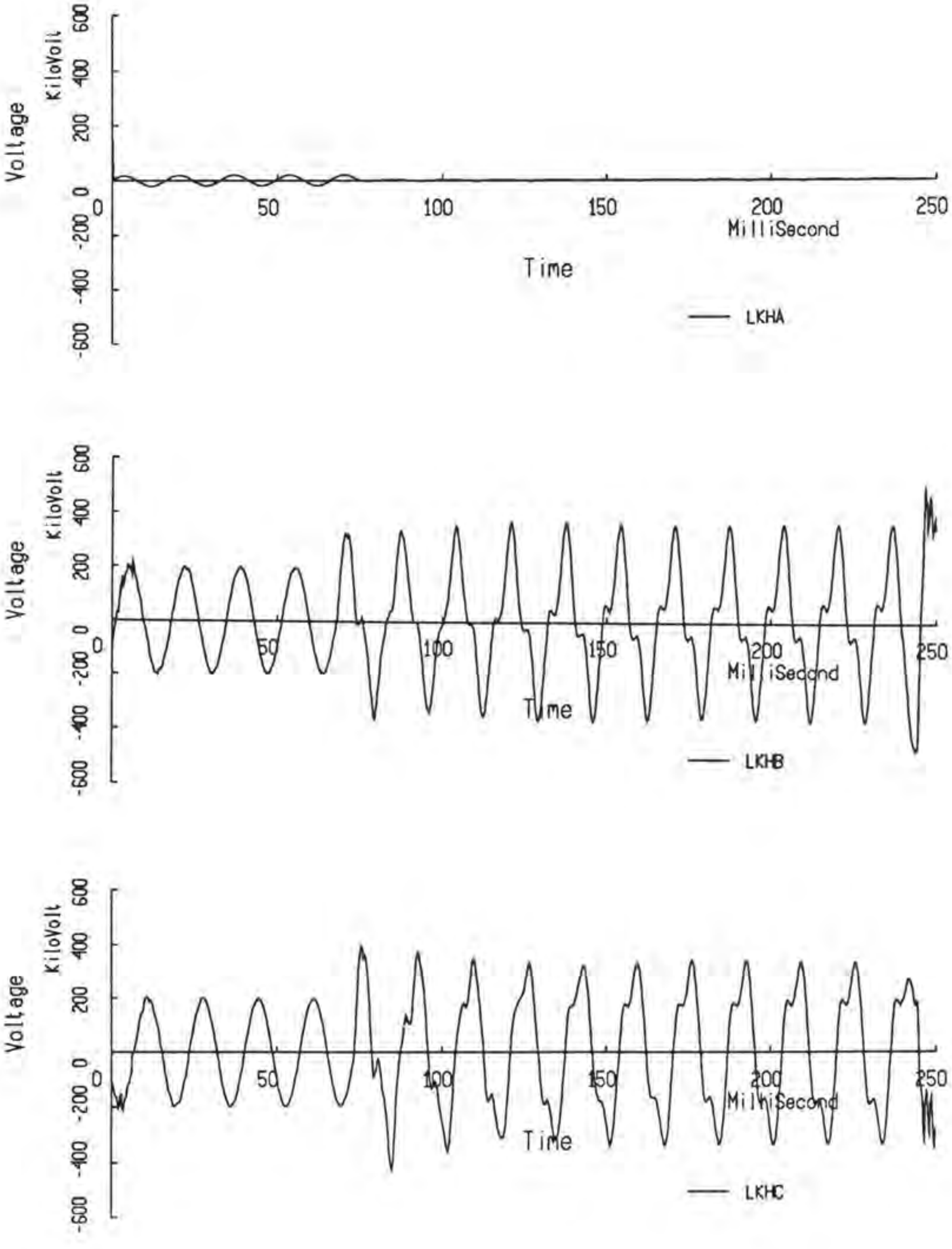


Figure B.6: Remote end voltages

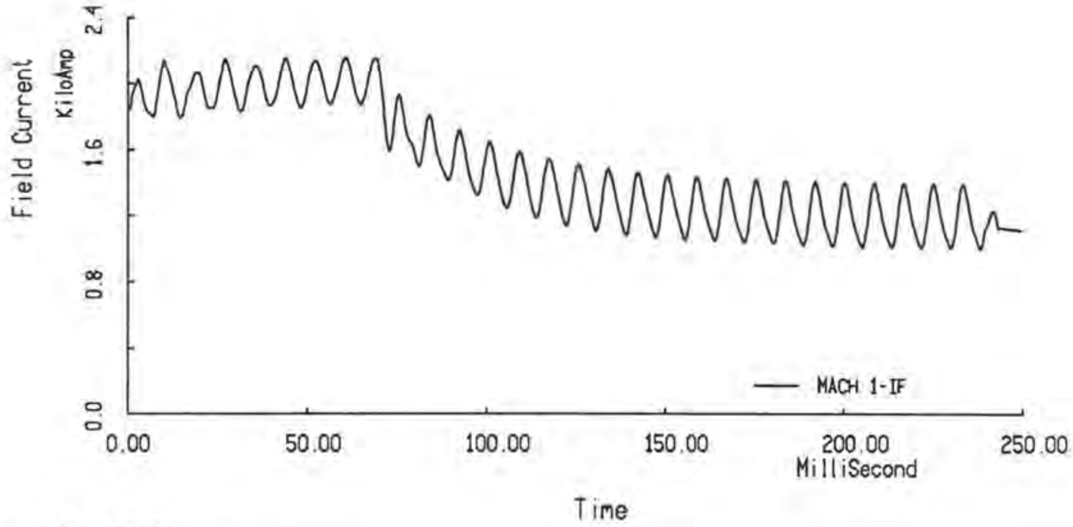


Figure B.7: Field current.

APPENDIX C

TRANSIENT RECOVERY VOLTAGE — CASE STUDY

Vladimir Brandwajn

C.1. Introduction

Transient faults on power systems develop a current which is limited primarily by the inductance (reactance) of the connected system. Conservation of flux linkages results in the formation of an arc in the disconnecting circuit breaker following the parting of its contacts. When the alternating current passes through zero, the AC breaker attempts to extinguish the arc and, thereby, clear the circuit. The interruption of the current produces a Transient Recovery Voltage (TRV) across the previously conducting arc space as the systems connected on each side of the breaker adjust to the new operating state. The transient recovery voltage is defined as the difference voltage measured between each side of the breaker to ground.

The breaker need not withstand the TRV in its partly open condition, but it must do so when fully open, or it will continuously restrike until it explodes.

Standards are available which describe the interrupting capability of standard breakers, but these standards do not necessarily meet the requirements of all systems, nor do they describe the maximum capability of most breakers.

In this study, it was attempted to determine the bus-side recovery voltage [1] for a group of 500 kV breakers for a range of fault levels and system configurations that they can reasonably be expected to encounter in their lifetime. The system being investigated is infamous for its high fault levels and limited number of transmission lines.

C.2. Procedure

1. By established practice, only the bus-side recovery voltage was calculated [1]. The line-side recovery voltage, which consists of a low magnitude high frequency saw tooth shaped wave, is left to the manufacturer since each breaker has its own critical position for the short line fault. Also, by established practice, the effect of the opening resistors on the recovery voltage were not accounted for.

2. A three-phase ungrounded fault results in the highest bus-side recovery voltage, the first phase to clear being the worst. Since ground currents are not involved, only positive sequence impedances can be used, and consequently a single phase representation is adequate. The effects of the second and third phase are taken into account simply by multiplying the obtained results by 1.5 [1].

3. The analysis was performed with the method of "current injection" which eliminates the need for the simulation of the entire sequence of events leading to the creation of the TRV's. The current zero is obtained as a result of injecting a current of equal magnitude and opposite sign to that flowing through the breaker. By superposition, the voltage caused by the injected current can be added to the negligible pre-injection voltage.

   The use of the "current injection" method is also recommended as means of avoiding numerical oscillations that may be caused by the EMTP switch model in some versions of the EMTP.

4. The 500 kV system, and the 230 kV underlying system were represented in detail out to the point where reflections could not arrive back at the breaker within the time of interest. The lines were represented with distributed parameters positive sequence models. Frequency dependence is normally not an important characteristic in the positive sequence.

5. Loads were represented as fixed impedances lumped at major buses. These loads provided a non-negligible amount of damping.

6. Generators and transformers were lumped into fixed impedances using subtransient generator reactances.

7. Bus capacitance of the operating breaker was represented since it has an appreciably delaying effect on the initial rate of rise of recovery voltage (IRRV).

C.3. Analysis of Results

Following the calculation of the recovery voltage, the resulting curves have to be compared with a set of curves calculated from ANSI standards (see attached). You will note from these curves an increase in the permitted peak recovery voltage as the fault current reduces. However, at very low fault currents, you will note a sudden reduction in the permissible initial rate of rise. This peculilarity is necessitated by the oil breaker's dependence for some of its initial recovery voltage on the effects of a gas bubble formed in the oil by the arc. At low currents, this bubble is ineffective. For other types of breakers this low current limitation does not exist, but special standards have not yet been developed.

The attached curves are for a 550 kV breaker, and indicate a peak recovery voltage from 1.76 to 2.0 p.u. of rated line-to-line RMS voltage or from 2.15 to 2.45 p.u. of rated peak line-to-ground voltage.

C.4. Comments

a) Choice of System Conditions

In selecting the particular study conditions, the practice is to consider the expected system arrangement at several points in time - as far ahead as possible. At each point in time, select the worst conceivable system contingency, attempting to maximize fault current while minimizing the number of transmission lines. Such a contingency usually involves maximum generation with some transmission circuits out of service. Consider a fault which is so positioned that no further reduction in fault level will result, determine the fault current, and then the recovery voltage.

b) Modelling Assumptions

The most questionable in the representation described above is the modelling of transformers and generators. It is, for example, known that for very high frequencies, a transformer behaves more as a capacitor than an inductance.

