SEL-PROFILE®

TRANSMISSION LINE
FAULT ANALYSIS PROGRAM

INSTRUCTION MANUAL

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Warning

This device is shipped with default passwords. Default passwords should be changed to private passwords at installation. Failure to change each default password to a private password may allow unauthorized access. SEL shall not be responsible for any damage resulting from unauthorized access.

ATTENTION!

Cet équipement est expédié avec des mots de passe par défaut. A l'installation, les mots de passe par défaut devront être changés pour des mots de passe confidentiels. Dans le cas contraire, un accès non-autorisé à l'équipement pourrait être possible. SEL décline toute responsabilité pour tout dommage résultant de cet accès non-autorisé.

20001120

Standard Product Warranty – Ten Years

Definition of Terms

Product:	All items manufactured by SEL that are sold to a customer.
New Product:	A product manufactured by SEL that is sold for the first time.
Customer:	An end-user of the product.

New Product Warranty

All new products sold to customers are warranted against defects in design, materials, and workmanship for a period of ten (10) years from the date of first retail delivery to a customer. If it is determined that the new product defect is covered under this warranty, SEL will repair, replace, or substitute an identical unit at its own discretion to the customer at no charge.

SEL may, at its own discretion, require the customer to ship the unit back to the factory for diagnosis before making a determination as to whether it is covered by this warranty. In such event, SEL may, at its own discretion, decide to provide the customer with a substitute unit which may be sent to the customer either from the SEL factory or from an authorized representative or distributor from their inventory.

All expenses related to the shipment of defective units back to SEL or the provision of a substitute unit to the customer are the responsibility of the customer. This expense may include, but is not limited to, freight, insurance, Customs clearance, and duties. All expenses related to the shipment of repaired units back to customers (or the provision of a new unit to the customer) will be borne by SEL.

Product Upgrade Policy

From time to time, SEL makes product upgrades to add to or enhance the performance of the products. Customers of a particular product being issued an upgrade will be notified either by SEL directly or through its authorized representatives or distributors.

Customers who have purchased an annual upgrade policy will receive all upgrades during the calendar year free of charge. Customers who did not purchase the annual upgrade policy may purchase each unit upgrade individually. The annual upgrade policy can be purchased at any time. Regardless of whether the upgrade policy is purchased, SEL will make reasonable efforts to notify all customers of all available upgrades.

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ISO 9001 CERTIFIED

Equipment Repair and Warranty

Repair costs of products not covered under this warranty are paid for by customers. Customers are responsible for the cost of shipping the products to SEL located at: 2350 NE Hopkins Court, Pullman, Washington 99163 USA.

All products repaired by SEL will be warranted against defects in material and workmanship for a period of one year from the date the equipment is returned to the customer or the remainder of the new product warranty, whichever is longer.

Limitations

SEL's warranty does not extend to (A) SEL's products subject to (i) improper installation, connection, operation, maintenance, or storage; (ii) accident, damage, abuse, or misuse; (iii) abnormal or unusual operating conditions or applications outside the specifications for the product; (iv) a purpose or application in any way different from that for which the products were designed; or (v) repairs conducted by persons other than SEL employees or an authorized representative or distributor; (B) Equipment and products not manufactured by SEL. Such equipment and products may be covered by a warranty issued by the respective manufacturer.

This warranty is in lieu of any other warranties, express or implied, including without limitation, any warranty of merchantability or fitness for a particular purpose, and is in lieu of any and all other obligations or liability of SEL. Under no circumstances shall SEL be liable for any accidential or consequential damages or for any other loss, injury, damage, or expense of any kind including loss of profits arising hereunder.

To the extent any court, arbitration panel, or other governmental body of competent jurisdiction shall declare any provision of this warranty invalid or unenforceable by reason of a rule of law or public policy, all the other provisions hereof shall remain in full force and effect.

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CHAPTER 1: INTRODUCTION

APPLICATIONS

Use the SEL-PROFILE program to:

- Reprocess event reports to compensate for line constant, scaling, and connection errors.
- Locate faults, accommodating lumped impedance elements and distributed capacitance.
- Accommodate the effects of mutual coupling from parallel circuits.
- Determine phase and sequence quantities to compare with those from your short circuit studies.
- Verify and improve line constants.
- Calculate fault resistance.
- Determine fault locations using oscillographic or other non-SEL records.
- Visualize the effects of line-constant changes on fault location accuracy.
- Aid in creating nomographs with which to calibrate fault locating relays for system inhomogeneities.

SPECIFICATIONS

- Calculates fault location with data from a single end of a transmission line, using Takagi or Reactance algorithms.
- Single-end Takagi and Reactance algorithms compensate for known zero sequence mutual coupling with a parallel circuit.
- Calculates fault location with data from both ends of a transmission line, using the Schweitzer algorithm.
- Two-end Schweitzer algorithm inherently compensates for known or unknown zero sequence mutual coupling with a parallel circuit.
- Accommodates one series and one shunt impedance/admittance lump at each line end. (Examples are capacitor banks and shunt reactors.)
- Accommodates distributed line capacitance.
- Displays voltage and current phasors at the bus, beyond the lumped elements, and at the fault or other user-selected locations. Displays phasors in phase or symmetrical component formats.

- Accepts disk copies of event reports from any SEL relay intended for line protection.

- Permits manual entry of phasor voltage and current data, as taken from oscillographic records or paper copies of SEL event reports.

- Conveniently accommodates operator judgment and intervention.

- Provides context sensitive help to minimize references to the instruction manual.

- Requires two-cycle minimum fault duration.

FAULT LOCATING ALGORITHMS

- General Capabilities
  Automatically determines fault type and selects data
  Convenient line-constant modification
  Input quantities may be permuted and rescaled

- Takagi Single-Ended Method
  Minimizes effects of load flow and fault resistance
  Includes mutual coupling compensation

- Reactance Single-Ended Algorithm
  Does not require prefault data
  Includes mutual coupling compensation

- Schweitzer Two-Ended Algorithm
  Least affected by fault resistance and load flow
  Results are provided from all three sequence networks

SYSTEM MODEL

- Transmission Line Model
  R0, X0, R1, X1 and line length obtained from relay event reports
  B0, B1, R0M, X0M are optional
  Line constants are easily modified

- Lumped Elements
  Accommodates shunt admittance and series impedance at each end of line, to model reactors and capacitors.

PROGRAM REPORTS

- Disk Directories
- Disk Files
- Data Set Summaries
- Configurations of Transmission Line and Terminals
- Reactance and Takagi Fault Location Reports
- Schweitzer Fault Location Reports
- Fault Location Reports for Evolving Faults
- System Voltage/Current Profile in Phase Quantities
- System Voltage/Current Profile in Sequence Quantities

PROGRAM OPERATION

- Menu-driven user interface eliminates need to memorize commands
- Select Terse or Verbose modes
- One-key context-sensitive help screens provide convenient guidance
- Program Reference Card describes all commands and procedures
- Reads SEL Event Reports stored on disk
- Accommodates manual entry of fault data

COMPUTER REQUIREMENTS

• Type:	IBM-PC or compatible computer
• Operating System:	Microsoft MS-DOS Version 3.2 or higher with a minimum of 256 KB RAM **or** Digital Research Concurrent DOS XM Version 6.2 or higher with a minimum of 512 KB RAM
• Disk Drives:	Two floppy drives, or one floppy drive and one hard drive
• Math Coprocessor:	Speeds operation, but is not required

PROGRAM OVERVIEW

The SEL-PROFILE program facilitates analysis of transmission line faults. The program is menu driven, and user interaction is conveniently accommodated.

Figure 1-1 graphically shows the SEL-PROFILE program fault analysis process.

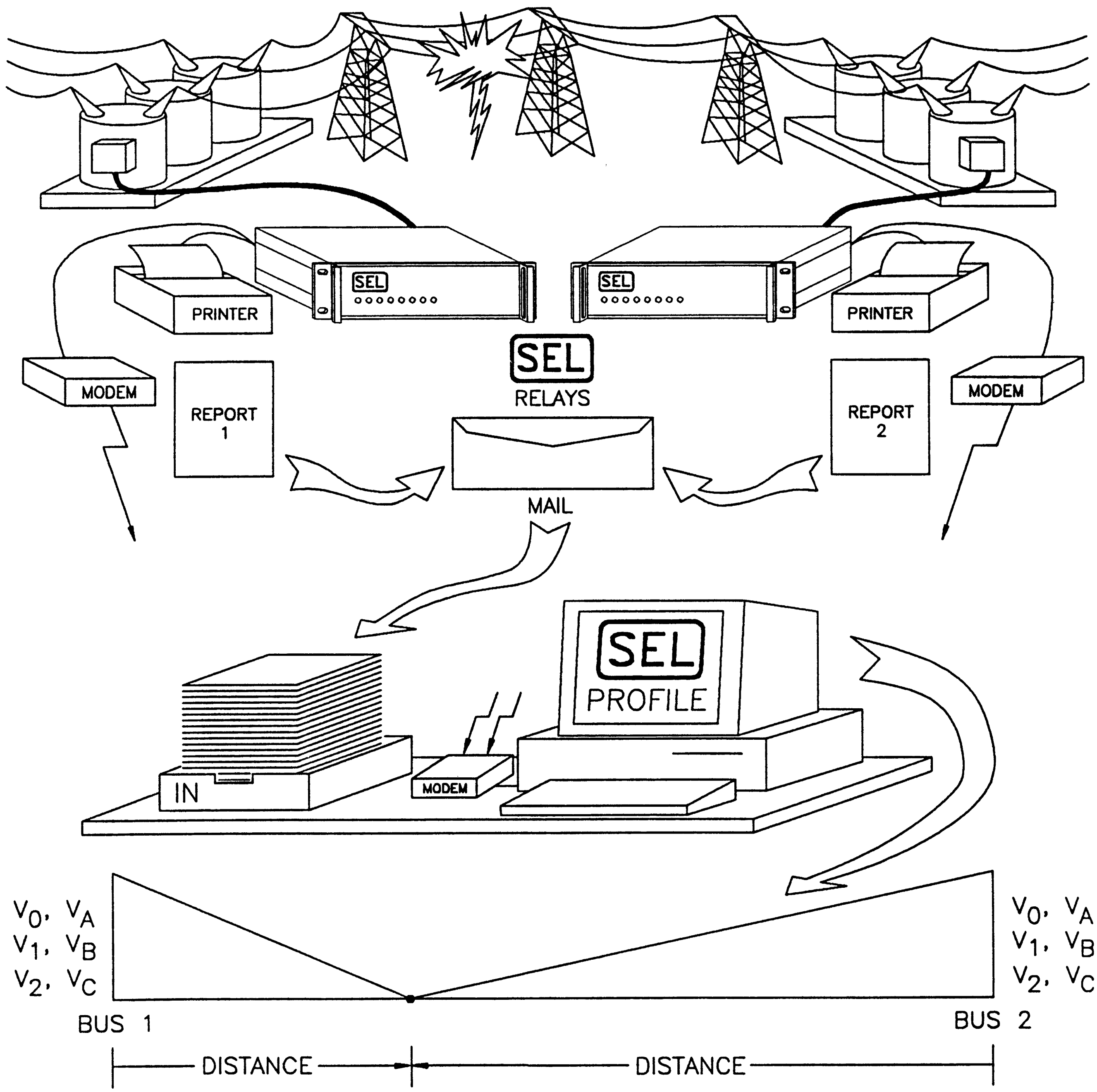


FIGURE 1-1. TYPICAL USAGE OF THE SEL-PROFILE PROGRAM

To use the SEL-PROFILE program, you must first retrieve phasor measurements of voltage and current from one or both line ends. SEL line-protection relays automatically record these data in the format required by the SEL-PROFILE program. You must only save the SEL event reports to a disk file to make them directly usable by the program. You can very conveniently save the event reports to disk using your favorite communications program, if the SEL relays and your computer are equipped with modems. Otherwise, you can manually enter the phasor data into the SEL-PROFILE program, either reading from paper copies of SEL event reports, or interpreting phasor data from other sources, such as oscillographic records.

Once the fault data are entered into the program, you can locate faults by any of several different methods. These include the single-end Takagi method, which employs prefault data to mitigate errors caused by fault resistance and load flow; the single-end Reactance method, which requires no knowledge of prefault conditions; and the two-end Schweitzer method, which inherently minimizes the effects of zero sequence mutual coupling to parallel circuits, and is least affected by fault resistance and load flow.

After locating the fault, the SEL-PROFILE program displays a voltage and current profile of the transmission line. This feature shows phasor quantities at the bus, beyond local lumped impedance elements, and at the fault. You select either phase or symmetrical component quantities for display.

HOW TO USE THIS MANUAL

Use the "COMMANDS" chapter while you are learning the program. It teaches you many of the analysis features provided. The chapter "HOW TO USE THE SEL-PROFILE PROGRAM" walks you through a typical fault analysis session. Step through this chapter when running the program for the first time.

The manual shows computer-generated screens in boxes as illustrated below.

```
This is an example of the compressed font and boxed enclosure used throughout
this manual to indicate what you should see on your computer screen.
```

Where you must type a response to a prompt, we precede the appropriate response with "Type:"

For example, to start the program you must type its name, "PROFILE", at the system prompt, followed by pressing the carriage return or enter key. We indicate this process as:

Type: PROFILE <CR>

Note how the "<CR>" symbol sequence refers to the pressing of the carriage return or enter key, not the literal symbols.

CHAPTER 2: INSTALLATION

HOW TO INSTALL THE SEL-PROFILE PROGRAM

We have automated most of the installation process for you in a batch program named "LOADPROF.BAT". To install the program, perform the following steps:

(1) Put the SEL-PROFILE program distribution floppy into a floppy drive of your computer, say drive A.

(2) Change the current drive to that containing the distribution floppy.

    Type: A: <CR>

(3) Run the LOADPROF.BAT program, naming the source drive and destination drive for the SEL-PROFILE software. For example, to install it on the C drive:

    Type: LOADPROF A C <CR>

(4) The LOADPROF.BAT program now takes over to complete the installation. Observe the process to verify that no errors are detected.

(5) Refer to Chapter 4: "HOW TO USE THE SEL-PROFILE PROGRAM" for instructions on how to start up and use the program.

CHAPTER 3: COMMANDS

INTRODUCTION

Study this chapter to learn the SEL-PROFILE program command set. We first discuss command usage and then describe each command and its options.

VERBOSE AND TERSE PROGRAM MODES

You can operate the SEL-PROFILE program in one of two modes, TERSE or VERBOSE. In TERSE mode, the program interacts minimally with you. It selects alignment angles, fault data, and fault types without requesting your intervention, unless it detects problems. It proceeds directly to presentations of fault locations and voltage/current profiles.

In VERBOSE mode, on the other hand, the program pauses at key points throughout its fault analysis, and presents intermediate data to you, requesting your approval or modification of the intermediate analysis results. For example, the program presents phasor fault data to you, along with its determination of fault type, and requests you to concur with its analysis, or to examine the data and select the fault type yourself. The subsequent fault analysis steps will be influenced by your intervention, allowing you to shape the analysis process using your own engineering expertise and specific details of the power system, or knowledge about a particular fault.

The program is in VERBOSE mode when it starts up. To change modes from VERBOSE to TERSE, or from TERSE to VERBOSE,

Type: V <CR>

The menus presented to you are different in VERBOSE and TERSE modes. They are both displayed below:

TERSE Mode Menu

```
DATA: < Dir, List file, Read data, Print summary, Enter, Configure >
LOCATE: < Schweitzer, Xreactance, Takagi, Mutual >
MISC: < Verbose, (U)start-up, (F1)help, (Esc)quit >
ENTER COMMAND: <   >
```

VERBOSE Mode Menu

```
DATA HANDLING ============================================== EXAMPLES ======
  < D >  <DIRECTORY> of disk  ............................. "D <CR>"
  < L >  <LIST> disk file to screen  ..................... "L filename <CR>"
  < R >  <READ> event report into data set  .............. "R filename <CR>"
  < P >  <PRINT> data set summaries to screen............. "P <CR>"
  < E >  <ENTER> fault data manually
  < C >  <CONFIGURE> Modify/View/File line/terminal CONFIGURATION settings

FAULT LOCATING AND PROFILING ==============================================
  < S >  <SCHWEITZER> two-end method  ....................../  USE < R > \...
  < X >  <REACTANCE> single-end method  .................../  OR  <E,C>  \..
  < T >  <TAKAGI> single-end method  .....................\  COMMANDS   /..
  < M >  <MUTUAL> compensation <X,T> (for parallel ckt).....\  FIRST     /...

MISCELLANEOUS =============================================================
  < V >  <VERBOSE> (more interactive) and <TERSE> modes (V toggles)
  < U >  <START-UP> Modify/View start-up directory defaults

  <F1 >  <HELP> Type FUNCTION KEY F1 for help with a command
  <Esc>  <ESCAPE> program and return to DOS

ENTER COMMAND ==================================( PROFILE:1.05 )===========
  <   >
```

COMMAND SYNTAX

For most commands you must type one or two characters (upper or lower case is irrelevant) designating the command itself, followed in some cases by a command parameter, and usually followed in turn by the carriage return or enter key, <CR>. The general command syntax requires you to

Type: command designator command parameter <CR>

where the command parameters are not required for all commands. An example of a command requiring a parameter is an option of the DIRECTORY command for which you must name the directory to be displayed. To invoke the command,

Type: DD C:\PROFILE*.* <CR>

where for "C" and "PROFILE" you substitute the drive and directory you wish to examine. An example of a command requiring no parameter is another option of the DIRECTORY command. For this option, the specific directory which you last accessed will be assumed by the program when you

Type: D <CR>

Commands invoked by pressing any function or cursor key, or the ***Esc*** key, do not require the terminating <CR>.

ONE-LETTER AND TWO-LETTER COMMAND OPTIONS

As in the examples of the DIRECTORY command above, many of the SEL-PROFILE program commands have options which you invoke by adding one more character to the one-letter command designator. For example, the DIRECTORY command has options invoked by the character sequences "D", "DD", "D1", "D2", "D3", and "D4". Table 3-1 below shows all of the one- and two-letter command options and summarizes their specific behaviors. The DETAILED COMMAND DESCRIPTIONS section provides more details.

TABLE 3-1: COMMAND OPTION SUMMARIES

Command Option	Summary Explanation
D	Display the previously accessed disk directory.
DD directory	Display the named disk directory.
D1, D2, D3, D4	Display default directory one through four, which you specify using the < U > (START-UP) command.
L file	List the named file which resides in the previously accessed directory.
LL directory/file	List the named file which resides in the named directory (and drive).
L1 file L2 file L3 file L4 file	List the named file which resides in default directory one through four, which you specify using the < U > (START-UP) command.
R file	Read in the named event report file which resides in the previously accessed directory.
RR directory/file	Read in the named event report file which resides in the named directory (and drive).
R1 file R2 file R3 file R4 file	Read in the named event report file which resides in default directory one through four, which you specify using the < U > (START-UP) command.
P	Display summaries of the event reports you read into the program using the < R > (READ) command or the < E > (ENTER) and < C > (CONFIGURATION) commands.
PP	Display summaries just like the < P > command, but also display the voltage and current sample data.
E	Enter prefault and/or fault voltage and current phasor data into the program via your keyboard.