Some questions could also be raised about load representation (frequency dependence). The representation used in this case results in a conservative estimate of the damping caused by loads in the system.

An idea about the influence of loads on the obtained results can be obtained from Figure C.3.

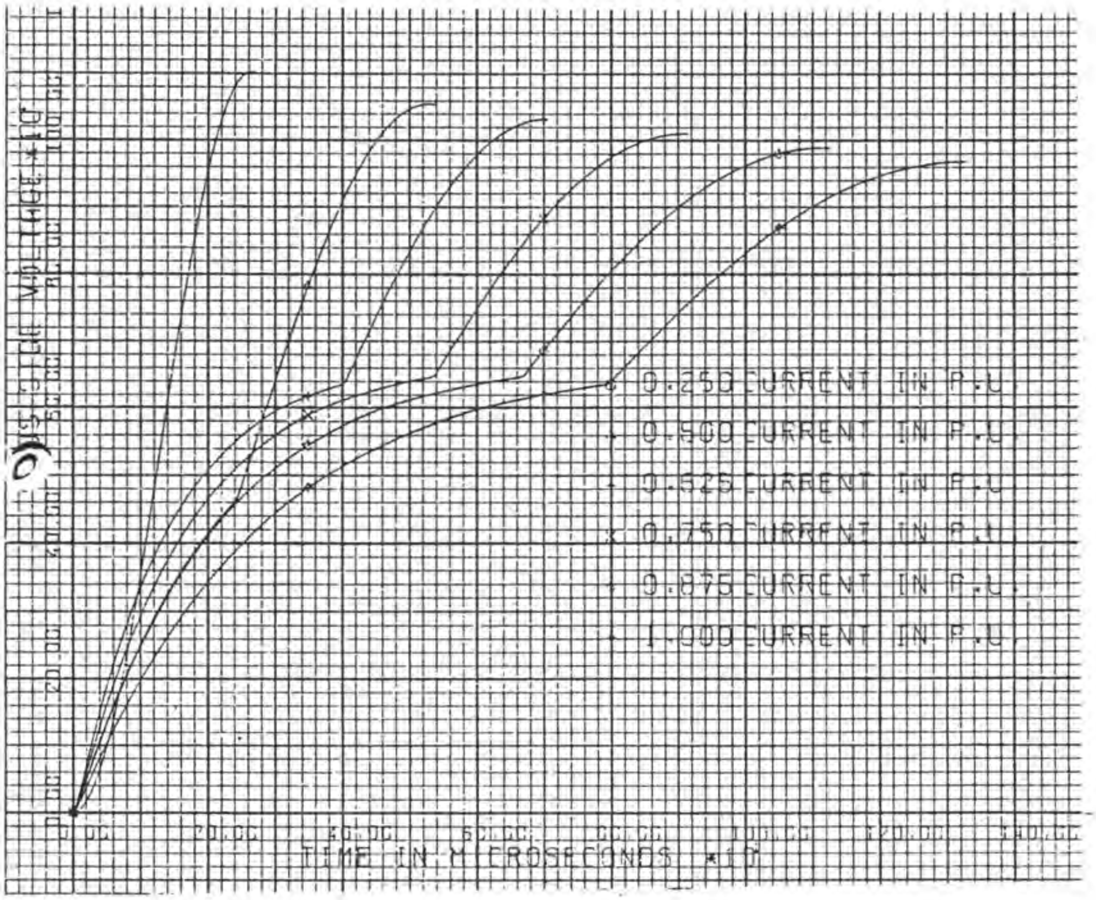


Figure C.1: Recovery curves from standards.

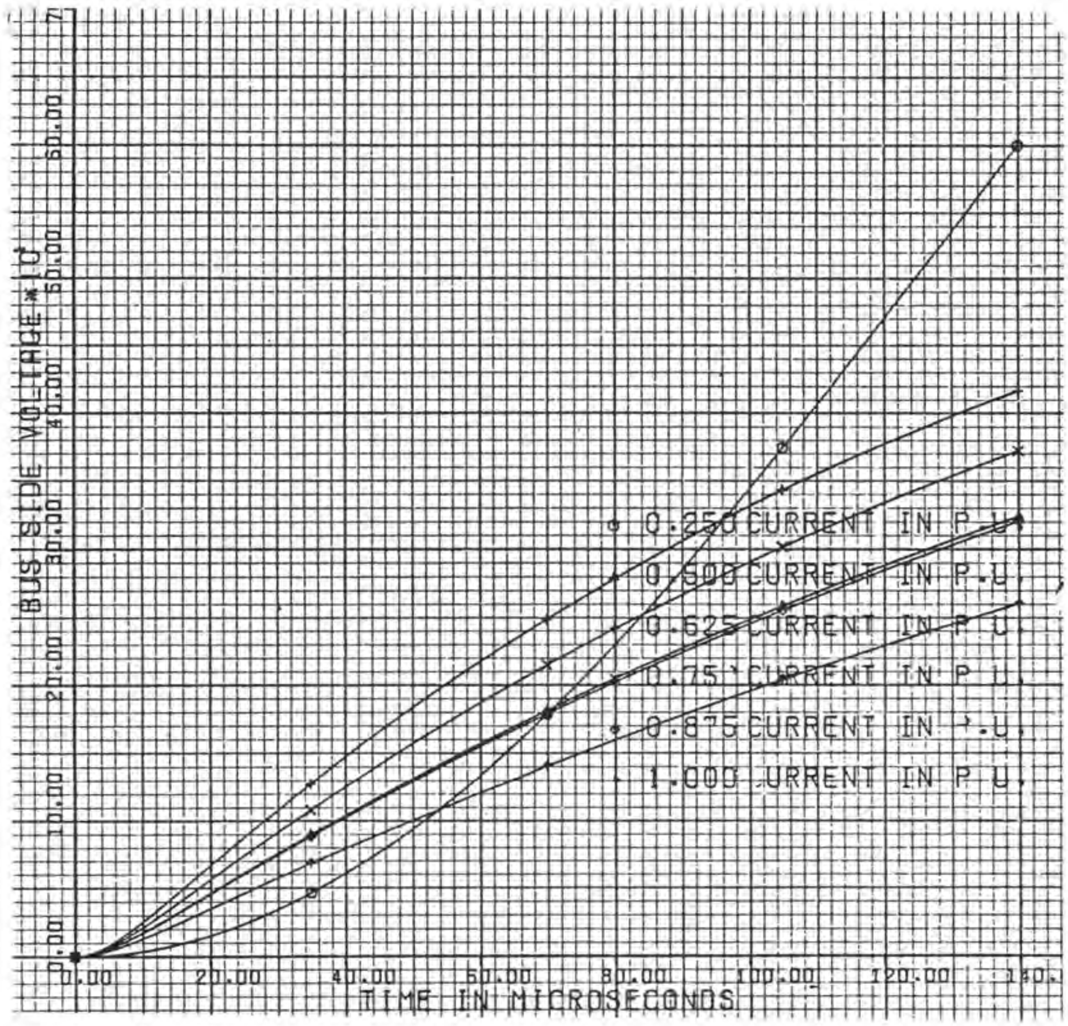


Figure C.2: Recovery curves from standards.

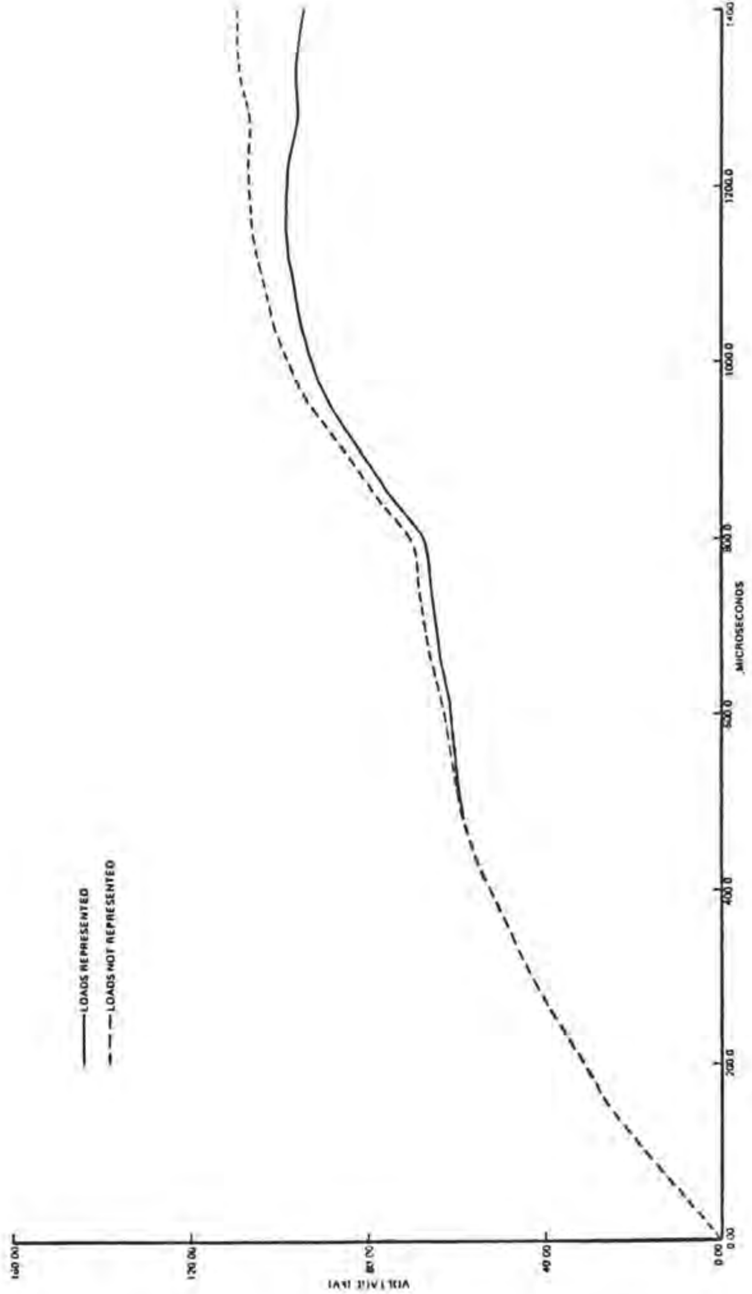


Figure C.3: Simulated recovery curves.