Command Option	Summary Explanation
ER	Erase both data sets, returning them to their startup states.
C	Modify the line constants and terminal constants employed by the fault locating and profiling functions.
S	Perform the SCHWEITZER two-end fault location algorithm on the two data sets you read into the program using the < R > (READ) command, or the < E > (ENTER) and < C > (CONFIGURATION) commands. Then show two-end voltage and current profiles of the transmission line.
X	Perform the REACTANCE one-end fault location algorithm on the data set you read into the program using the < R > (READ) command, or the < E > (ENTER) and < C > (CONFIGURATION) commands. Then show one-end voltage and current profile of the transmission line.
XX	Perform the REACTANCE one-end fault location algorithm, on a row by row basis per six fault types, in a format suitable for analysis of evolving faults.
T	Perform the TAKAGI one-end fault location algorithm on the data set you read into the program using the < R > (READ) command, or the < E > (ENTER) and < C > (CONFIGURATION) commands. Then show one-end voltage and current profile of the transmission line.
TT	Perform the TAKAGI one-end fault location algorithm, on a row by row basis per six fault types, in a format suitable for analysis of evolving faults.
M	Perform the REACTANCE or TAKAGI one-end fault location algorithm on the two data sets you read into the program using the < R > (READ) command or the < E > (ENTER) and < C > (CONFIGURATION) commands. Compensate one of the data sets for zero sequence mutual coupling effects measured in the other data set, which you retrieved from a circuit parallel to the faulted circuit. Then show the one-end voltage and current profile of the transmission line.
MM	Perform the mutual coupling compensated REACTANCE or TAKAGI fault location algorithm as for the < M > command, but on a row by row basis per six fault types, in a format suitable for analysis of evolving faults.
V	Toggle between VERBOSE and TERSE program modes.
U	Modify the default directories which you may reference using the < DN >, < LN >, and < RN > commands (N = 1, 2, 3, 4).

Special Keys	Summary Explanation
F1	Press the *F1* function key to examine a help screen related to the present context of the SEL-PROFILE program.
Esc	Press the ***Esc*** key twice from the main menu prompt to exit the SEL-PROFILE program and return to the operating system.

DETAILED COMMAND DESCRIPTIONS

This section gives detailed descriptions of the commands available from the main menu of the SEL-PROFILE program. Part of the descriptions include reprints of the help screen summaries provided for each of the commands. These help screen summaries are available for viewing on your computer screen whenever the SEL-PROFILE program is running. To view the help screen, just press the "*F1*" function key at the main menu prompt. Then enter the key letter of the command for which you wish to view a help screen. Once you become familiar with the SEL-PROFILE program, you should rarely have to refer to this manual, since the help screens are always instantly available.

Detailed descriptions of each main menu command follow.

D Command: Show Directory Contents

Use this command to display the names of all files residing in the directory last accessed by any of the < D >, < L >, or < R > commands. This is helpful, for example, when you are searching for a particular event report to read into the SEL-PROFILE program data sets.

```
< D > USAGE:     Type:  DD DRIVE:\PATH\FILENAME.EXT <CR>
      EXAMPLE:   Type:  DD C:\LINE6440\8805????.P* <CR>
                        (Faults in May 88 at PEAVY sub)
      OPTIONS:   Type:  D <CR>
                 Shows the last directory accessed by any of the
                 following commands:
                    < D > (Directory of disk)
                    < R > (Read event report into memory)
                    < L > (List any DOS file)
                    < D1, D2, D3, D4 > Shows the default directory number 1, 2, 3,
                    or 4, as specified using the < U > (START-UP) command.

NOTES:  You may employ the DOS wildcard characters "*" and "?" in specifying the
        "FILENAME.EXT". This saves you time and effort if you are careful to employ
        a simple system in storing your files. We recommend a separate directory
        or floppy for each transmission line, containing files named as
        "YYMMDDFT.SR#", where "YYMMDD" indicates year, month, and day of the fault
        (eg: 880424), "FT" indicates fault type, as AG, BG, CG, AB, BC, CA, 3P, 3G,
        A2, B2, or C2, (eg:A2=BCG). "S" is a one letter mnemonic indicating the
        line terminal, "R" is a character identifying the relay (P=Primary,
        B=Backup), and "#" is the fault number occurring on the indicated date.

        See the < U > (START-UP) command to simplify access to frequently read
        directories.
```

L Command: List Disk File to Screen

Use this command to examine SEL relay event reports or any other ASCII text files in your computer. The command lists one screen of text at a time, simplifying examination of fault data.

```
< L >  USAGE:    Type:  LL DRIVE:\PATH\FILENAME.EXT <CR>
     EXAMPLE:    Type:  LL C:\LINE6440\880512BG.BP4 <CR> (List 4th BG flt at BRULE sub)
     OPTIONS:    Type:  L FILENAME.EXT <CR>
                 Lists the DOS file FILENAME.EXT onto your screen from the
                 last directory accessed by any of the following commands:
                     < R >  (Read event report into memory)
                     < D >  (Directory of disk)
                     < L >  (List any DOS file)
                     < L1, L2, L3, L4 FILENAME.EXT > Lists FILENAME.EXT
                     from the default directory number 1, 2, 3, or 4, (as
                     specified by invoking the < U > (START-UP) command).

NOTE:   See the < U > (START-UP) command to simplify access to frequently read
        directories.
```

R Command: Read Event Report into Program

You must use this command to read SEL relay event reports from your disk into the SEL-PROFILE program, before the program can analyze SEL event reports.

```
< R >  USAGE:    Type:  RR DRIVE:\PATH\FILENAME.EXT <CR>
                 The SEL-PROFILE program allocates data memory to load two SEL relay
                 event reports into data sets.  Upon start-up, these data sets are
                 cleared by the SEL-PROFILE program.  When reading in an event report,
                 the SEL-PROFILE program automatically stores the event report in the
                 first empty data set.  If neither data set is empty, you will be asked
                 which data set you wish to overwrite.
     EXAMPLE:    Type:  RR C:\LINE6440\880512BG.PB1 <CR> (Read 1st BG flt at PEAVY sub)
     OPTIONS:    Type:  R FILENAME.EXT <CR>
                 Reads FILENAME.EXT into the SEL-PROFILE program working memory from the
                 last directory accessed by any of the following commands:
                     < R >  (Read event report into memory)
                     < D >  (Directory of disk)
                     < L >  (List any DOS file)
                     < R1, R2,  R3,  R4  FILENAME.EXT > Reads  FILENAME.EXT  from  the
                     default directory number 1, 2, 3, or 4, (as specified by invoking
                     the < U > (START-UP) command).

NOTE:   See the < U > (START-UP) command to simplify access to frequently read
        directories.
```

P Command: Print Data Set Summaries to Screen

Use this command to review summary information about the fault and transmission line. It presents key data such as fault type, fault current, and line constants. Use the summary display when you need to verify that you have read in the event report you intended. (Note that you must first read in an event report, using the < R > command, before you can examine the data set summary with the < P > command.)

< P >	USAGE:	Type: P <CR> Prints the event report summary data generated by the relay, and indicates the file path and name from which the event report was read. Use this to verify that the data that the SEL-PROFILE program read from disk are what you wanted.
	OPTIONS:	Type: PP <CR> Prints not only the summary data, but also the actual sample data read by the SEL-PROFILE program.

E Command: Enter Fault Data Manually

Use this command to manually enter phasor fault data into the program, say from paper copies of SEL relay event reports, or from oscillographic records.

Manual data entry is much less convenient than automatic entry using the < R > command, so you should save your SEL event reports on disk if possible.

< E >	USAGE:	Type: E <CR> The SEL-PROFILE program allows you to manually enter prefault and fault data. You are prompted for Y and X phasor components of the currents and voltages, in the order IA, IB, IC, VA, VB, VC. If you are taking data from an SEL event report, remember to use prefault data rows and fault data rows which correspond to the same quadrant of the power system cycle. (Take prefault and fault data 4*N rows apart; N = 1,2,3...)
	OPTIONS:	Type: ER <CR> This .option erases both data sets from the SEL-PROFILE program's memory, and returns them to their initialized start-up state. When reading in more than two data files, you may wish to use this command between pairs of data reads, to avoid having to answer the prompt as to which data set to overwrite.

C Command: Modify or View the Line/Terminal Configuration Settings

Use this command to modify or view the settings used by the SEL-PROFILE program to model the transmission line and terminal. All settings must be entered in primary quantities.

The SEL-PROFILE program models the positive and zero sequence impedances and susceptances of transmission lines, as well as the zero sequence mutual coupling to a parallel circuit. The transmission line terminal is modeled by lumped impedance elements, such as series capacitor banks or shunt reactors. Three groups of six settings each control permutation, rescaling, and deskewing of the analog channels. With these settings you can conveniently correct the data for wiring, ratio, and phase shift errors.

Figure 3-1 depicts each line/terminal configuration setting.

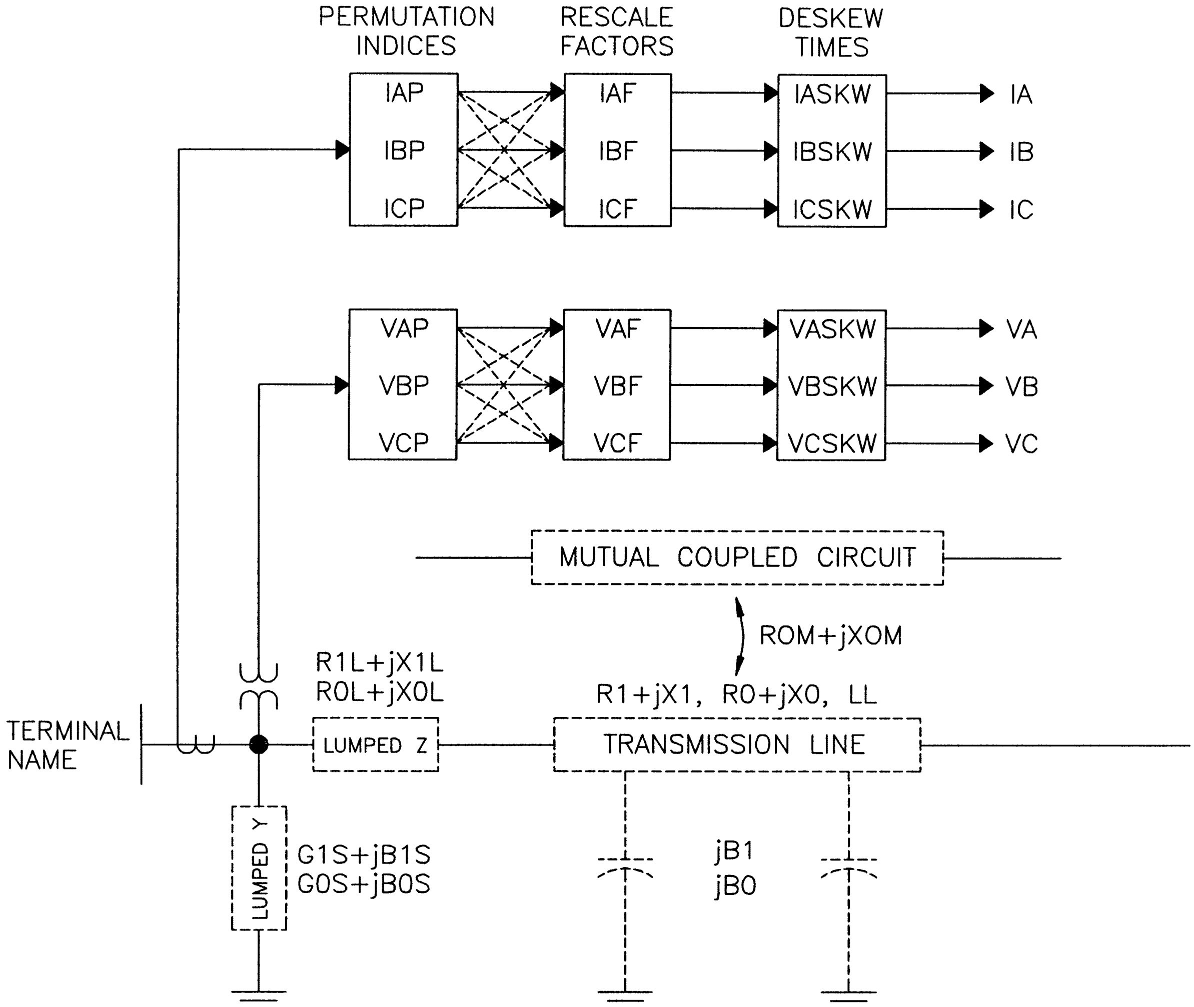


FIGURE 3-1. LINE/TERMINAL CONFIGURATION SETTINGS

Although 36 settings are employed by the SEL-PROFILE program, the default settings typically suffice for all but five of them. The five essential settings are the line constants, (R1, X1, R0, X0), and the line length, (LL). Since these five settings are read directly from SEL relay event reports, you must rarely use the <C> (CONFIGURATION) command; except when SEL event reports are not available on disk.

Even when you require nondefault settings, or settings different from those in the SEL relay event reports, you need not type any of the 36 settings in by hand. Just use the < C > (CONFIGURATION) command to enter the settings once for a given transmission line and terminal, and to save the settings to disk. Then, whenever you read an event report from that terminal into the program, you can also read in from disk all the settings required by the program.

We call this collection of settings the "Line/Terminal Configuration Settings", and you store them using the < C > (CONFIGURATION) command, into a file which we call a "Line/Terminal Configuration File". The Line/Terminal Configuration files are automatically given a ".CNF" file name extension. Store them in the same directory as event reports from a given transmission line, so you can easily find them when you are analyzing event reports from that transmission line. Give the .CNF files a file name related to its associated transmission line and terminal.

The < C > command help screen is reprinted below. Following the help screen is a listing of all 36 settings employed by the SEL-PROFILE program.

```
< C >  USAGE:    Type:  C <CR>
                 This command allows you to configure the line/terminal constants used
                 by the fault locating methods. These constants may have already been
                 read from the settings data in event reports or be the manually entered
                 line/terminal constants.  This can be useful when you wish to
                 investigate the effects on fault location of using different line-
                 constants than set in the recording instrument when the fault occurred,
                 or when you wish to accommodate the distributed capacitance of the line
                 or lumped series or shunt elements at the terminals.

                 You may save the line/terminal configuration settings into disk files,
                 and read them from disk files. This eliminates having to retype the
                 settings every time you read in a new data file. Be sure to name the
                 configuration file so as to make it easy to remember and associate with
                 the particular terminal.
```

Line/Terminal settings used by the SEL-PROFILE program:

Default
<u>Settings</u>

- Line Constant Settings

X0: Zero Sequence Reactance of the transmission line	88888.8
R0: Zero Sequence Resistance of the line	88888.8
X1: Positive Sequence Reactance of the line	88888.8
R1: Positive Sequence Resistance of the line	88888.8
(X0S is only used with delta-connected VT voltages)	
X0S: Zero Sequence Source Reactance	0
(R0S is only used with delta-connected VT voltages)	
R0S: Zero Sequence Source Resistance	0
LL: Length of the transmission line	88888.8
B0: Zero Sequence Susceptance of line	0
B1: Positive Sequence Susceptance of line	0
X0M: Zero Sequence Mutual Reactance (parallel circuit)	0
R0M: Zero Sequence Mutual Resistance (parallel circuit)	0

- Terminal Settings:

NAME:	<The Name of the Terminal> (Less than 40 Characters)	
XOL:	Zero Sequence Reactance of Series Lump	0
ROL:	Zero Sequence Resistance of Series Lump	0
X1L:	Positive Sequence Reactance of Series Lump	0
R1L:	Positive Sequence Resistance of Series Lump	0
BOS:	Zero Sequence Susceptance of Shunt Lump	0
GOS:	Zero Sequence Conductance of Shunt Lump	0
B1S:	Positive Sequence Susceptance of Shunt Lump	0
G1S:	Positive Sequence Conductance of Shunt Lump	0

Default
Settings

- Analog Channel Permutation Indices:

IAP:	<A> Channel Permutation index (A,B,C)	A
IBP:	<B> Channel Permutation index (A,B,C)	B
ICP:	<C> Channel Permutation index (A,B,C)	C
VAP:	<A> Channel Permutation index (A,B,C)	A
VBP:	<B> Channel Permutation index (A,B,C)	B
VCP:	<C> Channel Permutation index (A,B,C)	C

Enter the channel index (A, B, or C) of the original data, which the SEL-PROFILE program should re-interpret as the indexed channel. For example, if data originally entered as IC samples are really IA samples, then set:

IAP = C

(This tells the program which channel really contains IA.)

- Analog Channel Rescale Factors:

IAF:	Channel rescaling factor	1
IBF:	Channel rescaling factor	1
ICF:	Channel rescaling factor	1
VAF:	Channel rescaling factor	1
VBF:	Channel rescaling factor	1
VCF:	Channel rescaling factor	1

Enter a multiplicative scale factor with which to correct the indexed channel. For example, if IA is underscaled by 10%, then to correct the error, set:

IAF = 1.10

• Analog Channel Deskew Times:

```
IASKW:  Channel Deskew time (microseconds)                         0
IBSKW:  Channel Deskew time (microseconds)                         0
ICSKW:  Channel Deskew time (microseconds)                         0
VASKW:  Channel Deskew time (microseconds)                         0
VBSKW:  Channel Deskew time (microseconds)                         0
VCSKW:  Channel Deskew time (microseconds)                         0
```

For each channel, enter the sampling time difference from a common reference. (Note that nonzero settings are not generally required when the data are generated by SEL relays, except to correct phase errors in external circuits.) For example, if channel IA is taken as the reference, and if channel IB was sampled 25 microseconds after IA, then set:

IASKW = 0.0

and

IBSKW = 25.0

(Note that this deskewing procedure assumes a 60 Hz system. For a 50 Hz system, enter settings which are 5/6 (83.33%) of the actual sampling time differences.)

(See Appendix A for further explanation of the Line/Terminal configuration settings.)

S Command: Schweitzer Two-End Fault Locating

Use this command to analyze faults when you have fault data from both ends of a transmission line. (First, use the < R > (READ) command or the < E > (ENTER) and < C > (CONFIGURATION) commands to enter the fault data into the program.)

This fault locating method was invented by Dr. E. O. Schweitzer, III in 1982, and presented that year to the Western Protective Relay Conference in Spokane, Washington. The basis of the technique is that the voltage at the fault is unique, and may be determined as a function of the distance to the fault from either end. Equating the two solutions from both line ends, the fault voltage is eliminated. The resulting equation may be solved for the distance to the fault using only the voltages and currents measured at each end, and the sequence impedances of the transmission line.