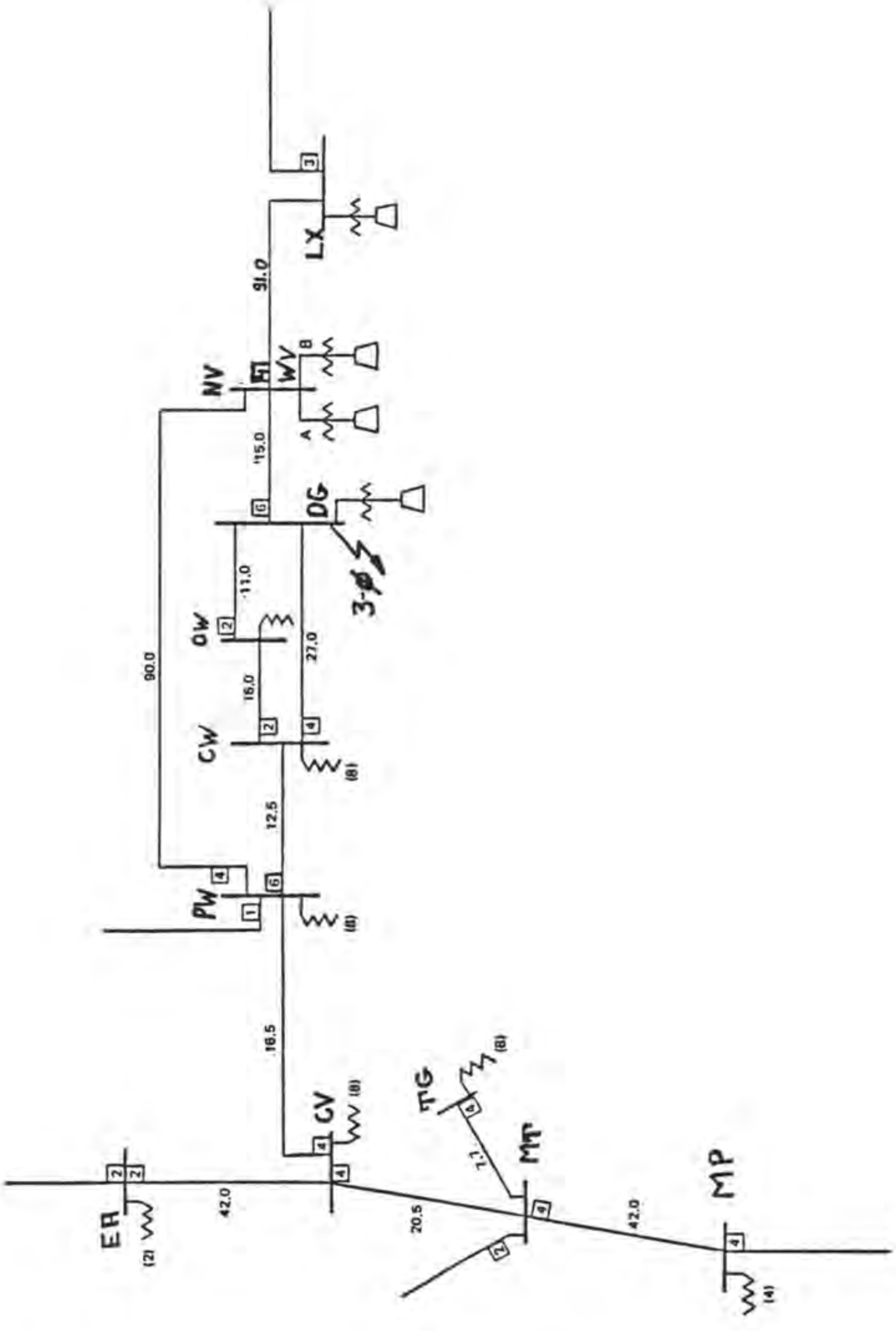
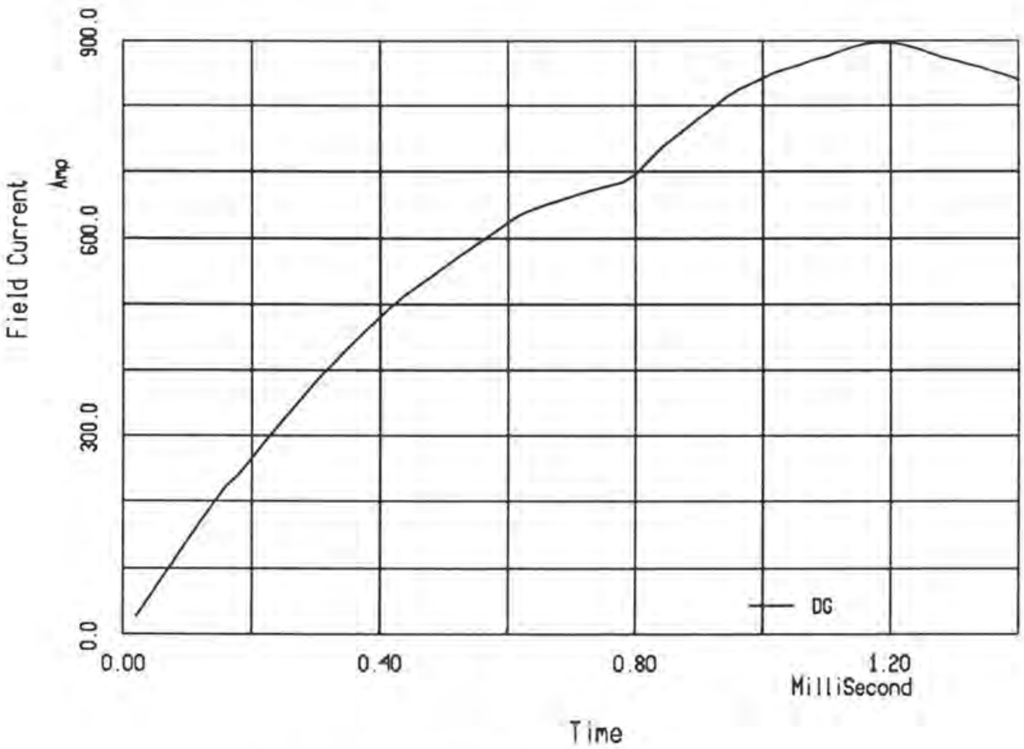


Figure C.4: Circuit diagram.

```
C Transient recovery voltage - case study.
BEGIN NEW DATA CASE
C ............................ Misoelaneous data ...............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   4.E-6  1.4E-3      60.      60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
     200       5       1       1       1                       1
C
C ............................ Circuit data  ...................................
C Distributed parameter line (in p.u.).
C           Distributed parameter line 500 KV system
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<--------------------->O
-1LX    NV                .469-5.506-48.41+4   91. 0 0                         0
-1NV    WV                .156-5.166-42.52+5  1.25 0 0                         0
-1NV    PW                .469-5.101-34.20+4   90. 0 0                         0
-1NV    DG                .313-5.337-41.20+5   15. 0 0                         0
-1DG    OW                .939-5.101-34.20+4   11. 0 0                         0
-1DG    CW                .469-5.506-48.41+4   27. 0 0                         0
-1OW    CW                .939-5.101-34.20+4   16. 0 0                         0
-1CW    PW                .313-5.337-41.20+5  12.5 0 0                         0
-1PW    CV                .469-5.506-48.41+4  16.5 0 0                         0
-1CV    MT                .469-5.506-48.41+4  20.5 0 0                         0
-1CV    EA                .939-5.101-34.20+4   42. 0 0                         0
-1MT    TG                .469-5.506-48.41+4   7.7 0 0                         0
-1MT    MP                .469-5.506-48.41+4   42. 0 0                         0
C           Distributed lines 220 KV system
C Bus-->Bus-->Bus-->Bus--><---R'<---L'<---C'<--len 0 0 0<--------------------->O
-1CW1   PR1               .662-4.421-31.02+4   4.5 0 0                         0
-1RV1   TG1               .662-4.421-31.02+4   14. 0 0                         0
-1RV1   LV1               .529-4.334-31.27+4   10. 0 0                         0
-1CW1   PW1               .424-4.281-31.53+4   15. 0 0                         0
-1PW1   RV1               .424-4.281-31.53+4   20. 0 0                         0
-1OW1   CW1               .331-4.210-32.04+4   18. 0 0                         0
-1CV1   RV1               .331-4.210-32.04+4    7. 0 0                         0
C           Surge impedance to represent long lines
C                      500 KV system
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LX                      .03467
  MT                      .052
  EA                      .052
  PW                      .104
  MP                      .026
C                       220 KV system
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LX1                     .19886
  OW1                     .26515
  TG1                     .13258
  EA1                     .13258
C             Transformer connecting the two systems
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LX    LX1                     .00217
  CW    CW1   LX    LX1
  PW    PW1   LX    LX1
  CV    CV1   LX    LX1
  TG    TG1   LX    LX1
  MP    MP1   LX    LX1
  OW    OW1                     .00289
  EA    EA1                     .00867
C          Load equivalent  (connected to 220 KV system)
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LX1                     .06190.02979
  CW1                     .02166.00944
  TG1                     .02805.01223
  EA1                     .03628.01581
```

```
  RV1                     .02244.00978
  PW1                     .03429.01495
  MP1                     .05005.02421
C                    500 KV generator equivalent
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  WV                            .00425
  DG                            .00875
  LX                            .02975
C                    220 KV Generator equivalent
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  LX1                           .00661
  PR1                           .01488
  LV1                           .01239
C                        Bus capacitance
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  DG                                  9.43+4
BLANK card terminates circuit data
C
C ...........................  Switch data  ....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
BLANK card terminates switch data
C
C ...........................Source data  ......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14DG    -1 466690.78       60.      -90.
BLANK card terminates source data
C
C ...........................  Output Request Data  ............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  DG
BLANK card terminates output requests
BLANK card terminates plot request
BLANK card terminates EMTP solution-mode
```

(a) EMTP data case.