We have noticed that the positive sequence location results are far more sensitive to synchronization angle measurement errors than either the negative or zero sequence results. This makes the positive sequence results somewhat less reliable than the zero or negative sequence results, in our opinion. For balanced three-phase faults use the positive sequence results.

Some disagreement between the three sequence results seems common. For ground faults, the zero sequence results have been the most reliable, with negative a close second, and positive a distant third. However, if zero sequence mutual coupling is a concern, use the negative sequence result.

We present all three sequence results from several data points near the middle of the fault. The highlighted location row is just a convenient visual reference to the point that the SEL-PROFILE program calls the middle of the fault. Frequently, a better choice will be a few rows up or back from the highlighted row. Look for convergence between data rows and between the three sequence results. Wild disagreement between any of these should alert you that the SEL-PROFILE program may not be able to locate that particular fault successfully.

< S > USAGE: Type: S <CR>
Solves for the location of a fault based on the line/terminal constants and the I and V data captured at both line-ends during the fault. You must first use the < R > command to read in event reports from the two ends, or the < C > and < E > commands to type in line/terminal constants and two sample rows of fault and prefault data manually.

X Command: Reactance One-End Fault Locating

Use this command to analyze faults when you have fault data from one end of a transmission line, but unreliable or no prefault data. (First, use the < R > (READ) command or the < E > (ENTER) and < C > (CONFIGURATION) commands to enter the fault data into the program.)

> This fault locating method prorates the apparent reactance during the fault to the known positive sequence reactance of the transmission line (X1).
>
> The only advantage of the pure reactance calculation over the Takagi method is that no prefault data are required. Use it when no prefault data were recorded. (This can occur, for example, during a boundary fault, for which the relay may pickup too slowly to capture any prefault data.)
>
> < X > USAGE: Type: X <CR>
> Solves for the location of a fault based on the line/terminal constants and the I and V data captured at one line-end during the fault.
>
> The Simple Reactance algorithm computes fault locations using several different choices of fault data from the event report. Then, it employs a weighted sum algorithm to select the fault location from these results.
>
> You must first use the < R > command to read in an event report, or the < C > and < E > commands to type in line constants and two sample rows of fault and prefault data manually. If you have entered more than one data set, the SEL-PROFILE program will ask which data set you want to work with.
>
> OPTIONS: Type: XX <CR>
> Use the < XX > option to view the raw (unweighted) results as an array. The rows of the array correspond to the rows of sample data in the SEL event report. The columns present the fault locations for six different fault types. Use this for rapidly evolving or short duration faults, for which the fault type and/or data selection algorithm may not be able to converge well. Nonevolving faults of two cycles or more generally converge very well.

T Command: Takagi One-End Fault Locating

Use this command to analyze faults when you have fault data from one end of a transmission line, along with reliable prefault data. (First, use the < R > (Read) command or the < E > (ENTER) and < C > (CONFIGURATION) commands to enter the fault data into the program.)

T Command: Takagi One-End Fault Locating

Use this command to analyze faults when you have fault data from one end of a transmission line, along with reliable prefault data. (First, use the < R > (Read) command or the < E > (ENTER) and < C > (CONFIGURATION) commands to enter the fault data into the program.)

This fault locating method was invented by Takagi et. al., and presented in the IEEE Transactions on Power Apparatus and Systems Vol PAS 101, No. 8, August 1982, pp. 2892-2898. The basis of the technique is that prefault current data can be used to compensate the fault data, reducing the effects of load on the distance calculation, as compared to a pure reactance measurement.

The Takagi algorithm computes fault locations using several different choices of fault data from the event report. Then, a weighted sum algorithm is employed to select the fault location from these results.

< T > USAGE: Type: T <CR>
Solves for the location of a fault based on the line/terminal constants and the I and V data captured at one line-end during the fault.

You must first use the < R > command to read in an event report, or the < C > and < E > commands to type in line constants and two sample rows of fault and prefault data manually. If you have entered more than one data set, the SEL-PROFILE program will ask which data set you want to work with.

OPTIONS: Type: TT <CR>
Use the < TT > option to view the raw (unweighted) results as an array. The rows of the array correspond to the rows of sample data in the SEL event report. The columns present the fault location assuming six different fault types. Use this for rapidly evolving or short duration faults, for which the fault type and/or data selection algorithm may not be able to converge well. Nonevolving faults of two cycles or more generally converge very well.

M Command: Mutual Compensated Reactance or Takagi Fault Locating

Use this command to analyze faults when you have fault data from one end of two parallel transmission lines, for which the zero sequence mutual coupling is known. (First, use the < R > (READ) command or the < E > (ENTER) command to enter fault data from each terminal into the two program data sets. Then use the < C > (CONFIGURATION) command to enter the zero sequence mutual coupling constants (ROM and XOM) into the program, or read them from a Line/Terminal configuration file on disk.)

< M > USAGE:	Type: M <CR> This function uses either a modified Takagi method or a modified reactance method to determine fault location. (The program asks you which data set contains the fault data, and which fault locating algorithm to perform--Reactance or Takagi.) The <M> command computes fault locations using several different choices of fault data from the event report. Then, a weighted sum algorithm is employed to select the fault location from these results. The modified methods apply compensation for zero-sequence currents induced on the faulted transmission line due to mutual coupling with a parallel line. These methods require current and voltage sample data from both the faulted and the parallel circuit, as well as knowledge of the zero sequence mutual coupling constants (XOM, and ROM) in addition to the other line/terminal constants. First use the <R> command or the <E> command to enter fault data into the two program data sets, one set of data from the faulted circuit, and the other from the parallel circuit at the same line end. Then use the <C> command to enter the zero sequence mutual coupling constants (ROM and XOM) into the program, or read them from a line/terminal configuration file on disk.
OPTIONS:	Type: MM <CR> Use the < MM > option to view the raw (unweighted) results as an array. The rows of the array correspond to the rows of sample data in the SEL event reports. The columns present the fault location assuming six different fault types. Use this for rapidly evolving or short duration faults, for which the fault type and/or data selection algorithm may not be able to converge well. Nonevolving faults of two cycles or more generally converge very well.

V Command: VERBOSE and TERSE Program Modes

Use this command to change the program operating mode from VERBOSE to TERSE, or vice versa.

It is easier to learn the SEL-PROFILE program using the VERBOSE menu, but cumbersome after you are familiar with the commands and options. In TERSE mode, you need only provide the event report file name(s), and the SEL-PROFILE program will select the prefault and fault data, determine fault type, and calculate fault location without any further effort on your part. For complicated cases, such as evolving or very short duration faults, you may wish to follow or change the selection of fault data, determination of fault type, or selection of other fault location algorithm details. This can be done in VERBOSE mode. < V > USAGE: Type V <CR> Toggles between VERBOSE and TERSE user interaction modes.

U Command: Set Default Event Report Directories

Use this command to simplify access to four directories. You may specify four complete drive/directory paths. If, for example, you use the < U > command to specify default directory number 3 as "C:\FAULTS\KNOWNLOC*.*", then whenever you wish to examine your directory of event reports with known fault locations, you can simply

Type: D3 <CR>

instead of having to

Type: DD C:\FAULTS\KNOWNLOC*.*

< U > USAGE:	Type: U <CR> Allows you to specify the default event report path directories of the SEL-PROFILE program. There are four default directories accessible at any time by the SEL-PROFILE program, using any of the following commands: < R > (Read event report into memory) < D > (Directory of disk) < L > (List any DOS file) When you invoke one of these commands by supplying a digit (1-4) immediately after the key-letter (no intervening space, eg: R1, D2, L4), the SEL-PROFILE program will supply the appropriate drive and path to DOS from its default table. This means that you need to enter these defaults only once.

F1 Command: Provide Context Sensitive Help

Use this command whenever you need help understanding a program prompt or message.

```
Use the < F1 > command to get general help on any of the other commands.  Each time you
use the < F1 > command, an example user command sequence is displayed.

< F1 > USAGE:     < F1 KEYLETTER >
     EXAMPLE:     < F1 R > (Provides help for the < R > command.)

                  At almost every prompt that requests information, you can press the
                  F1 function key for a context sensitive help screen.  When you are
                  done reading the help screen, press any key to return to the prompt.
                  The range of permissible responses is usually indicated in the
                  prompts.  Their meanings are:

          (CR):    Skip the current entry; use the highlighted value.
    (up arrow):    Back up to the previous prompt.
    (dn arrow):    Proceed to the next prompt.
          (F1):    Provide context sensitive help.
         (Esc):    Press the ESCAPE key to terminate the present function.
         (XXX):    Type any key to get the alternative response to those explicitly
                   indicated.
```

Esc Command: Exit the SEL-PROFILE Program

When you are finished running the SEL-PROFILE program, just press the ***Esc*** key twice to return to the operating system.

CHAPTER 4: HOW TO USE THE SEL-PROFILE PROGRAM

INTRODUCTION

The step-by-step operating procedures are divided into three stages:

Stage 1). Shows you how to use the Takagi and Simple Reactance methods using only the data entered into Data Set #1. These are Steps 1 to 10.

Stage 2). Shows you how to use the Takagi and Simple Reactance methods using only the data entered into Data Set #2. These are Steps 11 to 16.

Stage 3). Shows you how to use the Schweitzer method using the data already entered into Data Sets 1 and 2 from Stages 1 and 2. These are Steps 17 and 18.

OVERVIEW

After completing this section, you should be familiar with:

- How to enter data from disk.
- How to review the contents of data sets, disk files, and event reports.
- How to perform the Takagi algorithm.
- How to perform the Simple Reactance algorithm.
- How to perform the Schweitzer algorithm.
- How to create a line profile using any of the three fault locating algorithms.

HOW TO USE THE SEL-PROFILE PROGRAM

Learn to operate the SEL-PROFILE program by analyzing the sample data records provided with the program.

The sample data consists of two event reports from SEL relays located at both ends of a simulated 100-mile line. The simulated fault is A-phase to ground with eight ohms of fault resistance, located 50 miles from either end.

The event reports have file names "S.END" and "R.END".

Keep the program in the VERBOSE mode throughout this section. The ability to create VOLTAGE/CURRENT profiles in sequence quantities, and to select data rows for each data set is only available in the VERBOSE mode. If you are in the TERSE mode, the data rows are automatically selected by the program and the sequence quantity line profile is not available.

STAGE 1

STEP 1: Select the directory for the SEL-PROFILE program.

Type: CD C:\PROFILE <CR>

where for "C:", substitute the name of the disk drive on which you installed the program.

STEP 2: Start up the SEL-PROFILE program.

Type: PROFILE <CR>

STEP 3: View the contents of your default directory (1) using the < D1 > command. The D1 directory should contain S.END and R.END. Note that in Stage 1 you use the S.END event report, while in Stage 2 you use the R.END event report.

Type: D1 <CR>

```
Directory = <C:\PROFILE\EVENTS\*.*>
S.END  R.END

Press any key to return to the main menu.
```

Step 4: List the S.END file to screen with the < L > command.

Type: L S.END <CR>

The S.END event report appears in Figure 4-1. Always view the first 15 rows of prefault data before selecting the method of fault locating. The reason for this is that the Takagi algorithm depends on sound prefault current while the Reactance method does not.

Press the RETURN key to scroll through the event report.

STEP 5: Read the S.END data into the first empty data set with the < R > command.

Type: R S.END <CR>

The next prompt lets you read in an (optional) line/terminal configuration file.

```
Do you want to read in a line/terminal configuration file?
(N,XXX,F1,Esc):  <Y>
```

```
END S: 50 MI FLT WITH LOAD AND FLT RES     Date: 4/6/89     Time: 09:08:52.541
FID=SEL-121G3-R103-V656mptr11s-D890330

             Currents                             Voltages       Relays Outputs Inputs
                       (amps)                                (kV)
                                                                   52265L TCAAAAA DPBD5E
  IPOL     IR      IA      IB      IC      VA      VB      VC   011710 PL1234L TTTC2T
                                                                   P3PNNP              A

     0     -9    -724    1510    -787   -27.9    69.4   -41.4   M..... ....... ....*.
     0    -14   -1353      31    1290   -64.2     7.9    56.3   M..... ....... ....*.
     0     14     724   -1510     787    27.9   -69.4    41.4   M..... ....... ....*.
     0     14    1353     -31   -1290    64.3    -7.9   -56.3   M..... ....... ....*.

     0    -14    -739    1510    -787   -28.0    69.4   -41.4   M..... ....... ....*.
     0     -9   -1337      31    1290   -64.2     7.9    56.4   M..... ....... ....*.
     0      9     739   -1510     787    28.1   -69.4    41.3   M..... ....... ....*.
     0      9    1337     -31   -1290    64.2    -7.9   -56.4   M..... ....... ....*.

     0     -9    -739    1510    -787   -28.1    69.4   -41.2   M..... ....... ....*.
     0     -9   -1337      31    1290   -64.2     7.9    56.4   M..... ....... ....*.
     0      9     739   -1510     787    28.1   -69.4    41.2   M..... ....... ....*.
     0      9    1337     -31   -1290    63.9    -7.9   -56.5   M..... ....... ....*.

     0    107    -613    1510    -787   -26.6    69.9   -40.6   M..... ....... ....*.
     0   -761   -2108      31    1290   -61.8     8.7    57.2   M..... ....... ....*.
     0   -341     393   -1510     787    21.8   -71.8    38.5   M..... ....... ....*.
     0   2316    3649     -31   -1290    60.0    -9.3   -57.8   M...P. ....... ....*.

     0    523    -204    1510    -787   -17.9    73.2   -37.0   M..1P. *.*.*.. ....*.
     0  -3232   -4546      31    1290   -59.9     9.2    57.7   M..1P. *.*.*.. ....*.
     0   -598     110   -1510     787    17.4   -73.3    36.8   M..1P. *.*.*.. ....*.
     0   3353    4688     -31   -1290    59.8    -9.3   -57.7   M..1P. *.*.*.. ....*.

     0    612    -110    1510    -787   -17.4    73.3   -36.7   M..1P. *.*.*.. ....*.
     0  -3367   -4703      31    1290   -59.8     9.3    57.7   M..1P. *.*.*.. ......
     0   -612     110   -1510     787    17.3   -73.3    36.7   M..1P. *.*.*.. ......
     0   3372    4688     -31   -1290    60.1    -9.2   -57.7   M..1P. *.*.*.. ......

     0    486    -142    1321    -676   -19.3    73.0   -37.0   M..1P. *.*.*.. ......
     0  -2615   -3555     -94    1038   -62.0     7.7    57.6   M..1P. *.*.*.. ......
     0   -248      47    -661     362    25.3   -71.4    37.9   M..1P. *.*.*.. ......
     0   1051    1369     126    -456    63.3    -5.6   -57.9   M..... *...... ......

     0     75      63     110     -79   -30.0    69.9   -38.6   M..... *...... ......
     0   -140    -189     -31      63   -62.9     4.8    58.2   ...... *...... ......
     0     -5       0     -16       0    30.8   -69.7    38.7   ...... *...... ......
     0     19      31      16       0    62.9    -4.7   -58.2   ...... *...... ......

     0     -5     -16       0       0   -30.9    69.7   -38.7   ...... ....... ......
     0     -5       0       0       0   -62.9     4.6    58.2   ...... ....... ......
     0      5       0       0       0    30.9   -69.7    38.7   ...... ....... ......
     0      9       0       0       0    62.9    -4.6   -58.2   ...... ....... ......

     0     -9       0       0       0   -30.9    69.7   -38.7   ...... ....... ......
     0     -9       0       0       0   -62.9     4.6    58.2   ...... ....... ......
     0      9       0      16       0    30.9   -69.7    38.7   ...... ....... ......
     0      5       0       0       0    62.9    -4.6   -58.2   ...... ....... ......

     0     -5       0     -31       0   -30.9    69.7   -38.7   ...... ....... ......
     0     -5       0       0       0   -62.9     4.6    58.2   ...... ....... ......
     0      5       0      16       0    30.9   -69.7    38.6   ...... ....... ......
     0      5       0       0       0    62.9    -4.6   -58.2   ...... ....... ......

Event    : 1AG     Location    : 49.01  mi   3.92    ohms sec
Duration: 3.00     Flt Current: 4704.7

R1    =1.39       X1    =7.88       R0    =4.17       X0    =24.86      LL    =100.00
CTR   =1000.00    PTR   =1000.00    MTA   =80.00      LOCAT=Y
79OI1=40.00       79OI2=60.00       79OI3=80.00       79RS =240.00
Z1%   =80.00      Z2%   =120.00     Z3%   =150.00
Z1DP =0.00        Z2DP =30.00       Z3DP =60.00
50L   =500.00     50M   =1000.00    50MFD=20.00       50H   =15000.00
51NP =500.00      51NTD=3.00        51NC =2           51NTC=Y
50N1P=2000.00     50N2P=1500.00     50N3P=1000.00
Z1DG =0.00        Z2DG =20.00       Z3DG =40.00
52BT =30.00       ZONE3=F           32QE =Y           32VE =N           32IE =N
OSB1 =Y           OSB2 =Y           OSB3 =Y           OSBT =30.00       LOPE =Y
TIME1=0           TIME2=0           AUTO =2           RINGS=3

Logic settings:

MTU   MPT   MTB   MTO   MA1   MA2   MA3   MA4   MRI   MRC
84    C4    00    F4    C4    00    00    00    00    EC
C4    E6    00    E7    E6    80    00    00    44    80
C8    C8    00    C8    88    00    02    04    00    C8
33    03    00    33    02    00    00    00    00    33
```

FIGURE 4-1. S-END EXAMPLE EVENT REPORT

For this example case, type N <CR> since a line/terminal configuration file does not exist. (This feature allows you to use a line/terminal configuration file that models series capacitors, shunt reactors, distributed capacitance, etc. Appendix A covers creating and storing line/terminal configuration files.) When you use the < R > command to read an SEL event report into the program, some line/terminal configuration settings are automatically entered. These settings are R0, X0, R1, X1, (R0S and X0S for SEL delta version relays) and line length.

STEP 6: Print to screen the event report summaries of both data sets with the < P > command.

Type: P <CR>

```
Data set #1 contents:
file name     <c:\profile\events\s.end>
terminal name <END S: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>        location <49.01>
duration   <3.00>       current  <4704.7>
event date <4/6/89>   time      <09:08:52.541>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Data set #2 contents:   <...THIS DATA SET IS RESET...>

event type <>
event date <>   time  <>

R1=<>       X1=<>       R0=<>       X0=<>       LL=<>
```

<u>NOTE</u>: Data Set #2 is empty at this time.

Press any key to return to the main menu.

STEP 7: View short event report summaries and data set rows of IA, IB, IC, VA, VB, and VC with the < PP > command. The next prompt lets you select which data set you would like to view. Data Set #1 is the default.

Use this command to identify the row number where the current reaches a maximum (or minimum). You are asked later in the program to either select the data row of the data set, or to concur with the data row selected by the program. The SEL-PROFILE program automatically selects data rows near the middle of the fault. Therefore, view the screen contents carefully, making certain to remember the row numbers that interest you.