(b) Simulation result.

Figure C.5: Recovery curve from EMTP simulation.

C.5. References

[1] "Application of Power Circuit Breakers", IEEE Tutorial Course 75 CH0975-3-PWR, New York, 1975.

APPENDIX D

CAPACITOR BANK DE-ENERGIZATION — CASE STUDY

Vladimir Brandwajn

D.1. Introduction

Switching of capacitor banks (energization as well as de-energization) creates a varied and interesting group of transient phenomena. Some of the phenomena have been known to engineers for a long time, while others have been recognized only recently.

a) Energization

At the instant of energization, a fully discharged capacitor bank looks like a short-circuit and, therefore, causes a collapse of bus voltage. The capacitor bank charges then to the system voltage in an oscillatory manner (with a possible overshoot). The frequency of these oscillations depends on the effective system inductance and the capacitance of the bank (400Hz - 1000 Hz). Peak voltages of 2.0 p.u. can be theoretically expected for grounded banks, and 2.5 p.u. for ungrounded banks. Lower voltages will, however, result in practice due to system damping.

Some unusually high voltages can also be expected at the remote ends of transmission lines fed radially from the capacitor bank's bus. Especially vulnerable are transformer stations at line terminations due to the doubling effect at these points.

If a second bank exists in the immediate vicinity, the energizing oscillation contains very high current, at very high frequency. If the bank is grounded, these currents may, for example, burn out control circuits in the switchyard. The current in this back-to-back switching must be limited by appropriate spacing, lumped inductors, or closing resistors.

If the switching device is slow, and contains a good interrupting medium, it is possible for the device to prestrike, extinguish the arc at one of the high frequency current zeros, and strike again with the capacitor charged in opposite polarity to the system, with even higher resultant overvoltages.

b) De-energization

It may appear that any device capable of fault interruption should have little or no difficulty switching simple capacitive current, but, this is not necessarily true. The problems in switching capacitive current are two-fold:

1) smaller magnitude of the current;

2) more severe recovery voltage (across breaker contacts).

It is well known that capacitor's current leads its voltage by 90°. Thus, in the vicinity of current zero, the system voltage as well as capacitor voltage, are approximately at maximum and a considerable charge is locked in the bank. For a grounded bank, this locked charge results in a recovery voltage of 2.0 p.u. across the breaker contacts about

1/2 cycle after interruption. If the bank is ungrounded, it is important to distinguish between the following two cases:

i) Isolated Capacitor Bank

The sequence of switch contact parting determines the recovery voltage. For sequential interruption, an across-the-contacts voltage of 2.5 p.u. can be expected. If one phase opens at an earlier current zero, over 4 p.u. can be expected. Breaker standards state that the recovery voltage at low currents should not exceed $1.76 \times V_{LL} \times 1.13$ p.u.

ii) Capacitor Bank Connected in Parallel with a Large Transformer(s).

The presence of the transformer(s), can lead to a resonant condition which affects the breaker significantly. More details, later on in the case study.

Capacitive switching problems are particularly severe in oil circuit breakers, especially interrupters which require several half cycles of arcing prior to interruption of fault currents. For high fault currents, reignition of the arc produces several half cycles of arcing after contact separation. Finally, when the contacts are quite far apart, the dielectric strength of the gap results in successful interruption. The breaker is capable of interrupting the smaller capacitive current before its contacts have achieved sufficient separation to establish the dielectric strength required to withstand the resultant recovery voltage. In such a situation, the breaker can restrike resulting in high transient overvoltages. Some oil circuit breakers have been known to restrike a multiple number of times on a single line dropping or capacitive switching operation.

Typically, gas circuit breakers (air blast and SF_6) and vacuum interrupters have a greater capacitive switching capability resulting from faster contact separation and faster increase of dielectric strength. They are, however, expensive in relation to the size of currents they are to interrupt (few thousand A at the most).

Some systems, well protected from overvoltages by surge arresters, can tolerate breaker restrikes, although the wear and tear on the arresters and the breaker contacts has to be considered. Other systems, with transformers protected by rod gaps, cannot tolerate restrikes, since they result in ground faults and possible loss of load.

The industry practice is to use a Vacuum Switch for normal bank switching with fault clearing handled sometimes by oil breakers. SF_6 breakers for bank switching may be acceptable, with some concern about what would happen if these breakers were to stick. Ungrounded banks may avoid possible damage to switchyard control cables.

D.2. Single-pole Resonance

This phenomenon, occurring during the de-energization of large ungrounded capacitor banks, has been discovered in field tests. The three-phase diagram of the test system is shown in Figure D.1.

An oil breaker, located on the 230 kV side, was used to de-energize the 96 MVar capacitor bank connected to the 115 kV side of the autotransformer. The first two poles of the breaker (phases a and c) cleared without problems at their first current zeroes. The third pole kept on arcing for approximately 1.0 cycle (on 60 Hz base).

Analysis of test records indicated the existence of a resonance at a frequency approximately equal to 180 Hz. The resonance occurs due to magnetic saturation effects in the autotransformer operating in parallel with the capacitor bank. The tertiary winding provides low impedance path to ground and transformer saturation provides harmonic voltages. The voltages at the disconnected terminals can rise significantly and, therefore, increase the chances of a restrike. The most characteristic field test records are shown in Figure D.2 and D.3.

The test records provided an opportunity to check the available simulation tools, TNA as well as digital programs. The Electromagnetic Transients Program (EMTP) was used in the simulation of the test system as well as the corresponding TNA set-up.

D.3. Duplication of TNA Set-up

The TNA model of the test system is shown in Figure D.4. The model transformer was used as a non-linear reactor connected to ground. The effects of delta windings were represented by the 3-limb core. The HL short-circuit impedance of the autotransformer was (incorrectly) included into the source impedance Z_e.

The TNA model was slightly rearranged to permit an easy simulation with the EMTP. The resulting equivalent system is shown in Figure D.5.

The zero sequence source impedance Z_n and the system equivalent impedance Z_e were lumped into one 3-phase impedance. The model transformer was represented by a combination of a 3-phase linear impedance and non-linear branches (type 98 pseudo-nonlinear reactance) simulating the effects of magnetic saturation.

A very good correlation of results between the TNA and the EMTP has been obtained. Figure D.6 contains a comparison of some of the TNA results with those calculated by the EMTP. The slight differences apparent in the voltage waveforms are most probably caused by inadequate data about magnetic saturation and possibly by remnant magnetism flux in the model transformer.

D.4. Duplication of Field Test Results

In this case, it was attempted to simulate the actual field conditions. Unfortunately, only partial information was available on the transformer. This was due to its total damage during one of the subsequent tests. The saturation characteristic had, therefore, to be guessed and a number of iterations were needed to achieve a good agreement. Additional complications were caused by the shell type construction of the transformer in question. While it is by now clear how to model saturation effects in 3-limb core transformers, no such clarity exists for shell type units. The 'sandwich type' construction of windings makes it more difficult to choose the correct location of the magnetizing branch (see Figure D.7).

A comparison of simulation results with those recorded during the field tests is shown in Figure D.8.

D.5. Points of Interest

Figure D.8 indicates the existence of an additional source of harmonics in the test system. This is an issue that deserves further investigation. The slight disagreement in voltage waveshape following current interruption can, most probably, be attributed to remanent magnetism in the transformer.

Editors note: Figure D.10 illustrates the voltage across the transformer after de-energization. The simulation was carried one cycle further than in the manuscript submitted by V. Brandwajn. In the last cycle we see the onset of numerical oscillations not seen prior to this cycle. Figure D.11 illustrates the same simulation but with the addition of oscillation damping resistors in parallel with the transformer winding.

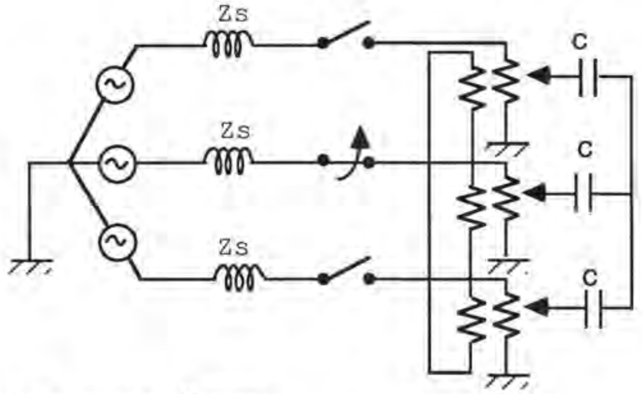


Figure D.1: Three phase system diagram.

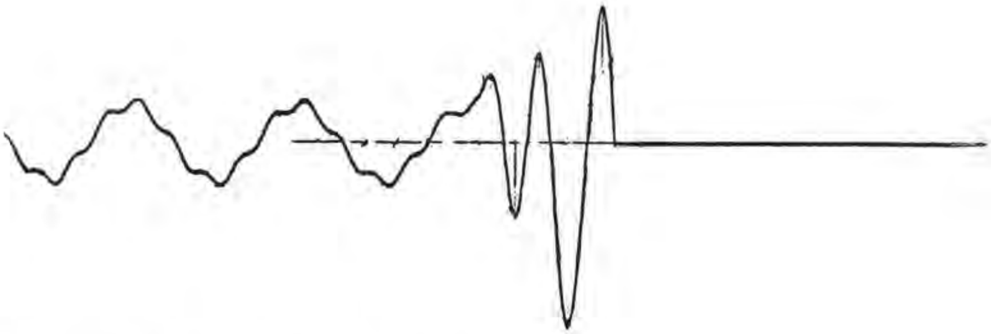


Figure D.2: Field test record of current in the 'stuck' pole.