Type: PP <CR>

```
Data set #1 contents:
file name     <c:\profile\events\s.end>
terminal name <END S: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>        location <49.01>
duration   <3.00>       current  <4704.7>
event date <4/6/89>     time     <09:08:52.541>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Data set #2 contents:   <...THIS DATA SET IS RESET...>

event type <>
event date <>   time  <>R1=<>        X1=<>        R0=<>

X0=<>       LL=<>

Enter data set number to display
(1,2,ESC): <1>
```

Type:1 <CR> or <CR>

After selecting Data Set #1, its contents scroll by on the screen:

ROW#	IA	IB	IC	VA	VB	VC
<01>	-724.00	1510.00	-787.00	-27.90	69.40	-41.40
<02>	-1353.00	31.00	1290.00	-64.20	7.90	56.30
<03>	724.00	-1510.00	787.00	27.90	-69.40	41.40
<04>	1353.00	-31.00	-1290.00	64.30	-7.90	-56.30
<05>	-739.00	1510.00	-787.00	-28.00	69.40	-41.40
<06>	-1337.00	31.00	1290.00	-64.20	7.90	56.40
<07>	739.00	-1510.00	787.00	28.10	-69.40	41.30
<08>	1337.00	-31.00	-1290.00	64.20	-7.90	-56.40
<09>	-739.00	1510.00	-787.00	-28.10	69.40	-41.20
<10>	-1337.00	31.00	1290.00	-64.20	7.90	56.40
<11>	739.00	-1510.00	787.00	28.10	-69.40	41.20
<12>	1337.00	-31.00	-1290.00	63.90	-7.90	-56.50
<13>	-613.00	1510.00	-787.00	-26.60	69.90	-40.60
<14>	-2108.00	31.00	1290.00	-61.80	8.70	57.20
<15>	393.00	-1510.00	787.00	21.80	-71.80	38.50
<16>	3649.00	-31.00	-1290.00	60.00	-9.30	-57.80
<17>	-204.00	1510.00	-787.00	-17.90	73.20	-37.00
<18>	-4546.00	31.00	1290.00	-59.90	9.20	57.70
<19>	110.00	-1510.00	787.00	17.40	-73.30	36.80
<20>	4688.00	-31.00	-1290.00	59.80	-9.30	-57.70
<21>	-110.00	1510.00	-787.00	-17.40	73.30	-36.70
<22>	-4703.00	31.00	1290.00	-59.80	9.30	57.70
<23>	110.00	-1510.00	787.00	17.30	-73.30	36.70
<24>	4688.00	-31.00	-1290.00	60.10	-9.20	-57.70
<25>	-142.00	1321.00	-676.00	-19.30	73.00	-37.00
<26>	-3555.00	-94.00	1038.00	-62.00	7.70	57.60
<27>	47.00	-661.00	362.00	25.30	-71.40	37.90
<28>	1369.00	126.00	-456.00	63.30	-5.60	-57.90
<29>	63.00	110.00	-79.00	-30.00	69.90	-38.60
<30>	-189.00	-31.00	63.00	-62.90	4.80	58.20
<31>	0.00	-16.00	0.00	30.80	-69.70	38.70
<32>	31.00	16.00	0.00	62.90	-4.70	-58.20
<33>	-16.00	0.00	0.00	-30.90	69.70	-38.70
<34>	0.00	0.00	0.00	-62.90	4.60	58.20
<35>	0.00	0.00	0.00	30.90	-69.70	38.70
<36>	0.00	0.00	0.00	62.90	-4.60	-58.20
<37>	0.00	0.00	0.00	-30.90	69.70	-38.70
<38>	0.00	0.00	0.00	-62.90	4.60	58.20
<39>	0.00	16.00	0.00	30.90	-69.70	38.70
<40>	0.00	0.00	0.00	62.90	-4.60	-58.20
<41>	0.00	-31.00	0.00	-30.90	69.70	-38.70
<42>	0.00	0.00	0.00	-62.90	4.60	58.20
<43>	0.00	16.00	0.00	30.90	-69.70	38.60
<44>	0.00	0.00	0.00	62.90	-4.60	-58.20

Press any key to continue

Press the RETURN key to scroll to the next grouping of rows until the 44th row is shown. Pressing any key returns you to the main menu.

Fault Locating Command Sequence

The < T > (Takagi) or < X > (Reactance) methods of fault locating require only a single data set. Had the prefault data you observed earlier not been valid, only the < X > (Reactance) method should be used, since the Takagi method relies on valid prefault data (i.e. not faulted or severely unbalanced) to accurately determine fault location. However, since the prefault data are valid, both methods (T and X) can be used.

NOTE: Fault locating procedures do not disturb the data set(s), so you can use more than one fault locating method on the same data set.

Step 8: Select the Takagi fault locating method with the < T > command.

Type: T <CR>

After you select the fault locating method, the SEL-PROFILE program provides the option of displaying the fault location in miles/kilometers, or per unit distance. (To read out the fault location in units of kilometers, select M and remember that where miles are indicated the units are instead kilometers.)

```
Show fault locations in Miles/km or per Unit
(M,U,Esc): <M>
```

Type: M <CR> or press the <CR> key to select the fault location readout in units of miles or kilometers.

```
Data set #1 contents:
file name     <c:\profile\events\s.end>
terminal name <END S: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>       location <49.01>
duration   <3.00>      current  <4704.7>
event date <4/6/89>    time     <09:08:52.541>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Enter location estimate from end <END S: 50 MI FLT WITH LOAD AND FLT RES>
(LOC, Esc): <49.004>
```

At this point, you can either concur, or enter your own fault location estimate. The SEL-PROFILE program uses this estimate to prorate the distributed capacitance of the line (if the distributed capacitance is modeled). In this example case, the distributed line-ground capacitance is not modeled. Therefore, any value entered has no effect on the final fault location. Where the actual fault location is known and the distributed capacitance is modeled, the actual fault location should be entered. Press the <CR> key to concur for this example case.

The SEL-PROFILE program next displays 19 rows of fault data, and selects a pair of rows near the middle of the fault. Either select your own data row pair or concur by pressing the <CR> key. When selecting the first row of the pair, you should select a data row near the middle of the fault where the current magnitude appears to level out. This option is only available in the VERBOSE mode. If a fault is evolving, you may wish to use the < TT > command to determine which fault type and data row to select. The < TT > command usage and explanation is described in detail in APPENDIX A (the fault in this example case is not evolving).

```
 ROW#      IA         IB         IC         VA         VB         VC
CYC#
  11     739.00   -1510.00     787.00      28.10     -69.40      41.20
  12    1337.00     -31.00   -1290.00      63.90      -7.90     -56.50
  13    -613.00    1510.00    -787.00     -26.60      69.90     -40.60   [4]
  14   -2108.00      31.00    1290.00     -61.80       8.70      57.20
  15     393.00   -1510.00     787.00      21.80     -71.80      38.50
  16    3649.00     -31.00   -1290.00      60.00      -9.30     -57.80
  17    -204.00    1510.00    -787.00     -17.90      73.20     -37.00   [5]
  18   -4546.00      31.00    1290.00     -59.90       9.20      57.70
  19     110.00   -1510.00     787.00      17.40     -73.30      36.80
<<20>>  4688.00     -31.00   -1290.00      59.80      -9.30     -57.70
<<21>>  -110.00    1510.00    -787.00     -17.40      73.30     -36.70   [6]
  22   -4703.00      31.00    1290.00     -59.80       9.30      57.70
  23     110.00   -1510.00     787.00      17.30     -73.30      36.70
  24    4688.00     -31.00   -1290.00      60.10      -9.20     -57.70
  25    -142.00    1321.00    -676.00     -19.30      73.00     -37.00   [7]
  26   -3555.00     -94.00    1038.00     -62.00       7.70      57.60
  27      47.00    -661.00     362.00      25.30     -71.40      37.90
  28    1369.00     126.00    -456.00      63.30      -5.60     -57.90
  29      63.00     110.00     -79.00     -30.00      69.90     -38.60   [8]

Enter first fault row for <END S: 50 MI FAULT WITH LOAD AND FLT RES>
(1-43,F1,Esc):  <20>
```

For this example, type either 20 <CR> or press the <CR> key to concur. The << >> symbols surrounding the data row numbers indicate those selected by the SEL-PROFILE program.

The next prompt lets you select the type of fault. You may either concur by pressing the <CR> key or enter your own fault type. Your choices are: G for ground faults, or P for phase faults (includes three phase, phase-phase, and phase-phase-ground faults). In this example case, the fault is classified as a ground fault.

```
For end <END S: 50 MI FLT WITH LOAD AND FLT RES>
    I0mag     I1mag     I2mag     V0mag     V1mag     V2mag
  1140.78   2500.71   1138.59      6.84     67.97      2.17

PROFILE classifies this as an <UNBALANCED> fault
PROFILE classifies this as a  <GROUND> fault
Select GROUND(G) or PHASE(P) fault analysis
(G,P,F1): <G>
```

Press the <CR> key to agree that the fault is a ground fault.

The SEL-PROFILE program next determines the faulted phase.

ROW# CYC#	IA	IB	IC	VA	VB	VC	
11	739.00	-1510.00	787.00	28.10	-69.40	41.20	
12	1337.00	-31.00	-1290.00	63.90	-7.90	-56.50	
13	-613.00	1510.00	-787.00	-26.60	69.90	-40.60	[4]
14	-2108.00	31.00	1290.00	-61.80	8.70	57.20	
15	393.00	-1510.00	787.00	21.80	-71.80	38.50	
16	3649.00	-31.00	-1290.00	60.00	-9.30	-57.80	
17	-204.00	1510.00	-787.00	-17.90	73.20	-37.00	[5]
18	-4546.00	31.00	1290.00	-59.90	9.20	57.70	
19	110.00	-1510.00	787.00	17.40	-73.30	36.80	
<<20>>	4688.00	-31.00	-1290.00	59.80	-9.30	-57.70	
<<21>>	-110.00	1510.00	-787.00	-17.40	73.30	-36.70	[6]
22	-4703.00	31.00	1290.00	-59.80	9.30	57.70	
23	110.00	-1510.00	787.00	17.30	-73.30	36.70	
24	4688.00	-31.00	-1290.00	60.10	-9.20	-57.70	
25	-142.00	1321.00	-676.00	-19.30	73.00	-37.00	[7]
26	-3555.00	-94.00	1038.00	-62.00	7.70	57.60	
27	47.00	-661.00	362.00	25.30	-71.40	37.90	
28	1369.00	126.00	-456.00	63.30	-5.60	-57.90	
29	63.00	110.00	-79.00	-30.00	69.90	-38.60	[8]

PROFILE chooses phase <A>
for end <END S: 50 MI FLT WITH LOAD AND FLT RES>
Select phase of fault (A,B,C,F1,Esc): <A>

For this example, the A-phase is determined as the faulted phase. Press the <CR> key to concur the fault involves only A-phase.

After selecting the faulted phase, the row, fault location, and weighting factors are displayed. The weighted average is displayed beneath the terminal identifying string. Using the Takagi method of fault location for this example case, the fault is 49.00 miles from the S terminal.

ROW	LOCATION	WEIGHT
19	49.120	0.50
20	49.115	1.00
21	48.867	0.50
22	48.700	0.33

From end <END S: 50 MI FLT WITH LOAD AND FLT RES>
Fault is <49.00> miles/km

View Phase or Symmetrical component voltage/current profiles (P,S,Esc): <P>

SYSTEM VOLTAGE/CURRENT PROFILE

The SEL-PROFILE program helps you create a profile of the faulted line from the terminal to the fault. Use this feature to determine the magnitudes and angles of the voltages and currents at the relaying location by selecting the phase quantities option. If you wish to see the sequence quantities of the profile, answer Y <CR> at the prompt to recalculate the voltage current profiles and select S instead of P. Use this option to determine polarizing quantities at the relay location, for instance. If you wish not to see this profile, strike the ***Esc*** key.

Step 9: If you wish to see the profile, first select the format: < P > for phase quantities or < S > for sequence quantities.

Type: P <CR> to select phase quantities for this example case.

After selecting phase quantities, you must select the fault location.

By concurring with the fault location determined by the SEL-PROFILE program, the FAULT column then contains the phase quantities <u>at the fault location</u>. If you select a location between the terminal and the actual fault location, the phase quantities at the entered location are displayed in the FAULT column. Use this feature to view the system quantities anywhere along the line by entering different location values.

```
ROW  LOCATION    WEIGHT
19   49.120       0.50
20   49.115       1.00
21   48.867       0.50
22   48.700       0.33

From end <END S: 50 MI FLT WITH LOAD AND FLT RES>
Fault is <49.00> miles/km

Enter location for fault voltage/current profile (location, Esc): <49.00>
```

Press the <CR> key to enter the fault location of 49.00 miles from the S Bus.

The next prompt lets you select the first data row. The data rows accented by the << >> symbols are those selected during the fault locating sequence.

ROW#	IA	IB	IC	VA	VB	VC	CYC#
11	739.00	-1510.00	787.00	28.10	-69.40	41.20	
12	1337.00	-31.00	-1290.00	63.90	-7.90	-56.50	
13	-613.00	1510.00	-787.00	-26.60	69.90	-40.60	[4]
14	-2108.00	31.00	1290.00	-61.80	8.70	57.20	
15	393.00	-1510.00	787.00	21.80	-71.80	38.50	
16	3649.00	-31.00	-1290.00	60.00	-9.30	-57.80	
17	-204.00	1510.00	-787.00	-17.90	73.20	-37.00	[5]
18	-4546.00	31.00	1290.00	-59.90	9.20	57.70	
19	110.00	-1510.00	787.00	17.40	-73.30	36.80	
<<20>>	4688.00	-31.00	-1290.00	59.80	-9.30	-57.70	
<<21>>	-110.00	1510.00	-787.00	-17.40	73.30	-36.70	[6]
22	-4703.00	31.00	1290.00	-59.80	9.30	57.70	
23	110.00	-1510.00	787.00	17.30	-73.30	36.70	
24	4688.00	-31.00	-1290.00	60.10	-9.20	-57.70	
25	-142.00	1321.00	-676.00	-19.30	73.00	-37.00	[7]
26	-3555.00	-94.00	1038.00	-62.00	7.70	57.60	
27	47.00	-661.00	362.00	25.30	-71.40	37.90	
28	1369.00	126.00	-456.00	63.30	-5.60	-57.90	
29	63.00	110.00	-79.00	-30.00	69.90	-38.60	[8]

Enter fault data row for end <END.S: 50 MI WITH LOAD AND FLT RES>
(1-43,Esc): <20>

Press the <CR> key to create the profile using data from rows 20 and 21.

The Takagi and Simple Reactance system voltage/current profiles consist of three points:

- **Bus** - This point is the actual S bus.
- **Line** - This is the point immediately following any series and/or shunt impedance elements connected to the S bus. Since there were no series capacitors or shunt reactors modeled in our example, the Bus and Line are the same point.
- **Fault** - This is the location selected at the fault location prompt.

System Voltage/Current Profile

Fault at <49> mi/km from <END S: 50 MI FLT WITH LOAD AND FLT RES>

		BUS	LINE	FAULT
VA	(kV)	62.28	62.28	54.69
	(deg)	/-7.31	/-7.31	/-33.89
VB	(kV)	73.89	73.89	83.26
	(deg)	/-120.76	/-120.76	/-126.26
VC	(kV)	68.38	68.38	65.42
	(deg)	/+124.01	/+124.01	/+127.10
IA	(amps)	4689.29	4689.29	4689.29
	(deg)	/-22.19	/-22.19	/-22.19
IB	(amps)	1510.32	1510.32	1510.32
	(deg)	/-114.71	/-114.71	/-114.71
IC	(amps)	1511.11	1511.11	1511.11
	(deg)	/+125.08	/+125.08	/+125.08

Do you want to recalculate voltage/current profiles (Y,XXX,Esc): <N>

Figure 4-2 shows the A-phase voltage magnitude profile for our example case.

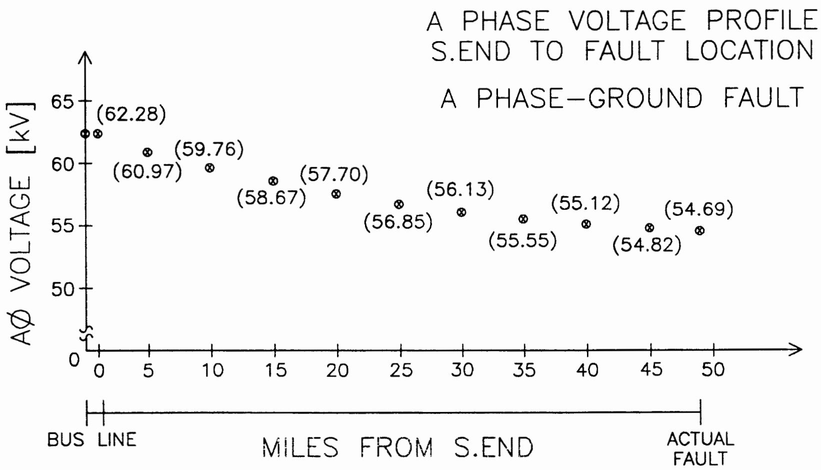


FIGURE 4-2. A-PHASE VOLTAGE MAGNITUDE PROFILE

Type: N <CR> to return to the main menu.

Verifying the Reactance (X) Method

Step 10: Select the Reactance method of fault locating.

Type: X <CR>

The prompts issued for the Takagi method are the same for this method. Continue with the Reactance method as you did in Step 8 for the Takagi method:

10.1 Select mi
10.2 Concur with the fault location estimate
10.3 Select the first data row as 20
10.4 Select the fault type as being a ground fault
10.5 Select A-phase as the involved phase

The results for the Reactance fault locating method are:

```
ROW  LOCATION    WEIGHT
19   35.510       0.50
20   35.508       1.00
21   35.365       0.50
22   35.190       0.33

From end <END S:50 MI FLT WITH LOAD AND FLT RES>
Fault is <35.43> miles/km

View Phase or Symmetrical component voltage/current profiles (P,S,ESC): <P>
```

The effect of fault resistance and load flow on the fault location is large.

Press the ***Esc*** key to return to the menu.

This completes the Takagi < T > and Reactance < X > methods for the S.END data.

STAGE 2:

Enter the data from the R.END event report. The same steps used to enter and analyze the S.END data should be followed for entering the R.End data except that this data is entered into and read from Data Set #2. Do not erase the contents of Data Set #1 as they are used in Stage 3.

STEP 11: List to screen the event report from the R.END terminal with the < L > command.

Type: L R.END <CR>

The R.END report appears in Figure 4-3.

STEP 12: Read the R.END data into Data Set #2 with the < R > command. If there is not an empty data set, a prompt appears asking you which data set to overwrite. In this example since Data Set #2 is empty the R.END data is automatically entered into this data set.

Type: R R.END <CR>

The next prompt lets you read in an optional line/terminal configuration file.

```
Do you want to read in a line/terminal configuration file
(N,XXX,F1,Esc):  <Y>
```

As with the S.END data set, type N <CR>.