Figure D.3: Field test record of L-G voltage (phase c).

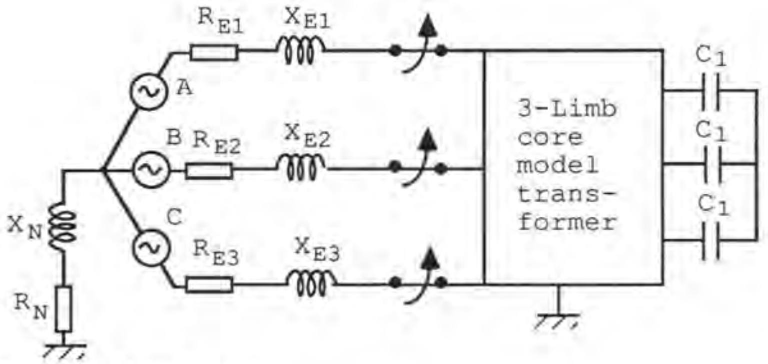


Figure D.4: TNA model of test system.

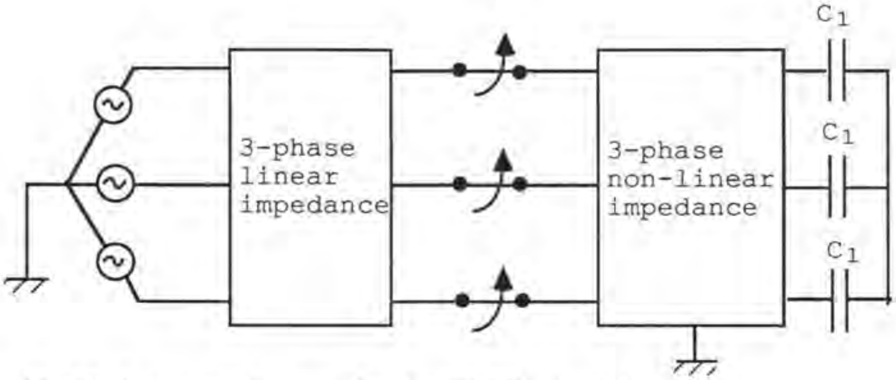
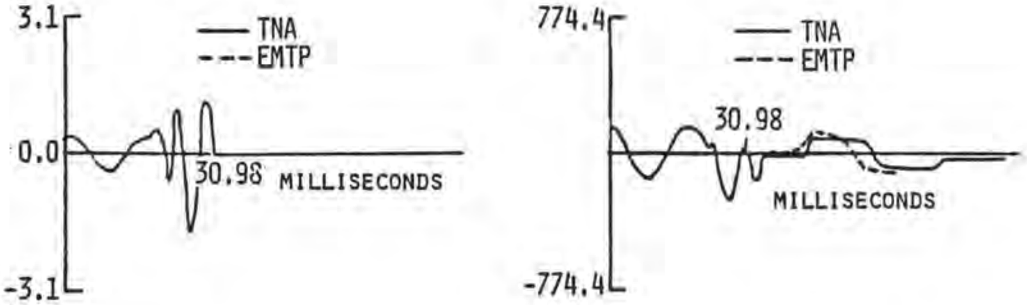
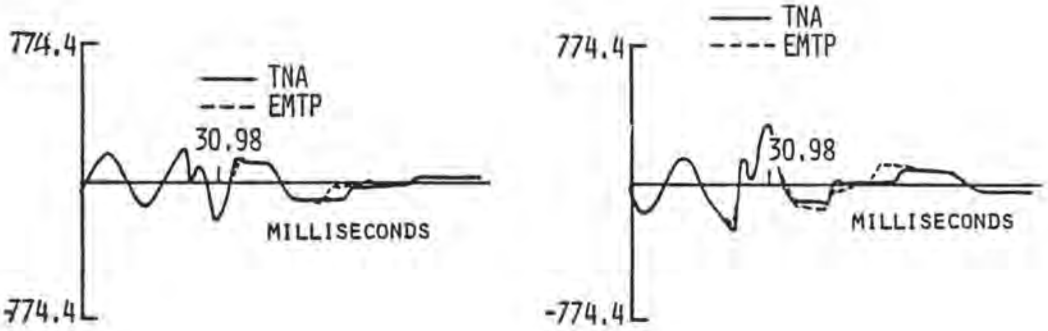


Figure D.5: Modified system diagram for the EMTP simulation.



(a) Current (phase b). (b) L-G voltage (phase a).



(c) L-G voltage (phase b). (d) L-G voltage (phase c).

Figure D.6: Comparison of the results.

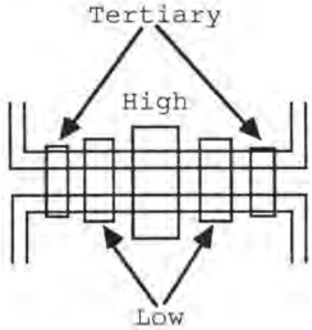
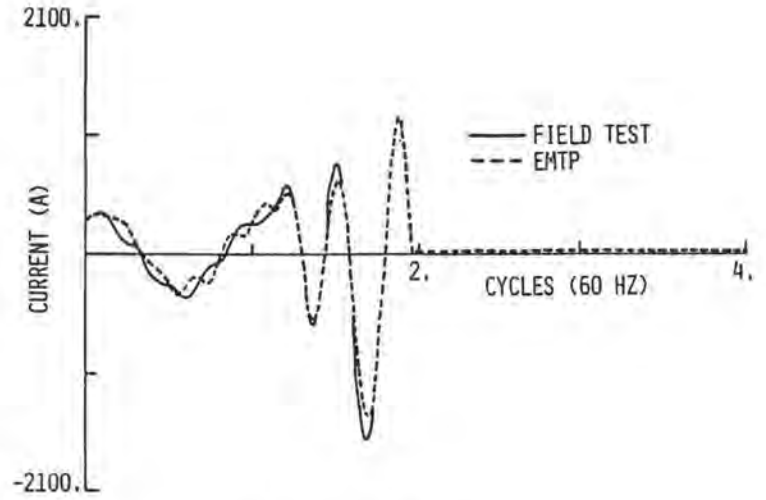
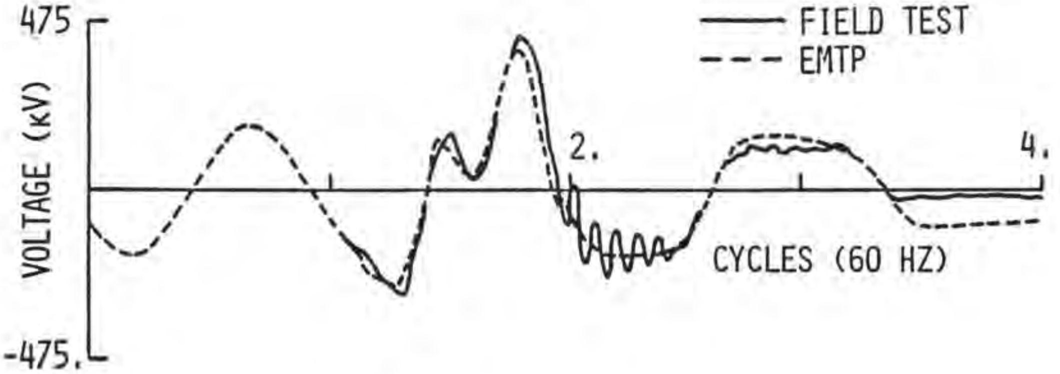


Figure D.7: 'Sandwich' type of winding construction.



(a) Current through the breaker.



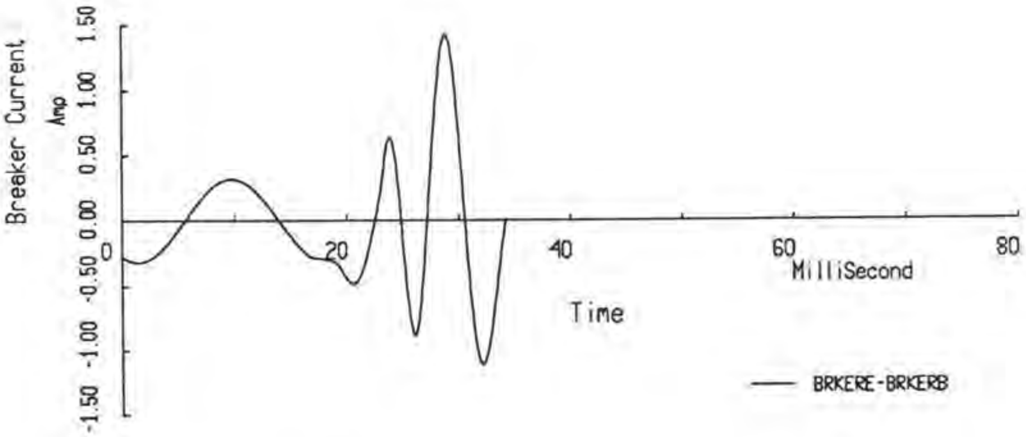
(b) L-G voltage (phase c).

Figure D.8: Comparsion of field test records with simulation results.

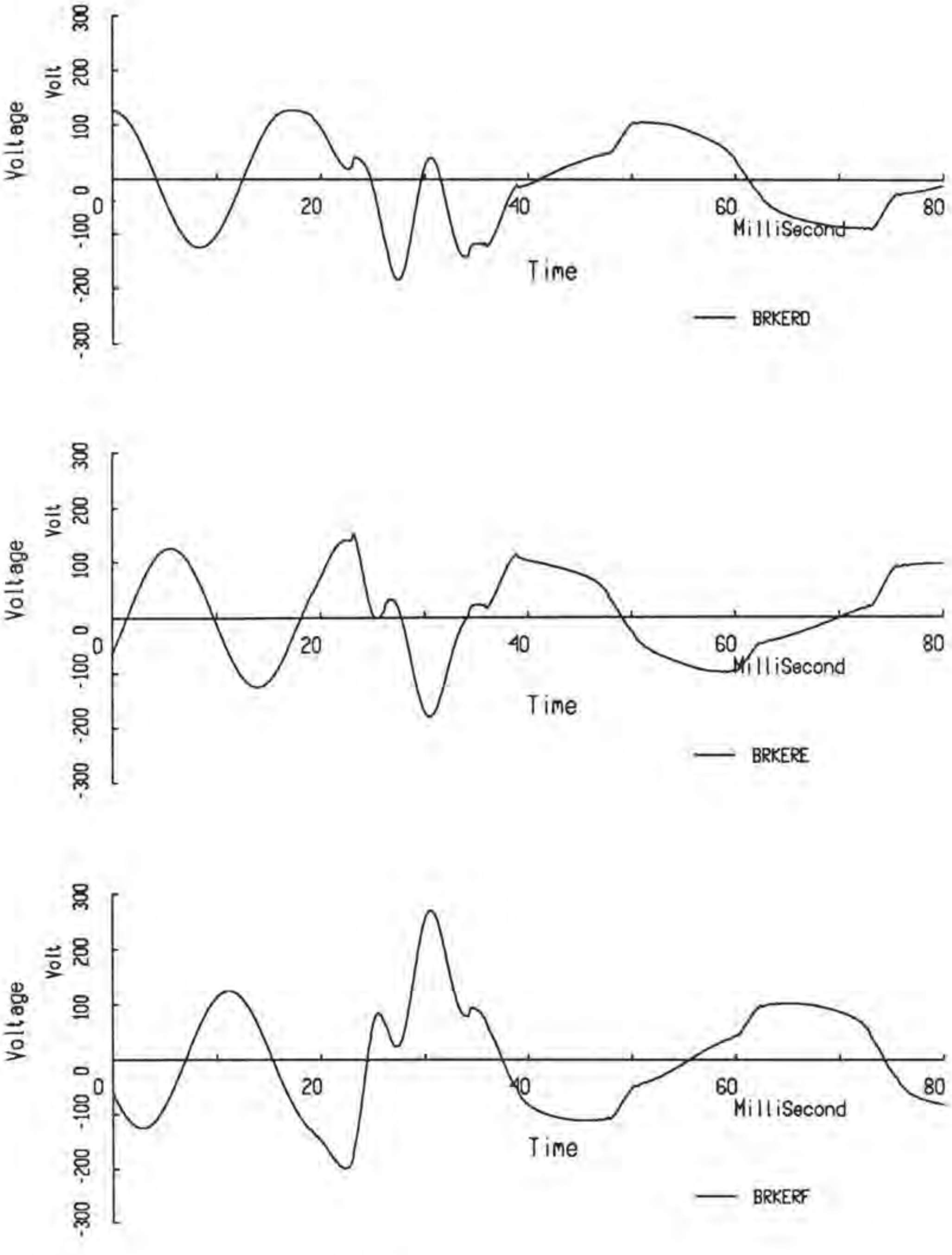
```
C Duplication of TNA simulation results.
C Reduced positive sequence magnetizing impedance (5 times less)
BEGIN NEW DATA CASE
C ........................... Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
  10.E-6     .08
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      35       5       1       1       1                       1
C
C ........................... Circuit data  ..................................
C Equivalent source impedance.
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51SORCEABRKER1               1.5    20.05822
52SORCEBBRKER2                       5.35822
53SORCECBRKER3
C Transformer leakage reactance and resistance
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BRKER1BRKERA                3.38.992
  BRKER2BRKERB                3.38.992
  BRKER3BRKERC                6.38.992
C Capacitor bank model
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BRKERDNEUT                             7.1
  BRKERENEUT  BRKERDNEUT
  BRKERFNEUT  BRKERDNEUT
C Three-limb core transformer model
C Magnetization branch representation
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51BRKERDA                          110.34743
52BRKEREB                          16086.016
53BRKERFC
C Saturatable type 98 branches (saturation characteristic)
C Bus-->Bus-->Bus-->Bus--><--Iss<Phiss                                         O
98BRKERDA                  .0028   .2252
C -------Current<-----------Flux
           .0028        .2252000
           .0039        .2997400
           .0055        .3740140
           .0093        .4138030
           .0137        .4509390
           .0183        .4880750
           .0243        .5252113
           .0377        .5623470
           .0700        .5994840
           .1640        .6366200
           .5030        .6764090
            9999.
C Bus-->Bus-->Bus-->Bus--><--Iss<Phiss                                         O
98BRKEREB     BRKERDA
98BRKERFC     BRKERDA
C Winding resistances
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51A                         12.2
52B                         12.2
53C
C Representation of eddy current lost effect
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51BRKERD                   730.0
52BRKERE                  60000.
53BRKERF
BLANK card terminates circuit data
C
C ........................... Switch data  ...................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                   O
```

```
  BRKERDBRKERA      -1.0      .016                                              1
  BRKEREBRKERB      -1.0      .031                                              1
  BRKERFBRKERC      -1.0      .016                                              1
BLANK card terminates switch data
C
C ..........................Source data  ......................................
C Bus-->< I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
14SORCEA  120.208153       60.       0.                              -1.0
14SORCEB  120.208153       60.    -120.                              -1.0
14SORCEC  120.208153       60.     120.                              -1.0
BLANK card terminates source data
C
C ..........................  Output requests ..................................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BRKERDBRKEREBRKERFBRKERABRKERBBRKERCBRKER1BRKER2BRKER3
BLANK card terminates output requests
BLANK card terminates plot request
BLANK card terminates EMTP solution-mode
```

(a) EMTP input data.



(b) Breaker current (phase b).



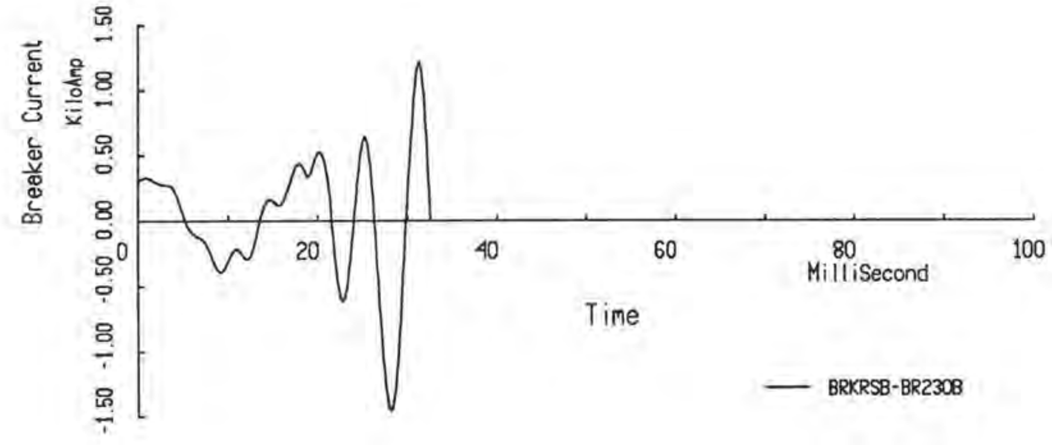
(c) L-G voltages.

Figure D.9: Duplication of TNA simulation results. Breaker current and voltages reproduced by DCG/EPRI EMTP version 1 are the same as Figure D.6.

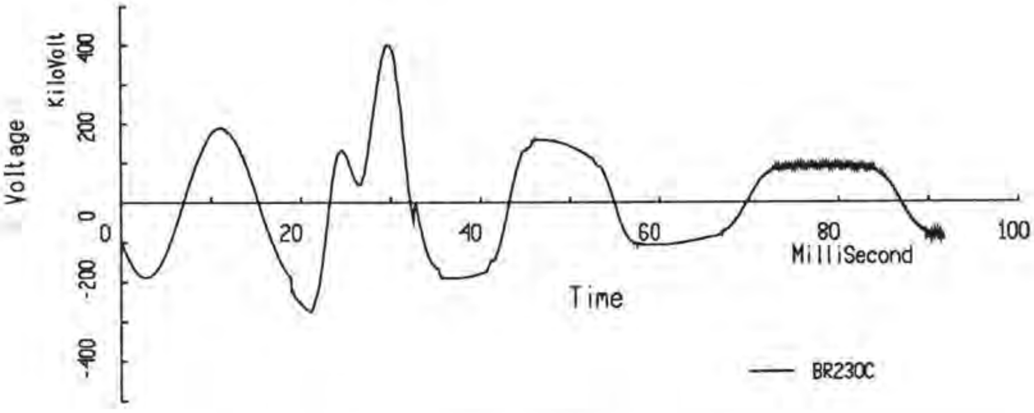
```
C Duplication of field test.
BEGIN NEW DATA CASE
C ........................... Miscellaneous data ..............................
C DeltaT<---TMax<---XOpt<---COpt<-Epsiln<-TolMat<-TStart
   .5E-4   .0917     60.     60.
C --IOut<--IPlot<-IDoubl<-KSSOut<-MaxOut<---IPun<-MemSav<---ICat<-NEnerg<-IPrSup
      15       1       1       1       1                       1
C
C ........................... Circuit data  ...................................
C Test transformer
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51,BR230A,,,,              .236999994+00, .395611045+05,,,,,
52,BR115A,,,,              .106943691-02, .204705872+05$
                           .649999985-01, .105981008+05,,,,,
53,BRTERA,BRTERB,,,       -.392821473-01, .396899545+04$
                          -.473155576-02, .205505548+04$
                           .649999990-02, .399022213+03,,,,,
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51BR230B      BR230A
52BR115B
53BRTERB
51BR230C      BR230A
52BR115C
53      BRTERA
C Test transformer saturation model (Located on the secondary winding)
C Bus-->Bus-->Bus-->Bus--><--Iss<Phiss                                         0
98RESTRA                    9.11240.40
C -------Current<-----------Flux
            9.11          240.40
           18.22          253.40
           36.44          259.90
           54.66          264.31
          109.32          272.11
          910.97          363.90
           9999.
C Bus-->Bus-->Bus-->Bus--><--Iss<Phiss                                         0
98RESTRB      RESTRA
98RESTRC      RESTRA
C Winding resistances used to provide additional damping in the saturation
C branches.
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BR115ARESTRA              .065
  BR115BRESTRB              .065
  BR115CRESTRC              .065
C Capacitor bank 96Mx@119Kv
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BR115ANEUTRL                          6722.6
  BR115BNEUTRLBR115ANEUTRL
  BR115CNEUTRLBR115ANEUTRL
C Equivalent source impedance obtained from a short circuit program
C Bus1->Bus2->Bus3->Bus4-><----R<----------L
51SOURCABRKRSA            .68244     4.86908
52SOURCBBRKRSB            .31944     3.25736
53SOURCCBRKRSC
C Capacitance of transformer's brushings and breakers
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BR115A                                 2.5
  BR115B                                 2.5
  BR115C                                 2.5
C Breaker resistances
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  BRKRSARBRKRA             2625.
  BRKRSBRBRKRB             2625.
  BRKRSCRBRKRC             2625.
```

```
  BR230ARBRKRD                2625.
  BR230BRBRKRE                2625.
  BR230CRBRKRF                2625.
BLANK card terminates circuit data
C
C ............................. Switch data .....................................
C Bus-->Bus--><---Tclose<----Topen<-------Ie                                     0
C Breaker main contacts
  BRKRSABR230A      -1.0     .0140                                               1
  BRKRSBBR230B      -1.0     .0310                                               1
  BRKRSCBR230C      -1.0     .0166                                               1
C Breaker secondary contacts
  RBRKRARBRKRD      -1.0     .0500
  RBRKRBRBRKRE      -1.0     .0643
  RBRKRCRBRKRF      -1.0     .0500
BLANK card terminates switch data
C
C ...........................Source data .......................................
C Bus--><I<Amplitude<Frequency<--T0|Phi0<---0=Phi0         <----Tstart<----Tstop
C Sinsoidal voltage sources (located behind the equivalent source).
14SOURCA    187794.2        60.        0.                           -1.0
14SOURCB    187794.2        60.     -120.                           -1.0
14SOURCC    187794.2        60.      120.                           -1.0
BLANK card terminates source data
C
C ............................ Output requests ... .............................
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
  BR115ABR115BBR115CBR230ABR230BBR230CBRKRSABRKRSBBRKRSC
BLANK card terminates output requests
BLANK card terminates plot request
BLANK card terminates EMTP solution-mode
```