STEP 13: Print to screen the event report summaries of both data sets with the < P > command.

Type: P <CR>

```
Data set #1 contents:
file name     <c:\profile\events\S.END>
terminal name <END S: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>       location <49.01>
duration   <3.00>      current  <4704.7>
event date <4/6/89>   time      <09:08:52.541>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Data set #2 contents:
file name     <c:\profile\events\R.END>
terminal name <END R: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>       location <49.23>
duration   <3.25>      current  <2412.7>
event date <4/6/89>   time      <09:08:52.558>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>
```

NOTE: Data Set #2 now contains the data recorded at the R.END of the line.

Press any key to return to the main menu.

The fault location results for R.END data using the Reactance method are:

```
ROW   LOCATION   WEIGHT
17    84.068      0.0
18    82.059      0.0
19    78.740      0.30
20    79.219      0.47
21    78.774      1.00
22    79.509      0.47
23    78.187      0.0

From end <END R:50 MI FLT WITH LOAD AND FLT RES>
Fault is <79.02> miles/km

View Phase or Symmetrical component voltage/current profiles (P,S,ESC): <P>
```

Press the ***Esc*** key to return to the menu.

SCHWEITZER METHOD OF FAULT LOCATING

STAGE 3

STEP 17: Select the Schweitzer double-ended method of fault locating. This method requires data in Data Set #1 and Data Set #2 from the same fault.

Type: S <CR>

Select the units of fault distance in miles (M), or per unit distance of the line (U) to the fault location.

```
Show fault locations in miles/km or per unit
(M,U,Esc):  <M>
```

Type: M <CR> or press the <CR> key, indicating that the fault location read-out is in units of miles.

The next prompt asks you either to concur with the ALIGNMENT ANGLE calculated by the program or enter your own value. The ALIGNMENT ANGLE is the angular difference between the sample times at the two ends of the line. APPENDIX B shows manual ALIGNMENT ANGLE calculations for this example case.

```
ALIGNMENT ANGLE = <15.40>
(This is the angle to be subtracted from data set #2 phasors
to remove the sampling time-skew relative to data set #1.)
Enter alignment angle.
(angle, F1, Esc):  <15.40>
```

Press the <CR> key to concur with the alignment angle of 15.40 degrees.

The next two prompts let you select the middle data row pairs of the fault for the two data sets.

The first data set shown is always Data Set #1 (shown below for the example case).

ROW#	IA	IB	IC	VA	VB	VC	CYC#
11	739.00	-1510.00	787.00	28.10	-69.40	41.20	
12	1337.00	-31.00	-1290.00	63.90	-7.90	-56.50	
13	-613.00	1510.00	-787.00	-26.60	69.90	-40.60	[4]
14	-2108.00	31.00	1290.00	-61.80	8.70	57.20	
15	393.00	-1510.00	787.00	21.80	-71.80	38.50	
16	3649.00	-31.00	-1290.00	60.00	-9.30	-57.80	
17	-204.00	1510.00	-787.00	-17.90	73.20	-37.00	[5]
18	-4546.00	31.00	1290.00	-59.90	9.20	57.70	
19	110.00	-1510.00	787.00	17.40	-73.30	36.80	
<<20>>	4688.00	-31.00	-1290.00	59.80	-9.30	-57.70	
<<21>>	-110.00	1510.00	-787.00	-17.40	73.30	-36.70	[6]
22	-4703.00	31.00	1290.00	-59.80	9.30	57.70	
23	110.00	-1510.00	787.00	17.30	-73.30	36.70	
24	4688.00	-31.00	-1290.00	60.10	-9.20	-57.70	
25	-142.00	1321.00	-676.00	-19.30	73.00	-37.00	[7]
26	-3555.00	-94.00	1038.00	-62.00	7.70	57.60	
27	47.00	-661.00	362.00	25.30	-71.40	37.90	
28	1369.00	126.00	-456.00	63.30	-5.60	-57.90	
29	63.00	110.00	-79.00	-30.00	69.90	-38.60	[8]

Enter first fault row for <END S: 50 MI FLT WITH LOAD AND FLT RES>
(1-43,F1,Esc): <20>

Press the <CR> key to agree with the row selected by the SEL-PROFILE program.

The second data set displayed is always Data Set #2 (shown below for the example case).

ROW#	IA	IB	IC	VA	VB	VC	CYC#
10	1101.00	378.00	-1447.00	-61.10	1.20	60.00	
11	-1054.00	1479.00	-440.00	33.90	-69.90	35.70	
12	-1085.00	-378.00	1447.00	60.70	-1.40	-60.10	
13	1148.00	-1479.00	440.00	-31.60	70.70	-34.70	[4]
14	189.00	378.00	-1447.00	-59.80	1.70	60.40	
15	-1007.00	1479.00	-440.00	26.20	-72.70	32.50	
16	1384.00	-378.00	1447.00	59.50	-1.70	-60.20	
17	771.00	-1479.00	440.00	-22.90	73.90	-31.20	[5]
18	-2171.00	378.00	-1447.00	-59.80	1.60	60.00	
<<19>>	-755.00	1479.00	-440.00	22.50	-74.20	31.00	
<<20>>	2265.00	-378.00	1447.00	59.70	-1.60	-59.90	
21	771.00	-1479.00	440.00	-22.40	74.20	-31.00	[6]
22	-2281.00	378.00	-1447.00	-59.80	1.50	59.90	
23	-787.00	1479.00	-440.00	22.40	-74.10	31.00	
24	2297.00	-378.00	1447.00	60.10	-1.30	-59.70	
25	551.00	-1211.00	299.00	-24.00	73.00	-32.30	[7]
26	-1715.00	346.00	-1085.00	-61.30	2.00	58.90	
27	-204.00	535.00	-94.00	28.10	-71.00	35.70	
28	645.00	-189.00	409.00	62.30	-3.30	-58.40	

Enter first fault row for <END R: 50 MI FLT WITH LOAD AND FLT RES>
(1-43,F1,Esc): <19>

Press the <CR> key to agree with the row selected by the SEL-PROFILE program.

STEP 18: After selecting the first data rows, the SEL-PROFILE program returns with the event summaries for both data sets followed by the initial fault approximation. The SEL-PROFILE program uses this estimate to prorate the distributed capacitance of the line. If the distributed capacitance is not modeled (as in our example), any value entered has no effect on the final fault location.

```
Data set #1 contents:
file name     <c:\profile\events\S.END>
terminal name <END S: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>       location <49.01>
duration   <3.00>      current  <4704.7>
event date <4/6/89>   time     <09:08:52.541>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Data set #2 contents:
file name     <c:\profile\events\R.END>
terminal name <END R: 50 MI FLT WITH LOAD AND FLT RES>
event type <1AG>       location <49.23>
duration   <3.25>      current  <2412.7>
event date <4/6/89>   time     <09:08:52.558>
R1=<1.39>  X1=<7.88>  R0=<4.17>  X0=<24.86>  LL=<100>

Enter location estimate from <END.S 50 MI FLT WITH LOAD AND FLT RES>
(loc,Esc): <49.783>
```

Notice this screen allows you to compare the SEL-PROFILE program initial estimate with those determined by the SEL relays. Press the <CR> key to concur.

The SEL-PROFILE program next computes the distance to the fault from both ends based upon the knowledge that the voltage at the fault is unique. The SEL-PROFILE program uses each of the sequence quantities separately to determine the fault locations.

Line-Ground Faults: In our experience, the zero sequence calculations have proven the most reliable. Where multiple lines occupy the same right-of-way or the same structures, you may wish to select the negative sequence results instead of the zero sequence results for line-ground faults. This avoids the effects of zero sequence mutual coupling between the circuits.

Phase-Phase Faults: You may prefer the results using the negative sequence quantities.

Three-Phase Faults: Use the results utilizing the positive sequence quantities.

The format of the Schweitzer fault locating results differs from the < T > (Takagi) and < X > (Reactance) command formats. The fault location for the selected data rows is shown for the zero, negative, and positive sequence quantities.

The SEL-PROFILE program declares the highlighted row as the middle of the fault. The most reliable fault locations usually reside at or near the highlighted row. The fault locations in each data row should show some form of convergence; i.e. for a ground fault example, the zero, positive and negative sequence locations should converge. Also, look for convergence between adjacent data rows in each of the sequence columns.

```
Schweitzer Method Two-End Fault Locations in Miles/km

FROM END:                                     FROM END:
<END S: 50 MI FLT WITH LOAD AND FLT RES> <END R: 50 MI FLT WITH LOAD AND FLT
RES>

ROW          LOCATIONS PER SEQUENCE          ROW        LOCATIONS PER SEQUENCE
NUMBER   ZERO     POSITIVE    NEGATIVE    NUMBER   ZERO      POSITIVE    NEGATIVE

13       12.61       11.64       16.21    12       87.39       88.36       83.79
14       39.10       39.06       42.38    13       60.90       60.94       57.62
15       30.89       31.27       32.46    14       69.11       68.73       67.54
16       47.41       47.77       47.89    15       52.59       52.23       52.11
17       43.77       44.35       44.31    16       56.23       55.65       55.69
18       49.56       50.04       49.69    17       50.44       49.96       50.31
19       48.98       48.97       49.01    18       51.02       51.03       50.99
20       49.57       49.90       49.75    19       50.43       50.10       50.25
21       49.57       49.99       49.88    20       50.43       50.01       50.12
22       49.55       49.69       49.95    21       50.45       50.31       50.05
23       49.82       50.32       50.17    22       50.18       49.68       49.83
24       51.37       56.01       51.49    23       48.63       43.99       48.51
25       55.88       74.61       57.67    24       44.12       25.39       42.33
26       53.92       97.50       53.19    25       46.08        2.50       46.81

Enter L to recalculate LOCATIONS, P for voltage/current PROFILES
(L,P,Esc): <P>
```

Note the rows where the greatest amount of convergence between the sequence locations occurs. Use the noted row when creating voltage/current profiles. The SEL-PROFILE program next asks if you wish to redo the fault locating procedure or if you wish to view the voltage and current profile of the line. Enter L <CR> to recalculate locations, or P <CR> for voltage/current profiles. For the example case select the profile option, by typing P <CR> or press the <CR> key.

```
View Phase or Symmetrical component voltage/current profiles (P,S,Esc): <P>
```

The next prompt lets you select the format of line profile:

- **P** selects the phase quantities of voltage and current.
- **S** displays the symmetrical component quantities of voltage and current.

For this example case select the phase quantities option by typing P <CR> or by pressing the <CR> key.

The next prompt lets you select the indicated fault location or enter your own, based upon your observations from the previous screen (or enter the exact location of the fault if it is already known from field patrols). For this example case, press the <CR> key.

```
Enter location for fault voltage/current profile (location, Esc):  <49.78>
```

The SEL-PROFILE program next prompts you to select the bracketed data row for each data set by pressing the <CR> key, or to enter your own row based upon your observations of the converging fault locations. In this example case select row 20 for Data Set #1, and row 19 for Data Set #2.

The SEL-PROFILE program next computes the voltage and current profiles for the line at three locations from both ends of the line:

BUS (1) This point is the bus at the 1 end (the first data set is always declared as 1).

LINE(1) This is the point immediately following the lumped elements connected to BUS 1. These elements can be either series capacitors, shunt reactors, transformers, etc.

FLT (1) This point is the location entered.

FLT (2) This point is at a distance equal to the modeled line length, minus the location entered.

LINE(2) This is the point immediately following the lumped elements connected to BUS 2. These elements can be either series capacitors, shunt reactors, transformers, etc.

BUS (2) This point is the bus at the 2 end (the second data set is always declared as 2).

```
System Voltage/Current Profile

Fault at <49.78> mi/km from 1: <END S: 50 MI FLT WITH LOAD AND FLT RES>
         <50.22> mi/km from 2: <END R: 50 MI FLT WITH LOAD AND FLT RES>

                 BUS  1    LINE 1    FLT  1    FLT  2    LINE 2    BUS  2

 VA  (kV)         62.28     62.28     54.68     54.54     63.77     63.77
     (deg)      /-7.31    /-7.31    /-34.36   /-34.22   /-18.28   /-18.28

 VB  (kV)         73.89     73.89     83.41     83.42     74.22     74.22
     (deg)      /-120.76  /-120.76  /-126.33  /-126.34  /-130.17  /-130.17

 VC  (kV)         68.38     68.38     65.37     65.38     67.45     67.45
     (deg)      /+124.01  /+124.01  /+127.15  /+126.92  /+113.71  /+113.71

 IA  (amps)       4689.29   4689.29   4689.29   2383.99   2383.99   2383.99
     (deg)      /-22.19   /-22.19   /-22.19   /-57.42   /-57.42   /-57.42

 IB  (amps)       1510.32   1510.32   1510.32   1526.54   1526.54   1526.54
     (deg)      /-114.71  /-114.71  /-114.71  /+65.41   /+65.41   /+65.41

 IC  (amps)       1511.11   1511.11   1511.11   1512.42   1512.42   1512.42
     (deg)      /+125.08  /+125.08  /+125.08  /-55.84   /-55.84   /-55.84

Do you want to recalculate voltage/current profiles (Y,XXX,Esc): <N>
```

Type N <CR> to return to the main menu.

APPENDIX A: APPLICATION DETAILS

HOW TO MANUALLY SELECT FAULT ROWS

In the examples of Chapter 4, you were asked to concur with the rows selected and the fault type determined by the program. The following steps show a method for:

(1) Rapidly evolving faults, (i.e. A-B, to A-B-G).
(2) Very short duration faults.

In the example case, the fault captured had none of the above qualities. Therefore, the TT (XX or MM) command was unnecessary to exactly determine the fault type or data row.

Use the TT (XX or MM) command to view the raw (unweighted) data. The SEL-PROFILE program processes each row of the data set, for each of six different fault types, and displays the resulting location in columns. As an example:

Step 1: Read the S.END data into the first empty data set.

Type: R S.END <CR>
Type: N <CR> when prompted for a line configuration file.

Step 2: Perform the Takagi fault location algorithm for each row of the event report.

Type: TT <CR> (no spaces between the letters)

The output is shown on the following page (after selecting the locations to be in units of miles and concurring with the initial fault location estimate). Follow the same steps for the simple Reactance (XX) or the Mutual (MM) methods.

Takagi Fault Locations

Takagi fault locations assuming fault type

ROW#	AG	BG	CG	AB	BC	CA
9	******	-872.24	70.62	******	******	409.48
10	******	-872.10	70.63	******	******	409.48
11	******	-882.85	70.74	******	******	411.67
12	******	16.06	******	-367.90	629.92	******
13	167.98	******	-547.46	611.42	629.31	12.89
14	204.09	-860.46	-202.06	820.82	-28.65	115.92
15	71.46	-578.04	984.78	345.80	-28.65	0.71
16	71.32	-523.29	754.94	358.82	-28.43	18.49
17	49.92	-409.53	333.40	275.48	-28.43	0.11
18	51.63	-397.38	307.99	280.10	-28.22	6.74
19	49.12	-383.85	285.79	270.07	243.82	4.59
20	49.11	-383.80	284.62	270.04	243.82	4.79
21	48.87	-382.40	282.50	269.02	243.82	4.58
22	48.70	-382.46	282.58	268.79	243.82	4.38
23	48.93	-376.91	286.64	271.45	244.33	4.68
24	53.11	-352.02	366.86	287.58	280.19	-2.22
25	84.62	-348.40	471.04	458.69	16.27	29.20
26	118.81	-335.19	940.22	581.70	405.55	7.85
27	-998.94	-213.17	-108.61	******	-51.77	-395.16
28	-913.41	-593.60	******	******	580.17	-144.61
29	-643.23	-242.36	******	******	-325.39	-650.48
30	-295.85	******	72.49	******	-381.22	-237.01
31	-720.30	******	915.98	******	******	******
32	-436.79	******	******	******	******	******
33	******	******	******	******	******	******
34	******	******	******	******	******	******
35	******	******	******	******	******	******
36	******	******	******	******	******	******
37	******	******	******	******	******	******
38	******	******	******	******	******	******
39	******	******	******	******	******	******
40	******	641.29	******	******	******	******

View the rows in each column using the TT (XX or MM) command in order to:

(1) Check the row choice made by the program, against your manual inspection of the event report. (Use the < L > command.)

Phase-phase faults

Observe the row containing the maximum current levels in the involved phases. Under ideal conditions, the residual current should be negligible in comparison with the phase current levels. If the fault evolves into a phase-phase-ground fault, there will be a corresponding increase in the residual fault current level at the point where the fault evolves.

Ground faults

Check the row containing the maximum phase current level and the maximum residual current level.

(2) If, at the point of maximum fault current, the mileage to the fault is negative (behind the terminal) and you know the direction of the fault is forward (positive), eliminate that fault-type possibility for that row.

Check the calculated fault location for the fault type declared in each row against the fault location and type declared in the original event report. This is useful to determine not only which row of data to look at for the most accurate fault location, but also to determine whether or not the fault evolved.

HOW TO MANUALLY ENTER LINE/TERMINAL CONFIGURATION AND FAULT DATA

The SEL-PROFILE program permits you to modify (or further define) the constants of the modeled line. This is useful when reviewing relay performance in locating faults; i.e. series capacitors inserted or by-passed, shunt reactors on- or off-line, etc.

Configuring a Line/Terminal, (C Command)

Use the < C > command to either change the modeled constants of a line/terminal or to enter all of the constants manually for either data set. All settings must be entered in primary quantities. For example, you enter the original constants into Data Set #1, and a modified set of constants for the same terminal into Data Set #2. This is an easy way to compare the effects of line-constant modifications.

Type: C <CR>

Select which data set to change.

Where existing line/terminal configuration files stored on disk can be modified with less effort than manually entering all the line/terminal configuration data, answer Y <CR> at the prompt to enter a configuration file. After answering Y <CR>, the directory of files with the CNF filename extension is displayed. Then select a configuration file. For this example, type N <CR>.

The SEL-PROFILE program automatically sets up the line/terminal configuration if SEL event reports are used. The automatically entered values are: X0, R0, X1, R1, X0S, R0S, and line length. Other line/terminal configuration values remain at their default value until changed.

The C command further defines the line/terminal for series and/or shunt elements, and the distributed capacitance of the line. The transmission line model shown in Figures A-1 and A-2 identify the constants used in modeling the line.