(a) EMTP input data.



(b) Breaker current.

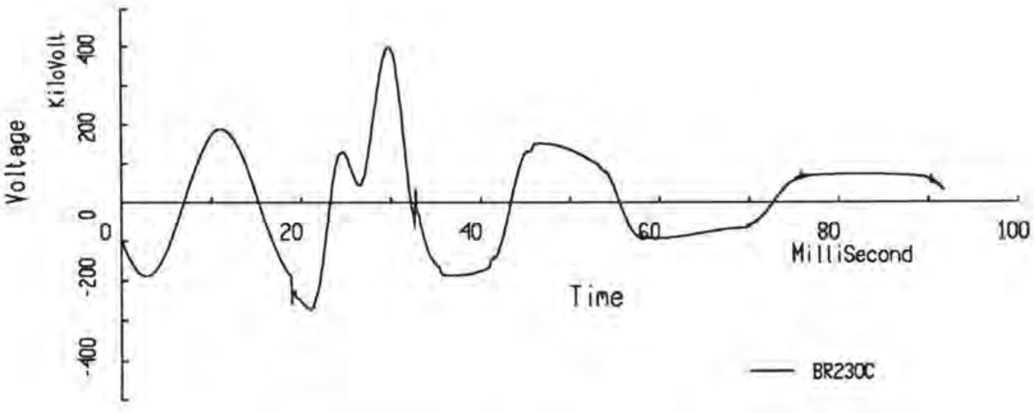


(c) L-G voltage (phase c). Notice oscillations in last cycle.

Figure D.10: Duplication of field test results. Breaker current and voltage reproduced by DCG/EPRI EMTP version 1 are the same as Figure D.8.

```
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  RESTRA                    1.8E4
  RESTRB      RESTRA
  RESTRC      RESTRA
```

(a) Input data for additional oscilation damping resistors.



(b) Voltage output with oscilation damped.

Figure D.11: Effect of parallel damping resistors to numerical oscillations as seen in Figure D.11(b)

APPENDIX E

SIMPLE OVERHEAD LINE MODELS FOR LIGHTNING SURGE STUDIES

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C. R. Torres, Instituto de Investigaciones Electricas, Cuernavaca, Mexico

E.1. Introduction

In lightning surge studies, many simplifying assumptions are made. For example, the waveshape and amplitude of the current source representing the lightning stroke is obviously not well known. Similarly, flashover criteria in the form of volt-time characteristics or integral formulas [1] are only approximate. In view of all these uncertainties, the use of highly sophisticated line models is not justified. Experts in the field of lightning surge studies normally use a simple line model in which all wave speeds are equal to the speed of light, with a surge impedance matrix $[Z_{surge}]$ in phase quantities, where

$$Z_{ii\text{-surge}} = 60 \ln\left(\frac{2h_i}{r_i}\right), \tag{1a}$$

$$Z_{ik\text{-surge}} = 60 \ln\left(\frac{D_{ik}}{d_{ik}}\right) \tag{1b}$$

$$\text{all wave speeds} = \text{speed of light} \tag{1c}$$

with

h_i = average height above ground
r_i = radius of conductor (or of equivalent conductor in case of bundles)
D_{ik} = distance from conductor i to image of conductor k
d_{ik} = direct distance between conductors i and k

Typically, each span between towers is represented separately as a line, and only a few spans are normally modelled (3 for shielded lines, or 18 for unshielded lines in [1]). For such short distances, losses in series resistances and differences in modal travel times are negligible. The effect of corona is sometimes included, however, by modifying the simple model of Equation (1) [1].

It is possible to develop a new line model based on Equation (1), in which all calculations are done in phase quantities. But as shown here, the simple model of Equation (1) can also be handled with the existing untransposed-line model of K.C. Lee [2].

E.2. Simple Model ("Lossless High-Frequency Approximation")

An M-phase transmission line is described by the following well-known phasor equations:

$$\left[\frac{d^2V}{dx^2}\right] = [Z'][Y'][V] \tag{2a}$$

$$\left[\frac{d^2I}{dx^2}\right] = [Y'][Z'][I] \tag{2b}$$

The simple model is derived from Equation (2) by making two assumptions for a "lossless high-frequency approximation":

1. Conductor resistances and ground return resistances are ignored.
2. The frequencies contained in the lightning surges are so high that all currents flow on the surface of the conductors, and on the surface of the ground.

Then the elements of $[Z']$ become

$$Z'_{ii} = j\omega\frac{\mu_0}{2\pi}\ \ln\left(\frac{2h_i}{r_i}\right) \tag{3a}$$

$$Z'_{ik} = j\omega\frac{\mu_0}{2\pi}\ \ln\left(\frac{D_{ik}}{d_{ik}}\right) \tag{3b}$$

with $\mu_0/2\pi = 2 \times 10^{-4}$ H/km. $[Y']$ is obtained by inverting the potential coefficient matrix,

$$[Y'] = j\omega[P']^{-1} \tag{4}$$

with the elements of $[P']$ being the same as in Equation (3) if the factor $j\omega\mu_0/2\pi$ is replaced by $1/2\pi\varepsilon_0$. Then both matrix products in Equation (2) become diagonal matrices with all elements being

$$\lambda_i = -\omega^2\varepsilon_0\mu_0, \quad i = 1, \ldots M \tag{5}$$

These values are automatically obtained from line constants programs as the eigenvalues of the matrix products in Equation (2) by simply using the above two assumptions in the input data (all conductor resistances = 0, GMR/r = 1.0, no Carson correction terms). The calculation of the eigenvector matrix $[T_i]$ needed for the untransposed line model [2] breaks down, however, because the matrix products in Equation (2) are already diagonal. To obtain $[T_i]$, let us first assume equal, but nonzero conductor resistances R'. Then the eigenvectors $[x_i]$ are defined by

$$\left(-\omega^2\varepsilon_0\mu_0[U] + j\omega R'[P']^{-1}\right)[x_i] = \lambda_i[x_i] \tag{6}$$

with the expression in parenthesis being the matrix product $[Y'][Z']$, and $[U]$ = unity matrix. Equation (6) can be rewritten as

$$[P']^{-1}[x_i] = \lambda_{i\text{-modified}}[x_i] \tag{7}$$

with modified eigenvalues

$$j\omega R'\lambda_{i\text{-modified}} = \lambda_i + \omega^2\varepsilon_0\mu_0 \tag{8}$$

Equation (7) is valid for any value of R', including zero. It therefore follows that $[T_i]$ is obtained as the eigenvectors of $[P']^{-1}$, or alternatively as the eigenvectors of $[P']$ since the eigenvectors of a matrix are equal to the eigenvectors of its inverse. The eigenvalues of $[P']^{-1}$ are not needed because they are already known from Equation (5), but they could also be obtained from Equation (8) by setting $R' = 0$.

For this simple model, $[T_i]$ is a real, orthogonal matrix,

$$[T_i][T_i]^t = [U] \tag{9}$$

and therefore,

$$[T_v] = [T_i] \tag{10}$$

D. E. Hedman has solved this case of the lossless high-frequency approximation more than 20 years ago [3]. He recommended that the eigenvectors be calculated from the surge impedance matrix of Equation (1), which is the same as calculating them from $[P']$ since both matrices differ only by a constant factor.

One can either modify a line constants programs to find the eigenvectors from $[P']$ in the lossless high-frequency approximation, as was done in UBC's version and will be done in version 2.0 of the DCG/EPRI EMTP, or use the same trick as in the explanations above in an unmodified program: Set all conductor resistances equal to some nonzero value R', set GMR/r=l, and ask for zero Carson correction terms.

In the process of modifying the UBC Line Constants Program, numerical overflow occurred occasionally. This problem was cured by scaling the matrices. In finding the eigenvectors from $[Y'][Z']$, all elements were multiplied with $-1/(\omega^2\varepsilon_0\mu_0)$, and 1.0 was subtracted from the diagonal elements, as suggested by Galloway, Shorrocks and Wedepohl [4]. In finding the eigenvectors from $[P']$, all elements were multiplied with $2\pi\varepsilon_0$.

The lossless high-frequency approximation produces eigenvectors which differ from those of the lossy case at very high frequencies [5]. This is unimportant for lightning surge studies, but important for power line carrier problems.

E.3. Example

For a distribution line with one ground wire as shown in Figure E.1, the lossless high-frequency approximation produces the modal surge impedances of Table E.1, the transformation matrix of Equation (11), and the phase surge impedance matrix $[T_i][Z_{mode}][T_i]^t$ of Equation (12). The elements

$$[T_i] = \begin{bmatrix} 0.52996 & 0.82860 & -0.18049 & 0 \\ 0.49080 & -0.21322 & 0.46222 & -0.70711 \\ 0.49080 & -0.21322 & 0.46222 & 0.70711 \\ 0.48721 & -0.47170 & -0.73493 & 0 \end{bmatrix} \tag{11}$$

$$[Z_{surge}] = \begin{bmatrix} 490.33 & & & \\ 176.95 & 484.89 & & \text{symmetric} \\ 176.95 & 174.27 & 484.89 & \\ 190.74 & 144.26 & 144.26 & 495.31 \end{bmatrix} \Omega \tag{12}$$

from Equation (1) are slightly larger, by a factor of 300,000/299,792, because the line constants program uses 299,792 km/s for the speed of light, versus 300,000 km/s implied in Equation (1).

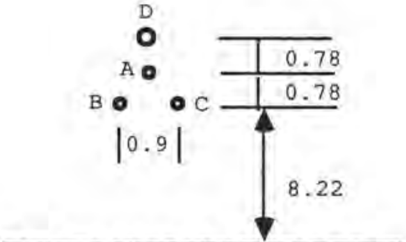

Figure E.1: Position of phase conductors A,B,C and ground wire D (average height, all dimensions in m). Conductor diameter = 10.1092 mm.

Table E.1: Modal Surge Impedances

mode	z_{surge} (Ω)
1	993.44
2	290.67
3	360.70
4	310.62

The circuit data portion of the transmission line part of an EMTP input file for modelling 4 spans, each 90 m long, would look as follows:

```
C Lightning surge studies
C Distributed parameter line
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<--------------------->0
-11A    2A                      993.440.3E-6       2   4                       0
-21B    2B                      290.670.3E-6       2                           0
-31C    2C                      360.700.3E-6       2                           0
-41D    2D                      310.620.3E-6       2                           0
C ---Ti(x,1)<----Ti(x,2)<----Ti(x,3)<----Ti(x,4)
     .529956     .828595    -.180491          0.
          0.          0.          0.          0.
     .490801    -.213224     .462222    -.707107
          0.          0.          0.          0.
     .490801    -.213224     .462222    -.707107
          0.          0.          0.          0.
     .487211    -.471701    -.734931          0.
          0.          0.          0.          0.
C Bus-->Bus-->Bus-->Bus--><---R'<----A<----B<--len 0 0 0<--------------------->0
-12A    3A    1A    2A                                                         0
-22B    3B                                                                     0
-32C    3C                                                                     0
-42D    3D                                                                     0
-13A    4A    1A    2A                                                         0
-23B    4B                                                                     0
-33C    4C                                                                     0
-43D    4D                                                                     0
-14A    5A    1A    2A                                                         0
-24B    5B                                                                     0
-34C    5C                                                                     0
-44D    5D                                                                     0
-11D    1DG                     390.00.03E-6       2                           0
-12D    2DG   1D    1DG                                                        0
-12D    2DG   1D    1DG                                                        0
-13D    3DG   1D    1DG                                                        0
-14D    4DG   1D    1DG                                                        0
-15D    5DG   1D    1DG                                                        0
C Bus1->Bus2->Bus3->Bus4-><----R<----L<----C
  1DG                        20.
  2DG         1DG
  4DG         1DG
  5DG         1DG
  3DG                        1.8
BLANK card terminates circuit data
```

The towers in node 1, 2, 3, 4, 5 are represented as surge impedances of 390 Ω, with $\tau = 0.03$ µs, and tower footing resistances of 20 Ω in 1, 2, 4 and 1.8 Ω in 3.

E.4. Long Lines

If a lightning stroke hits a conductor at a distance with travel time τ which is greater than $t_{max}/2$ from the substation (t_{max} = maximum time of transient simulation), and if no flashovers occur on this line (Figure E.2), then the line with its wave coming into the substation can be modelled very simply: Connect the line surge impedance as a resistance from substation to ground, and inject the current $i(t)$ directly into the struck phase of the substation, as shown in Figure E.3.

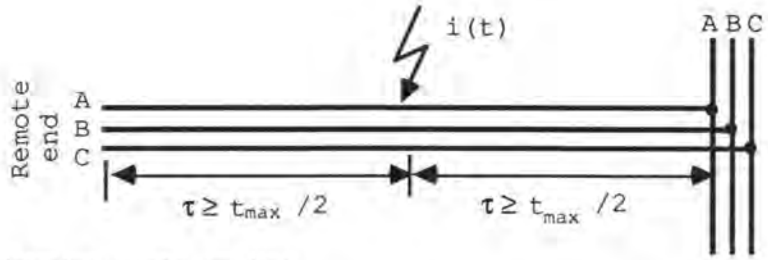

Figure E.2: Lightning stroke on line.

This simple model works only if the case starts from zero initial conditions, and if the travel time from the remote end to the stroke location has $\tau \geq t_{max}/2$.

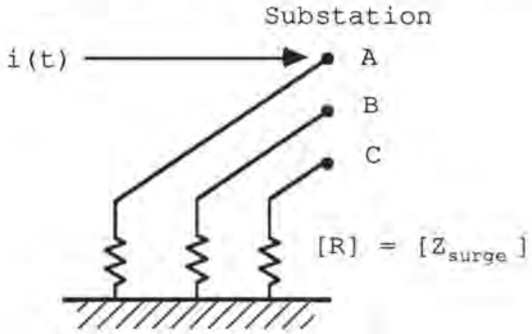

Figure E.3: Model of long line hit by `i(t)` in phase A far away from substation.

Similarly, an unfaulted line with τ which is greater than $t_{max}/2$ leaving the substation can also be represented as a shunt resistance matrix $[R] = [Z_{surge}]$. The EMTP automatically converts lines into shunt resistances (with no past history table updating in the time step loop) if the case starts from zero initial conditions and if τ is greater than t_{max}. For the lossless high-frequency approximation discussed here, τ will not influence the results, and any value tau is greater than t_{max} can be used. It is also advisable to set the second node names "blank"; in this way, no equations are wasted for the nodes of the remote ends.

E.5. More Accurate Models

For users who are reluctant to use the simple model discussed here, a few comments are in order. First, let us compare exact values with the approximate values. If we use constant parameters and choose 400 kHz as a reasonable frequency for lightning surge studies, then we obtain the results of Table E.2 for the test example of section E.3, assuming T/D = 0.333 for skin effect correction with the tubular conductor formula, $R'_{dc} = 0.53609$ Ω/km, and $\rho = 100$ Ω–m.

Table E.2: Exact Line Parameters at 400 kHz

mode	Z_{surge} (Ω)	wave velocity (m/s)	R' Ω/km
1	1027.6-j33.9	285.35	597.4
2	292.0-j0.5	299.32	7.9
3	361.9-j0.5	299.37	8.2
4	311.1-j0.5	299.32	8.0

The differences are less than 0.5% in surge impedance and wave speed for the aerial modes 2 to 4, and not more than 5% for the ground return mode 1. These are small differences, considering all the other approximations which are made in lightning surge studies. If series resistances are included by lumping them in 3 places, totally erroneous results may be obtained if the user forgets to check whether R/4 is less than Z_{surge} in the ground return mode. For the very short line length of 90 m in this example, this condition would still be fulfilled here.

Using constant parameters at a particular frequency is of course an approximation as well, and some users may therefore prefer frequency-dependent models. For very short line lengths, such as 90 m in the example, most frequency-dependent models may become unreliable, though tests with the `JMARTI` model in 1987 have shown that it works well for short lines too. It may therefore be more sensible to use the simple model described here, for which answers are reliable, rather than sophisticated models with possibly unreliable answers.

E.6. Acknowledgments

This appendix describes work done at the Instituto de Investigaciones Electricas, Cuernavaca, Mexico. The authors are grateful to Dr. A. Rodriguez and Dr. V. Gerez for their encouragement, and for their permission to publish the results.

E.7. References

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[2] Tsu-huei Liu, "A Practical New EMTP Model for Untransposed Transmission Lines: The Constant Parameter Distributed Option Provided by K. C. Lee of UBC". EMTP Newsletter, vol. 2, No. 1, June 1981.

[3] D. E. Hedman, "Propagation on Overhead Transmission Lines. I - Theory of Modal Analysis. II - Earth-Conduction Effects and Practical Results", IEEE Trans. Power App. Syst., vol. PAS-84, pp. 200-211, March 1965, and pp. 489-492, June 1965.

[4] R. H. Galloway, W. B. Shorrocks, and L. M. Wedepohl, "Calculation of Electric Parameters for Short and Long Polyphase Transmission Lines", Proc. IEE, vol. 111, pp. 2051-2059, Dec. 1964.

[5] L. M. Wedepohl, "Electrical Characteristics of Polyphase Transmission Systems with Special Reference to Boundary-Value Calculations at Power-Line Carrier Frequencies", Proc. IEEE, vol. 112, pp. 2103-2112, Nov. 1965.

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