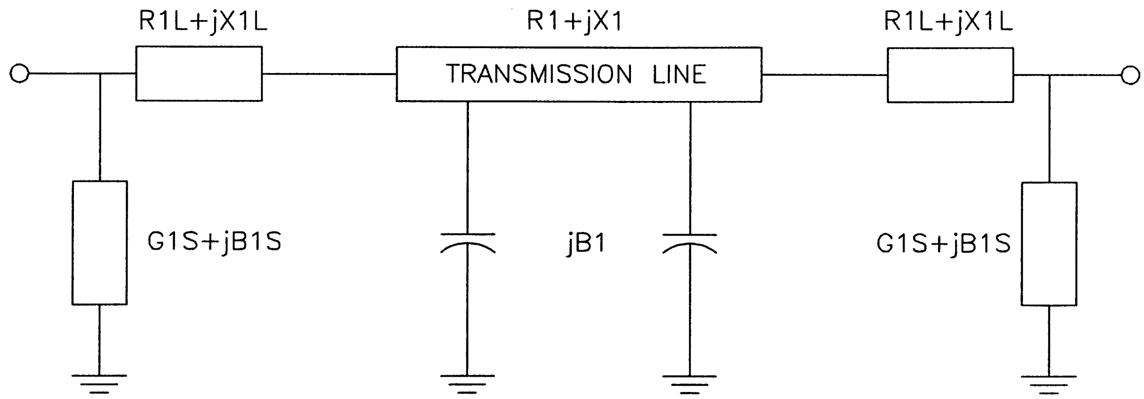


FIGURE A-1. POSITIVE SEQUENCE TRANSMISSION LINE MODEL

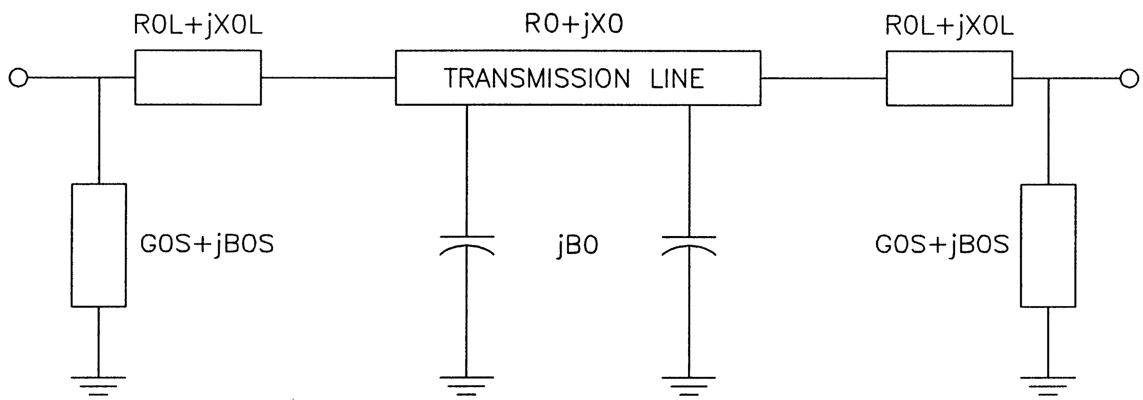


FIGURE A-2. ZERO SEQUENCE TRANSMISSION LINE MODEL

Line Constant Modeling

The configuration file for each end of a line must have the same line constants, but the series and shunt constants at each terminal may be unique. After answering Y <CR> to modify the line constants, the SEL-PROFILE program prompts for:

```
XO   ZERO SEQUENCE REACTANCE OF THE ENTIRE LINE
RO   ZERO SEQUENCE RESISTANCE OF THE ENTIRE LINE
X1   POSITIVE SEQUENCE REACTANCE OF THE ENTIRE LINE
R1   POSITIVE SEQUENCE RESISTANCE OF THE ENTIRE LINE
(XOS IS ONLY USED WITH DELTA-CONNECTED VT VOLTAGES)
XOS  ZERO SEQUENCE SOURCE REACTANCE
(ROS IS ONLY USED WITH DELTA-CONNECTED VT VOLTAGES)
ROS  ZERO SEQUENCE SOURCE RESISTANCE
LL   LENGTH OF THE ENTIRE LINE
BO   ZERO SEQUENCE SUSCEPTANCE OF THE ENTIRE LINE (DISTRIBUTED CAPACITANCE)
B1   POSITIVE SEQUENCE SUSCEPTANCE OF THE ENTIRE LINE (DISTRIBUTED CAPACITANCE)
XOM  ZERO SEQUENCE MUTUAL REACTANCE OF THE ENTIRE LINE (PARALLEL CIRCUIT)
ROM  ZERO SEQUENCE MUTUAL RESISTANCE OF THE ENTIRE LINE (PARALLEL CIRCUIT)
```

NOTE: The values of XO, RO, X1, R1 and LL are automatically entered when SEL event reports are entered as data files from disk. The values of BO, B1, XOM, and ROM are entered automatically at their default value of zero. The values of XOS and ROS are automatically entered when SEL event reports are entered from SEL delta-version relays.

After you have verified the line constants, type Y <CR> to enter the values into the data set.

Lumped Constant Modeling

To model the lumped constants unique to the terminal, answer Y <CR> to the prompt to modify/view the line/terminal settings. The line-terminal identifier is automatically entered when an SEL event report is entered into a data set from disk.

Enter the value of the constant after each prompt. The lumped constants are:

line/terminal identifier: (default is "...THIS DATA SET IS RESET...")
XOL ZERO SEQUENCE REACTANCE OF SERIES LUMP
ROL ZERO SEQUENCE RESISTANCE OF SERIES LUMP
X1L POSITIVE SEQUENCE REACTANCE OF SERIES LUMP
R1L POSITIVE SEQUENCE RESISTANCE OF SERIES LUMP
BOS ZERO SEQUENCE SUSCEPTANCE OF SHUNT LUMP
GOS ZERO SEQUENCE CONDUCTANCE OF SHUNT LUMP
B1S POSITIVE SEQUENCE SUSCEPTANCE OF SHUNT LUMP
G1S POSITIVE SEQUENCE CONDUCTANCE OF SHUNT LUMP

After you have verified the line terminal settings, type Y <CR> to enter the values into the data set. The default values of XOL, ROL, XIL, RIL, BOS, GOS, B1S, and G1S for this set are all zeros.

Analog Channel Permutation Indices

The SEL-PROFILE program can assign different phase identifiers to voltages and currents than that labeled in the event report header. This is particularly useful where the phase notation of the voltages and currents differ from the actual power system (such as could occur on an interconnecting line between utilities).

For example, Utility X has an ABC rotation and Utility Y has an ACB rotation. Each utility keeps its own rotation notation for its relay on each end of the interconnecting line. Since the SEL-PROFILE program assumes an ABC rotation, Utility Y's event report rotation must be changed to match that of Utility X.

Utility Y	Default Indices
IAP Channel Permutation Index = A	A
IBP Channel Permutation Index = C	B
ICP Channel Permutation Index = B	C
VAP Channel Permutation Index = A	A
VBP Channel Permutation Index = C	B
VCP Channel Permutation Index = B	C

After viewing the permutation indices for their correct assignments, type Y <CR> to correct the rotation of the phases in the data set.

Analog Channel Rescale Factors

The SEL-PROFILE program provides you the capability to adjust for potential and current transformer ratio errors. For example, if the nominal CT ratio is 1000/5 but the tested ratio is 1050/5, a ratio correction factor of 1.05 would be entered for that phase (or phases).

In the case where the relay CTs are wired in backwards (looking the wrong direction relative to the protected line), a Channel Rescale Factor of -1 could be entered to correct the input data and salvage the event record. Fractional values are accepted.

		Default Factors
IAF	Channel rescaling factor	1
IBF	Channel rescaling factor	1
ICF	Channel rescaling factor	1
VAF	Channel rescaling factor	1
VBF	Channel rescaling factor	1
VCF	Channel rescaling factor	1

Analog Channel Deskew Times

Analog channel deskew time compensates for known sampling time differences between the various channels. The default value is zero, indicating simultaneous sampling. (Nonzero settings are not required for use with SEL relays.) Each setting represents the effective sampling time error which must be subtracted from the sampling clock in order to achieve alignment of the given channel with the reference. For example, if IB is sampled 40 microseconds after IA, then the IBSKW setting is 40 microseconds greater than the IASKW setting. Shown below is the deskew setting for SEL event reports:

		Default Times
IASKW	Channel Deskew time (microseconds)	0
IBSKW	Channel Deskew time (microseconds)	0
ICSKW	Channel Deskew time (microseconds)	0
VASKW	Channel Deskew time (microseconds)	0
VBSKW	Channel Deskew time (microseconds)	0
VCSKW	Channel Deskew time (microseconds)	0

After entering the necessary values to model the transmission line, the next prompt gives you the option of storing the line configuration on disk for later use.

```
Do you want to save these settings on disk for future access by SEL-PROFILE program?
(Y, XXX, F1, Esc): <N>
```

After typing Y <CR>, the SEL-PROFILE program next prompts you for a filename. The filename _must_ be a DOS-valid filename from one to eight characters in length. Do not enter an extension to the filename. A configuration extension filename CNF will automatically be added. After typing the filename you wish, a prompt for the verification of the drive, path, and filename with the CNF extension added appears. Concur by pressing the <CR> key.

Once you have completed the above steps, the line/terminal configuration file is stored on disk for future access. To verify that the correct filename has been stored, review the contents of the default directory.

Example of storing a configuration file:

(1)

```
Do you want to save these settings on disk for future access by PROFILE?
(Y, XXX, F1, Esc): <N>
```

Type: Y <CR> or <CR>

(2)

```
Enter a DOS-valid filename (one to eight characters) under which to store
these settings (filename, F1, ESC):
```

Type: TEST <CR>

(3)

```
Save these settings in file <C:\PROFILE\EVENTS\TEST.CNF>
(XXX, Y) <Y>
```

Type: Y <CR> or <CR>

(4)

```
Do you want to save these settings elsewhere also?
(Y, XXX, F1, Esc): <N>
```

If you wish to store the configuration file contents on another disk or under another filename, follow the procedure in Steps (1) and (2) above; otherwise:

Type: N <CR> or <CR>

Manually Entering Fault Data, (E Command)

If your only means of acquiring data is paper copies of SEL event reports, oscillograms, or some other recording devices, you must manually enter the data.

To enter data rows manually (assuming both data sets are empty for this example):

Type: E <CR>

```
Data set #1 contents:  <...THIS DATA SET IS RESET...>

event type <>
event date <>      time    <>

R1=<>        X1=<>       R0=<>     X0=<>     LL=<>

Data set #2 contents:  <...THIS DATA SET IS RESET...>

event type <>
event date <>      time    <>

R1=<>        X1=<>       R0=<>     X0=<>     LL=<>

Enter data set number to change
(1,2,P,F1,Esc):<1>
```

Type: 1 <CR> or <CR>

```
Are you entering delta VT voltages?  (Y,N,Esc):  <N>
```

Type: N <CR> or <CR>

This brings up the following screen:

```
Enter PREFLT (pre-fault) row exactly M cycles earlier (4*M rows earlier) than
your chosen FAULT  rows (M = 1, 2, 3 ...) (I amps pri, V kV pri)

Use cursor keys to select entry to change,
Or press <RTN> key to move to next entry,
Or enter data, followed by <RTN>, to change present entry.
Or press <Esc> key to quit, saving changes made so far.

                    IA        IB        IC        VA        VB       VC

PREFLT Y ROW =  88888.80  88888.80  88888.80  88888.80  88888.80 88888.80
PREFLT X ROW =  88888.80  88888.80  88888.80  88888.80  88888.80 88888.80
FAULT  Y ROW =  88888.80  88888.80  88888.80  88888.80  88888.80 88888.80
FAULT  X ROW =  88888.80  88888.80  88888.80  88888.80  88888.80 88888.80
```

Entering Data From Paper Copies of SEL Event Reports

Select the first row of fault data desired from the event report. Count M cycles earlier (4*M rows earlier in the event report from the fault row chosen) and enter the data of that row from left to right; this row is designated as the PREFLT Y row in determining phasor quantities. The row immediately following the first row chosen in the event report, should be entered beneath the PREFLT Y data row; this row is designated as the PREFLT X row in determining phasor quantities. This completes the entry of prefault data. Now enter the first row of fault data selected from the event report beneath the PREFLT X row; this row is designated as the FAULT Y row. Immediately following the FAULT Y row, enter the row immediately following the first fault row chosen in the event report in the FAULT X row. This completes entering the fault data.

Entering Data From Oscillographs

The procedure for entering data from an oscillograph recording is identical to that of the SEL Event Report method except you must measure and scale the quantities manually.

SEL event reports contain the (X,Y) phasor representation of the input signals every quarter cycle. To simulate the same format as an SEL relay, select a time reference point on the oscillograph recording where the fault current is of interest. For each trace of voltage and current, record the magnitude in the FAULT X row. One quarter cycle earlier from this reference point, record the magnitude of voltage and current of each trace in the FAULT Y row. This completes entering fault row quantities. As described in the SEL event report section, record the magnitudes of prefault voltage and current M cycles earlier on the oscillograph trace. Insert these values in the row labeled PREFLT X. One quarter cycle earlier, record the magnitudes of voltage and current traces in the row labeled PREFLT Y. If no prefault values exist, ignore this last step and set the PREFLT X and PREFLT Y rows to zero.

NOTE: On oscillographs with no prefault data, the only usable fault locating method is the Simple Reactance <X>.

HOW TO GENERATE NOMOGRAPHS

Engineers with a short-circuit program and the line lengths of the transmission line at their disposal can create a nomograph. A nomograph plots the indicated fault location against the actual distance to the fault location. If you have access to the fault location output of an SEL fault locating relay and a nomograph, you can more accurately establish the actual fault location for a less-than-ideal line.

Why Use A Nomograph?

When the line parameters of R1, X1, R0, X0, and line length (LL) are programmed into a fault-locating device, the assumption is made that the line has a constant ohms/mile characteristic. This assumption is valid for most two-terminal lines where the conductor size and line configuration are constant throughout the line. However, lines often contain different size conductors, series capacitors, taps, etc. In such cases the assumption is no longer valid. A nomograph is a convenient compensation tool.

Using PROFILE To Create A Nomograph

Creating a nomograph using the SEL-PROFILE program requires using the manual fault data and line/terminal configuration commands, E and C respectively. The basic steps are outlined below:

Step 1: Configure the line/terminal with only the values entered into the fault locating device. For an SEL relay these values are R1, X1, R0, X0, (R0S and X0S for delta version relays) and LL. Although the SEL-PROFILE program allows more accurate fault location by further defining the line/terminal model, do not do so as this defeats the purpose of simulating what the fault locating device prints out.

Step 2: Enter the values of currents and voltages from the short-circuit study into the FAULT Y and FAULT X rows using the E command. Only enter the values as seen by the relay. Make certain to note the known location of the fault entered into the short-circuit study.

SEL relays employ the Takagi algorithm to perform fault location. This requires entering sound prefault data into the PREFLT Y and PREFLT X rows. You may wish to consult a load flow study to determine the load flows based on generation patterns or use average quantities for voltage and current. Sound prefault values consist of not faulted or severely unbalanced quantities of voltage and current. Remember that the prefault data must be in the same power cycle quadrant as the fault data.

Step 3: Perform the Takagi fault locating algorithm on the data set entered above. Note the location by the SEL-PROFILE program.

You now have one point to plot on the nomograph. Continue the process by faulting differing locations throughout the transmission line where electrical discontinuities exist (i.e. a conductor size change). The SEL-PROFILE program fault location is the same as that determined by an SEL relay when the Takagi fault locating method is selected. When complete, the nomograph should resemble that shown in Figure A-3.

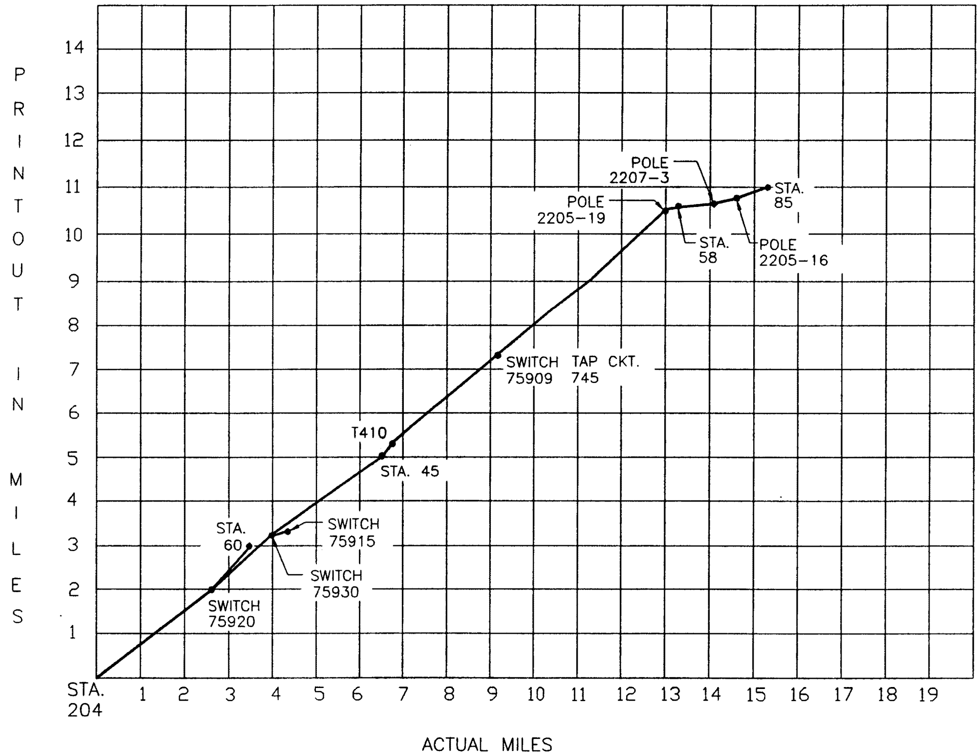


FIGURE A-3. NOMOGRAPH - 34.5 KV CIRCUIT 759 - STATION 204

APPENDIX B: ALGORITHM DETAILS

HOW THE SEL-PROFILE PROGRAM CALCULATES ALIGNMENT ANGLES

When two SEL relays at either end of the transmission line capture fault data, the data sets must be synchronized to remove any angular difference between the data sets due to differing sampling times. To calculate the sampling angle difference between the two ends of the line, start with one end as a reference; call this end R. The values of voltage and current measured at R are worked back to the remote end (S) through the transmission line model (shown in Figure B-2 below) to find V_S.

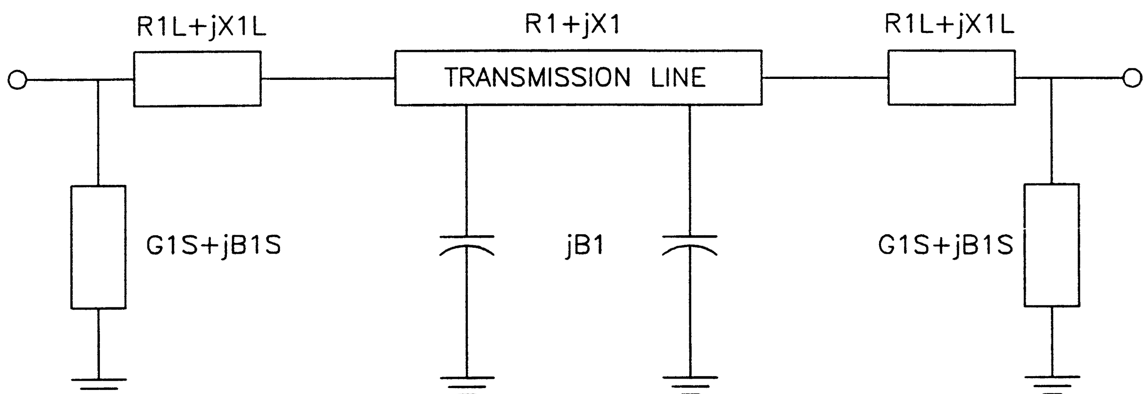


FIGURE B-1. POSITIVE SEQUENCE TRANSMISSION LINE MODEL

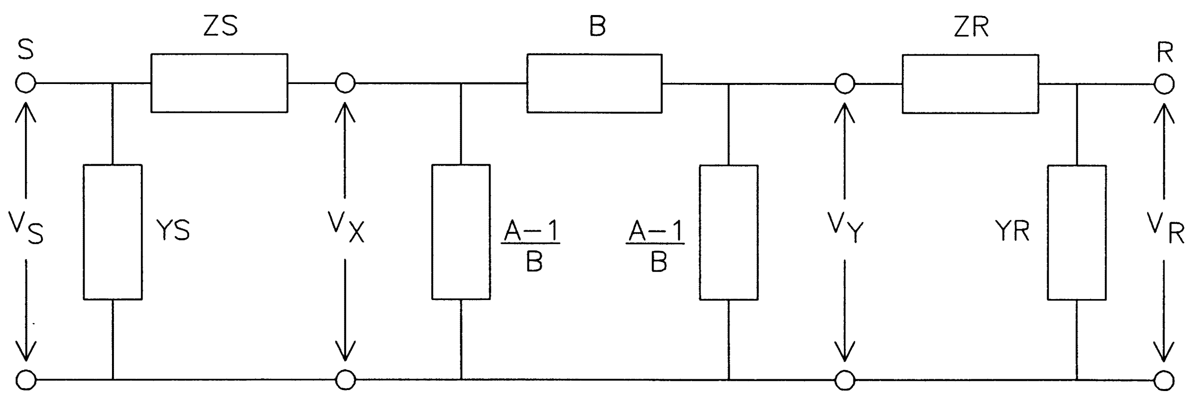


FIGURE B-2. POSITIVE SEQUENCE MODEL, ALIGNMENT ANGLE CALCULATION

The values of voltage and current at R (V_R, I_R) are references from which the value of V_S is calculated. The angular difference between the measured voltage angle of V_S and the calculated voltage angle of V_S is equal to the ALIGNMENT ANGLE. The alignment angle calculation is performed in the positive sequence network using sound prefault data.

Equations

$$
\begin{aligned}
I_Y &= I_R - Y_R V_R && \text{: current @ Point Y} \\
V_Y &= V_R - Z_R \cdot {}_Y && \text{: voltage @ Point Y} \\
V_X &= A \cdot V_Y - B \cdot I_Y && \text{: voltage @ Point X} \\
I_X &= C \cdot V_Y - D \cdot I_Y && \text{: current @ Point X} \\
V_S &= V_X + Z_S \cdot I_X && \text{: voltage @ Point S}
\end{aligned}
$$

$$
\begin{aligned}
D = A &= 1 + (ZY_1)/2 \\
B &= Z\ (1 + (ZY_1)/6) \\
C &= Y\ (1 + (ZY_1)/6)
\end{aligned}
$$

Input Variables - Example

Y_1 = Distributed Admittance = default of 0 since it is not modeled in this example.

$Z = Z_L$ = Series Impedance of the Transmission Line = 8 ohms ∠80

Calculations

$$
\begin{aligned}
A &= D \approx 1 + (ZY_1)/2 = 1 \\
B &= Z\ (1 + (ZY_1)/6) = 8 \text{ ohms } \angle 80
\end{aligned}
$$

Measured Reference Voltages and Currents at R, (R.END):

Va	Vb	Vc	Ia	Ib	Ic
69.91	70.01	69.78	1512.66	1526.54	1512.42
∠-151.09	∠88.94	∠-30.87	∠44.17	∠-75.66	∠163.09

$$I1@R = 1/3\ (I_a + aI_b + a^2 I_c)$$

$$= 1517.14 \text{ A } \angle 43.87$$

$$V1@R = 1/3\ (V_a + aV_b + a^2 V_c)$$

$$= 69.90 \text{ kV } \angle -151.01$$

Since there are no series capacitors or shunt reactors:

$V_Y = V_R$ and $I_Y = I_R$

$V_X = V_S$ and $I_X = I_S$

$V_X = A \cdot V_Y - B \cdot I_Y$

$= 69.90 \text{ kV } \angle -151.01 - 12.14 \text{ kV } \angle 123.87$
$= 69.92 \text{ kV } \angle -141.05$

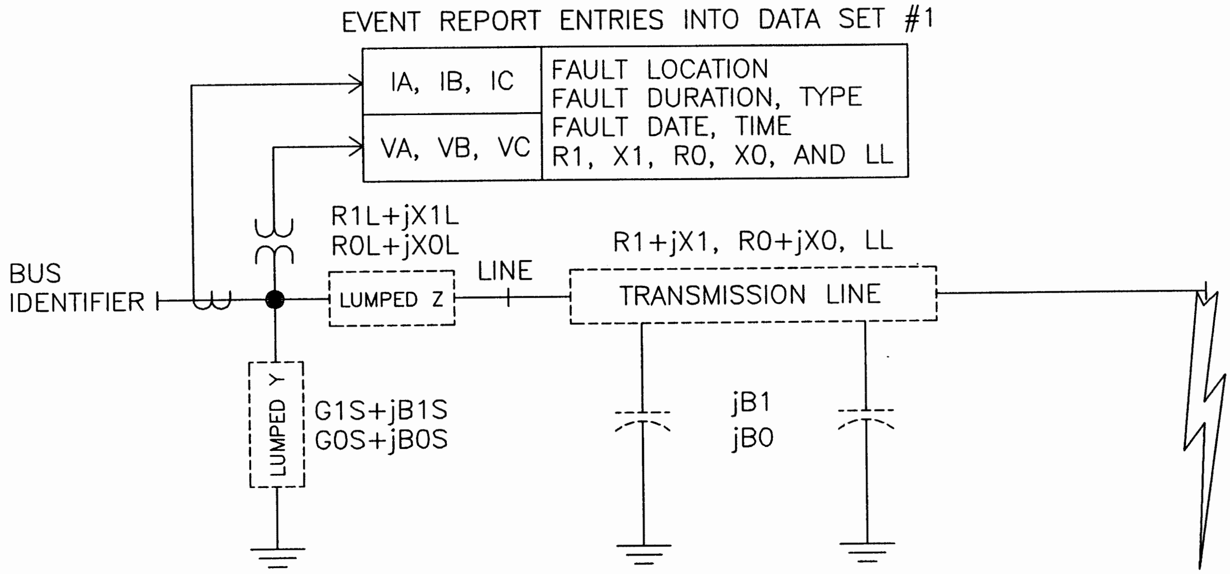
Measured voltages at S, (S.END):

Va	Vb	Vc
70.00	69.85	69.88
$\angle$-156.51	$\angle$83.51	$\angle$-36.33

$V_S = V_X = 1/3\ (V_a + aV_b + a^2V_c) = 69.91 \text{ kV } \angle -156.44$

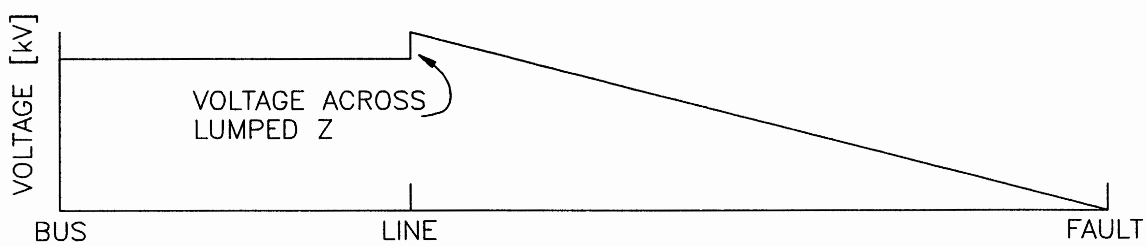
Alignment Angle = -156.44 - (141.05) = -15.40 degrees

APPENDIX C: TECHNICAL PAPERS



TRANSMISSION LINE MODEL — ONE END METHOD

NOTE: All quantities shown above are contained in the configuraiton file and data set for the respective line/terminal. The quantities outlined in dashed lines represent the parameters unique to the configuration file. The values of R1, X1, R0, X0, and LL in the data set from an SEL event report can be overridden by values entered into the configuration file with the <C> command. Use lumped Z and Y to model capacitors, reactors, transformers, etc.



FAULTED PHASE VOLTAGE PROFILE — ONE END METHOD

TYPICAL SINGLE-ENDED FAULT ANALYSIS COMMAND SEQUENCE

DATA HANDLING

TERSE MODE	VERBOSE MODE
(1) ER <CR>	(1) ER <CR>
(2) D1 <CR>	(2) D1 <CR>
(3) R S.END <CR>	(3) R S.END <CR> Read in line/terminal configuration file (Y,N)?

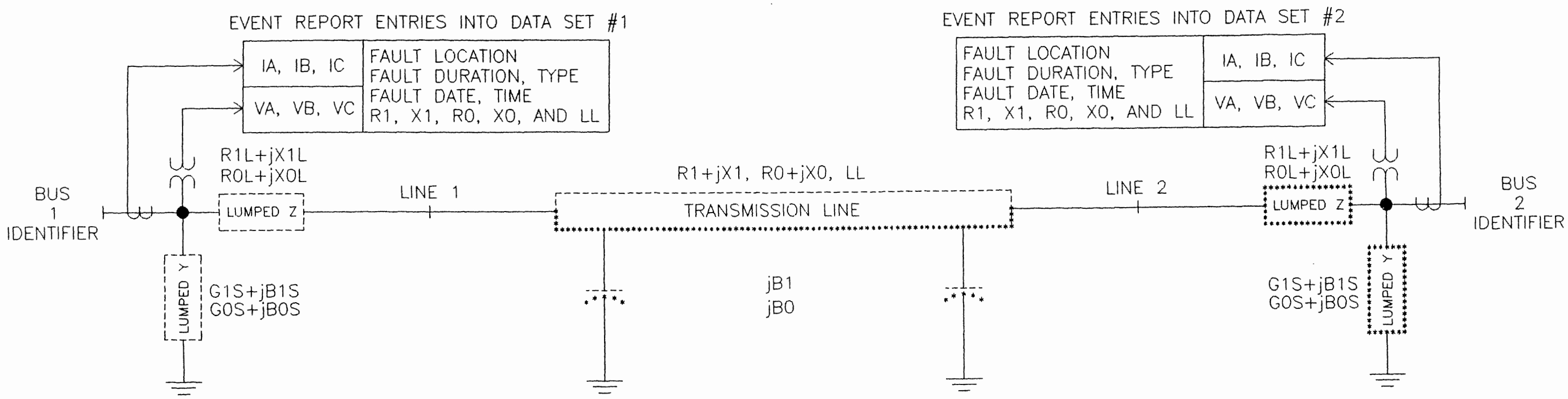
FAULT ANALYSIS

TERSE MODE	VERBOSE MODE
(4) T <CR>	(4) T <CR> -Select units of fault location -Select initial fault location -Select data rows -Select fault type -Select the involved phase(s)

NOTE: Replace T with X to perform the simple reactance fault analysis method

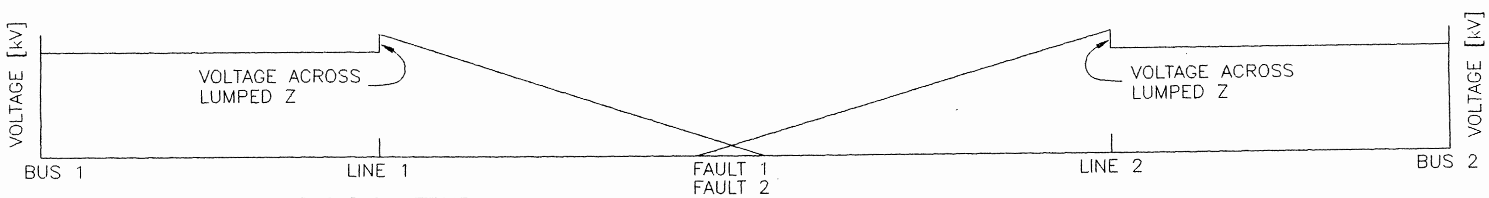
SYSTEM VOLTAGE/CURRENT PROFILE

TERSE MODE	VERBOSE MODE
(5) Elect to view profile -defaults to Phase quantity	(5) Elect to view profile -Select Phase or Sequence quantity profile -Select location for fault voltage/current profile -Select data rows



TRANSMISSION LINE MODEL – TWO END METHOD

NOTE: All quantities shown are contained in the configuration files and data sets. The dashed lines represent quantities unique to the configuration file relating to Bus 1. The asterisks indicate quantities unique to the configuration file relating to Bus 2. The values of R1, X1, R0, X0, and LL are common to both sets of SEL event reports and may be overridden by values entered in the configuration files with the <C> command. R1, X1, R0, X0, and LL must be equal in both configuration files. Use lumped Z and Y to model capacitors, reactors, transformers, etc.



FAULTED PHASE VOLTAGE PROFILE – TWO END METHOD

TYPICAL TWO-ENDED FAULT ANALYSIS COMMAND SEQUENCE

<u>DATA HANDLING</u>

TERSE MODE	VERBOSE MODE
(1) ER <CR>	(1) ER <CR>
(2) D1 <CR>	(2) D1 <CR>
(3) R S.END <CR>	(3) R S.END <CR> -Read in line/terminal configuration file (Y,N)?
(4) R R.END <CR>	(4) R R.END <CR> -Read in line/terminal configuration file (Y,N)?

<u>FAULT ANALYSIS</u>

TERSE MODE	VERBOSE MODE
(5) S <CR>	(5) S <CR> -Select units of fault location -Select alignment angle -Select data rows -Select initial fault location

<u>SYSTEM VOLTAGE/CURRENT PROFILE</u>

TERSE MODE	VERBOSE MODE
(6) Elect to view profile -Defaults to Phase quantity	(6) Elect to view profile -Select Phase or Sequence quantity profile -Select location for fault voltage/current profile -Select data rows

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A REVIEW OF IMPEDANCE-BASED FAULT LOCATING EXPERIENCE

BY

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PRESENTED BEFORE THE
FOURTEENTH ANNUAL
IOWA - NEBRASKA
SYSTEM PROTECTION SEMINAR
OCTOBER 16, 1990
OMAHA, NEBRASKA

INTRODUCTION

Five years of field experience with fault-locating distance relays demonstrate the value, performance, and practicality of these devices in protective relaying and fault-locating applications. The careful design of signal processing which has made these devices good relays also contributes to their good performance as fault locators even though the requirements for relaying and fault locating are quite different.

This paper reviews fundamental fault-locating principles and field experience, discusses and analyzes special cases, and points out how fault locating has benefitted protection as well as operation of power systems. Several unique applications are also presented.

REVIEW OF TRANSMISSION LINE FAULT-LOCATING TECHNIQUES

Electronic methods for locating transmission line faults include:

1. Relating oscillographic readings to short-circuit study data. This method is slow, requiring the oscillograms to be retrieved, and must be performed by individuals skilled in reading the oscillograms. It also depends on having short-circuit program data for the system configured as it was when the fault occurred. It is very intolerant of fault resistance.

2. Processing digital oscillograph records in a fault-locating program. This method is also slow. Large data records must be retrieved by computer, and then be processed by a person skilled in operation of the program. Skills include selecting the proper voltage and current channels, and selecting the data carefully from the faulted waveforms.

   Neither of the above schemes is of much use to an operator, who must make a decision to sectionalize, reclose, dispatch a crew, etc. soon after an event occurs.

3. Two-end travelling-wave fault locators. These schemes measure the relative time of arrival of the travelling wavefront produced by the fault, at the two ends of the line. The fault location is calculated from this measurement. A high-speed (wide bandwidth) communications channel is required for accurate time measurement. Equipment at both ends of the line, as well as the communications channel, must be operating in order to obtain a measurement. Traditionally, no remote communications of the fault location from the substation to the operator have been available.

4. One-end travelling-wave fault locators. A scheme has been developed for HVDC lines which does not require equipment at both line ends, and which needs no wide-bandwidth communications channel. Further research is necessary before the technique is practical for ac transmission lines.

5. One-end impedance-measuring fault locators. These devices calculate the fault location from the apparent impedance seen looking into the line from one end. They have proven to be the most practical, since no communications channel (other than possibly one for remote reading of the fault location) is required, and they are generally easy to install and operate. Commercial equipment based on analog techniques was not widely accepted, due to marginal performance. Several digital systems have been available for some time: these offer superior performance to the analog predecessors. Indeed, one-end impedance-measuring fault locators are included in several digital distance relay packages, and the feature of fault locating adds little or nothing to the cost of the total system.

6. Two-end impedance-based fault locators. Given the voltage and current information at both ends of the line during a fault, the fault location can be calculated. The advantage of one such scheme, described in Reference 1, is that ground faults can be located without knowing the zero-sequence impedance of the transmission line. The disadvantage of this scheme is similar to locating faults with digital oscillographs: the data must be retrieved and then processed by a relatively skilled individual. Although communications and computer resources could be applied to totally automate two-end schemes, the complexity and loss of availability (communications must be successful to both line ends, and the computer to process the two records must be available) may seldom be worth the performance advantage. Indeed, the techniques discussed for handling sources of error in single-end fault locating bring the performance of single-ended schemes up to par with two-ended schemes in most cases.

PRINCIPLES OF IMPEDANCE-BASED FAULT LOCATING

Locating faults requires many of the same signal processing steps as protecting transmission lines.

To accurately locate all fault types, the phase-to-ground voltages and the currents in each phase must be measured. (However, as we discuss later, when line-to-line voltages only are available, it is possible to locate phase-to-phase faults accurately. Ground faults can also be located reasonably well in most cases, if the zero-sequence source impedance is known.)

The phasor quantities must be extracted, a process which requires filtering to ensure that transients do not affect the measurement of phasor quantities. We have found a combination of analog and digital filtering that is simple and effective. An analog filter removes all high frequency components, and a digital filter removes dc offset.

Knowledge of the fault type is essential for accurate single-end fault locating, as the fault type determines the measuring loop to be used. In the digital distance relay/fault locator equipment of our manufacture, we use two different techniques. One technique is to determine the fault type from the relay elements which operate. The other technique is to use a separate fault-type determination process exclusively for the fault locator. This latter technique tests and compares the phase and residual currents. Another technique which has been used by others is to use the information from external starting elements. (Still another way, which has been used by programs that analyze digital oscillographic records, is manual specification of the fault type, relying on a skilled operator for fault-type determination.)

One of the following impedance calculations may be employed, depending on the fault type, to calculate the apparent positive-sequence impedance to the fault:

Ground Faults:

AG: Z1 = VA/(IA + k * IR)   Where k = (Z0 - Z1)/3 * Z1
BG: Z1 = VB/(IB + k * IR)
CG: Z1 = VC/(IC + k * IR)

Phase-to-Phase and Phase-to-Phase to Ground Faults:

AB or ABG: Z1 = VAB/IAB
BC or BCG: Z1 = VBC/IBC
CA or CAG: Z1 = VCA/ICA

Three-Phase Faults:

Any of the above equations.

The measured impedance unfortunately depends on many factors not represented in the equations. These include no or imperfect transposition between the fault and the measurement bus, mutual coupling to nearby circuits, load flow and fault resistance. Other problems arise from taps, conductor configuration changes, instrument transformer errors, nonuniform or unknown soil resistivity, etc. Fortunately, there are ways to handle or discover most of these problems, and many of them are often insignificant, as is explained later.

Once the apparent positive-sequence impedance to the fault is calculated, the distance to fault is determined by dividing the measured reactance by the total reactance for the line and multiplying by the line length. This eliminates the effects of fault resistance under conditions of light loading. On more heavily-loaded lines, faults with considerable resistance are not accurately located by this method, since the voltage drop at the fault in the fault resistance has both a resistive and a reactive component, as seen from either end. The reactive component of this drop is an error term not eliminated by this simple calculation. Takagi et al (Reference 2) provided a simple calculation which takes prefault load flow into account to reduce the effects of fault resistance and load flow on fault location calculations tenfold. Reference 1 works through some examples showing the difference between a straight reactance calculation and the Takagi approach, and a later section of this paper compares the reactance and Takagi methods for a ground fault.

The Takagi approach begins by writing the equation for the voltage at one line end, e.g. the "s" end, in terms of the current measured at the relay location during the fault, the total fault current and the fault resistance:

$$V_S = mZ_1 I_S + R_f I_f$$

Where:

m = Per-unit distance to the fault
Z_1 = Total positive-sequence impedance of the line
I_s = Relay current
R_f = Fault resistance
I_f = Total current in the fault

The total fault current is the sum of the fault current component from the "s" and "r" ends:

$$I_f = I_{fs} + I_{fr}$$

At the "s" end, the fault current component I_{fs} is the difference between the fault and prefault currents:

$$I_{fs} = I_s - I_{s0}$$

To minimize the effects of the fault-resistance term, the equation for V_s is multiplied by the complex conjugate of the fault-current component I_{fs}, and the imaginary parts are saved:

$$Im(V_s I_{fs}{}^*) = m\ Im(Z_1 I_s I_{fs}{}^*) + R_f\ Im((I_{fs} + I_{fr})\ I_{fs}{}^*)$$

The multiplication makes the fault-resistance term nearly real, so its imaginary part is, in general, negligible. Therefore, if we neglect the generally-small imaginary part of the last term, the distance to fault becomes the ratio:

$$m = Im(V_s I_{fs}{}^*) / Im(Z_1 I_s I_{fs}{}^*)$$

The Takagi paper (Reference 2) uses the alpha component of the fault current component for I_{fs}, since it is more uniform from line end to line end, and less affected by system grounding differences.

Reference 1 describes a two-ended algorithm. It uses the phasor information from both line ends to determine the fault location. The advantage of this scheme is that it does not need to depend on knowing the zero-sequence impedance of the line, a parameter which depends on the soil resistivity among other things. The scheme is also free of effects of zero-sequence mutual coupling. The two-ended algorithm recognizes that the voltage along the line from either end can be represented as a function of the distance to fault. If there is only one fault, then the equations for voltage computed from either end can be equated, and the distance to fault solved for as follows:

$$V_f = V_s - mZI_s$$
$$V_f = V_r - (1-m)ZI_r$$

Solving for m:

$$m = (V_s - V_r + ZI_r) / (Z(I_s + I_r))$$

Reference 3 gives an example of the application of this method to a 345 kV line.

MANAGING SOURCES OF ERROR IN IMPEDANCE-BASED FAULT LOCATING

Fault Resistance and Load Flow

The combination of these two factors introduces errors, which are serious in straight reactance calculations, and minimized by the Takagi algorithm.

On radial lines or any line where the infeed from the remote end is small compared to the total fault current, or when the load flow is small on an interconnection, the fault-locating errors due to fault resistance and load flow are negligible, even with a straight reactance calculation. This is useful to know, since a hand calculation of fault location using the reactance calculation is easier than a hand calculation using the Takagi algorithm. Indeed, when prefault information is not available, the Takagi algorithm cannot be used, and we are left with the reactance calculation.

Figure 2 shows a two-source equivalent system, with buses S and R. The EMF behind bus S leads that behind bus R by the power angle delta. To see the effects of fault resistance and load flow on the reactance and Takagi calculations, a ground fault, having resistance the same as the positive-sequence impedance of the line from S to R, was applied at the midpoint of the transmission line. Five test cases were produced using different power angle values, and with equal Thevenin impedances behind the buses. The system was homogeneous for these five cases.

As the theory predicts, the Takagi algorithm is unaffected by the fault resistance and the load flow. The table included with Figure 2 shows this, with per-unit distance to fault values of 0.5 from both ends for all five cases.

Base Case:

$Z_{S1} = Z_{R1} = 2 \angle 80°$
$Z_{S0} = Z_{R0} = 3Z_{S1}$
$Z_{L1} = 8 \angle 80°$
$Z_{L0} = 3Z_{L1}$

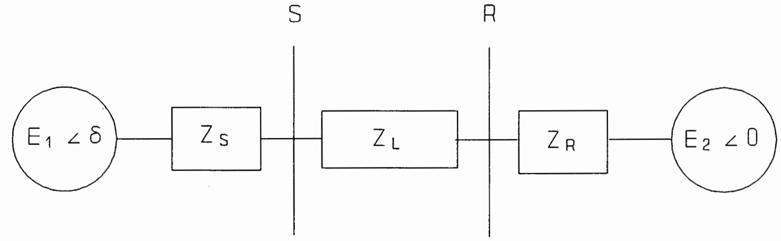

Figure 1: Ground faults at line midpoint (m = 0.5); R_F = 8

Test Cases:

	δ	mxs	mxr	mts	mtr
1.	0	0.5	0.5	0.5	0.5
2.	+15°	0.362	0.812	0.5	0.5
3.	+30°	0.305	1.425	0.5	0.5
4.	+45°	0.286	2.109	0.5	0.5
5.	+60°	0.286	2.127	0.5	0.5
	$\angle Z_{R1} = 60°$		$\angle Z_{R0} = 80°$		
6.	0°	0.528	0.507	0.547	0.507
7.	15°	0.369	0.831	0.539	0.509
	$Z_{R1} = 1 \angle 90°$		$Z_{R0} = 1 \angle 90°$		
8.	0°	0.482	0.524	0.478	0.523
9.	15°	0.826	0.787	0.483	0.530

mxs, mxr: Per unit distance from S or R indicated by the reactance algorithm.

mts, mtr: Per unit distance from S or R indicated by the Takagi algorithm.

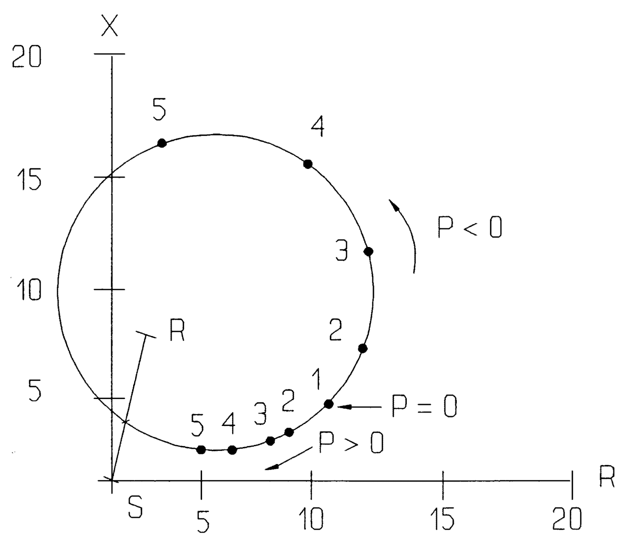

Figure 2: Apparent Positive-Sequence Reactance Locus for a Ground Fault Midway Between S and R

The reactance algorithm is strongly affected by load flow. When E1 leads E2 by 15° (Case 1), corresponding to left-to-right power flow, the fault appears much closer to S and farther from R. The apparent positive-sequence impedance is plotted in the figure, and we see that its locus is a circle, passing through the actual positive-sequence reactance values for the fault at two points, corresponding to power angles of 0° and 180°.

Two cases (6 and 7) show the effect of changing the angle of the source impedance at one end (R). The positive-sequence source impedance was changed from 80° to 60°. The reactance and Takagi algorithms are affected at both ends. Indeed, for a power angle of zero, the Takagi result at R is actually worse than the reactance value (0.547 vs 0.528)! Once power begins to flow, the reactance algorithm shows serious degradation similar to the first five cases, but the Takagi algorithm is much better behaved.

In Cases 8 and 9, we set the positive and zero-sequence source impedances at R equal to each other, as might be the case for a grounded transformer bank. Again, when the power angle is zero, the reactance and Takagi algorithms are both affected in similar amounts. However, power flow favors the Takagi algorithm.

Zero-Sequence Impedance Errors

An examination of Carson's equations shows that the zero-sequence impedance of a transmission line depends on the soil resistivity, as well as the conductor size, configuration, and height. Since the soil resistivity is not known precisely, and is not constant, Z0 is never precisely known. Clearly, the positive-sequence impedance-to-fault calculation for ground faults, given earlier, depends on the k factor, which, in turn, depends on Z0. As an example for a 345 kV line, if the actual Z0 is 20% lower than the value used in the fault locator equation (or in a distance relay setting), then the fault locator will indicate about 15% short (or a distance relay would overreach its setting by 15%).

When the fault location is known and the fault resistance is low, Z0 can be solved for. Z1 is assumed known accurately, and the k factor is found using the impedance-to-fault equation given earlier, with the faulted phase voltage, the faulted phase current, and the residual currents as inputs. Then, Z0 is found from the k factor and Z1.

Because the setting and coordination of ground distance and overcurrent relays depend so heavily on Z0, verifying the zero-sequence impedance is useful in improving the protection, as well as improving fault locating. References 3 and 4 both discuss cases where substantial zero-sequence impedance errors were discovered, and where improved Z0 values were calculated from the data saved by fault-locating relays.

Zero-Sequence Mutual Coupling

On well-transposed lines, mutual coupling from parallel circuits is significant only in the zero-sequence network. Accurate fault locating from one line end theoretically requires knowing the voltage at the line end, the currents there, and the currents of any other circuits having significant mutual coupling to the monitored circuit.

On a parallel line application, where Z0M, the mutual zero-sequence impedance, is uniform along the double circuit, it is possible to modify the fault locating equation to include the effects of currents in the parallel unfaulted circuit. This requires another measurement, namely the residual current in the parallel circuit. Relays and fault locators have been made which take advantage of this.

More often than not, the problem is more difficult. The mutual coupling may not be uniform, if conductor size changes or the line configuration changes along the line. Even worse, circuits may parallel the monitored line for only part of the way, and not bus into the same substation where the monitored circuit is. Figure 3 shows some difficult situations. Thus, there are many cases where there is not enough information at any one substation to make an accurate calculation of fault location without communications or other help.

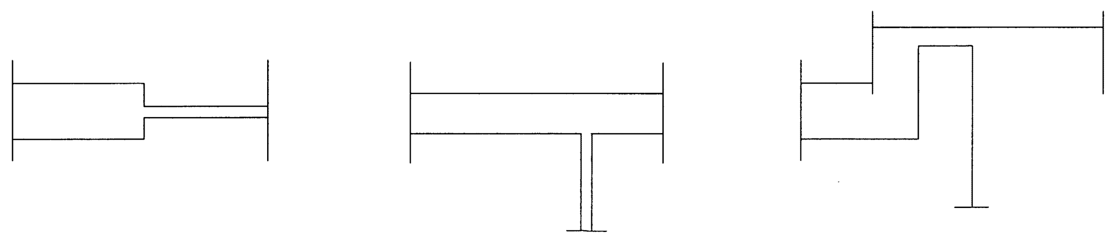

Figure 3: Difficult System Arrangements for Zero-Sequence Compensation

Several approaches are available to attack these problems:

1. Calculate the effects of possible mutual-coupling errors and explain them to the users of fault locating information if the errors are significant.

2. Calculate the effects, and make a correction chart or charts. One way to do this is to use a short circuit program to generate short circuit data for faults along the line of interest, and to present these voltages and currents to a fault locator with the help of a test set. Then the indications can be plotted against the actual locations, resulting in a correction chart. This need only be done for ground faults, as the zero-sequence mutual coupling does not affect phase faults. An analytic way is to use the short-circuit study data as input to the apparent-impedance equations given earlier, and then construct a nomograph.

3. Use a fault locator with an input for the residual current from the offending circuit. This is a simple solution if the parallel circuit is uniformly coupled and the current signal is available.

4. Use the two-ended algorithm. It does not depend on zero-sequence self or mutual impedance. It does require that the data from both ends of the line be brought together and processed, a procedure that is not very convenient or fast, from an operations point of view.

5. Completely represent the power system in the area of interest, and bring together measurements from all points in the system affecting the measurement. This "total solution" approach is possible with today's communications and data recording equipment, but the speed, modelling (setting), expense, and complexity are probably not justified.

Series Compensation

Series capacitor compensation offers steady-state as well as transient error problems.

Figure 4 shows two different fault locating problems, where series capacitors are applied. In 4a, the desired line-side potentials are available, and no steady-state problem exists. These potentials may be used with the phase currents as always.

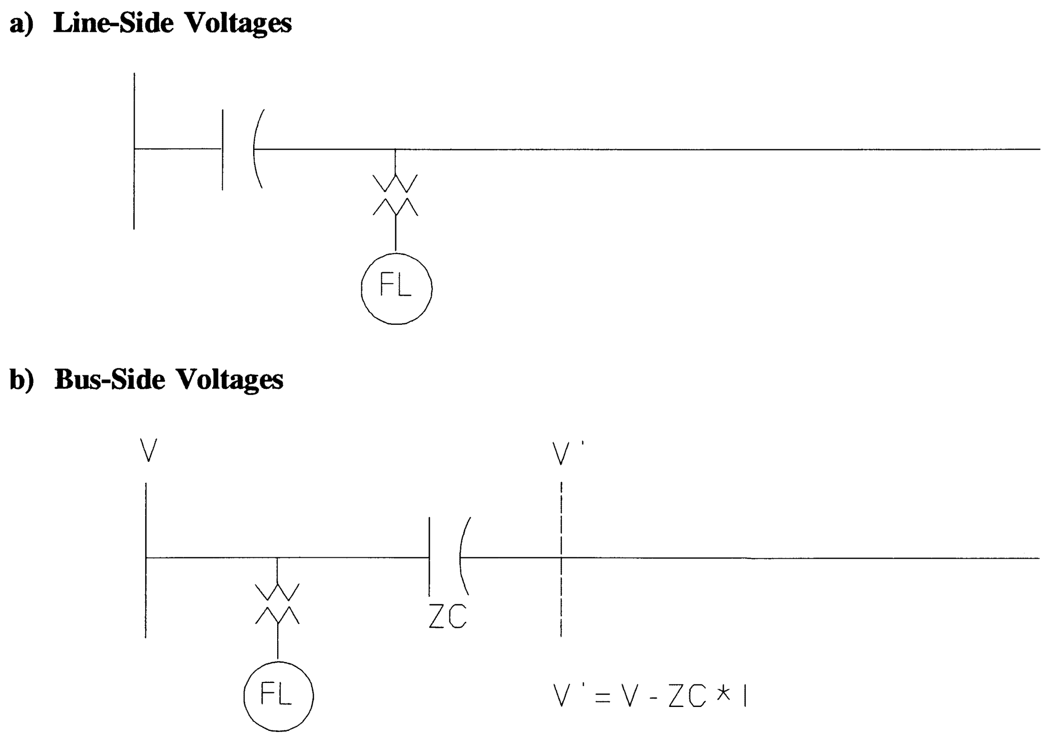

Figure 4: Series Compensated Line Considerations

In 4b, a steady-state source of error is possible, because the voltages measured by the bus potential transformers include the line drops to the fault and the potential differences across the capacitors. If protective gaps flash, shorting out the capacitors, then the steady-state error vanishes. If they do not flash, then the voltage drop must be compensated for. This can be done analytically, as follows. Consider a fictitious bus on the line side of the capacitors. Calculate the voltage at this bus, using the measured phase currents, voltages, and the impedance of the capacitors. That is, for each phase:

$$V' = V - ZC * I$$

Reference 4 describes a test of this approach on a 500 kV line. Practical problems for bus voltages include knowing whether or not the gaps flashed, and how much compensation was in service at the time of the fault. The presence of the series capacitors presents a serious transient problem, unless the protection around the capacitors operates. The transients may have signal components at frequencies below 60 Hz, making them difficult to filter out. If the fault duration is several cycles, then averaging several fault location calculations, made with well-filtered data, does a reasonable job of reducing the effect of the transients to acceptable levels.

Fortunately, the protection around the capacitors operates for many faults, especially close-in ones, so that the performance of impedance-based schemes is acceptable without much additional consideration. If fault locators are used at both line ends, then their results can be compared for validity.

Conductor Size and Configuration Changes

Often, especially at lower voltages, Z0 and Z1 may change along the line, due to changes in the size or configuration of the conductors. The following calculation procedure for locating a phase fault on such a line could be used:

1. Calculate the apparent positive-sequence impedance to the fault.

2a. If it is less than Z1 for the first line section, then determine the fault location as usual.

2b. If it is greater than Z1 for the first line section, then subtract the impedance for that line section, and compare the result against the impedance of the next line section. If the difference is less than the second section impedance, then the fault location is the sum of the length of the first section and the fraction of the length of the second section determined by the usual procedure. Continue the procedure if the difference is greater than the impedance of the second section, by subtracting out the impedance of the second section, etc.

Ground faults are more complicated, because Z0 and Z1 may not stay in constant proportion, making the k factor depend on the line section.

The following calculation procedure for locating a ground fault on such a line could be used:

1. Calculate the apparent impedance, using the k factor for the first section, if it is a ground fault. If the impedance is less than that of the first section, then the fault location can be computed. If it is greater, then create a fictitious bus at the end of the first section. Compute the voltage there as follows (for an AG fault):

$$VA' = VA - Z1 * (IA + k * IR),$$

where VA' is the fictitious bus voltage, VA is the measured voltage, Z1 is the positive-sequence impedance of the first line section, k is the k factor for the first line section, and IA and IR are the faulted phase and residual currents.

2. Use VA', IA, IR and k' (the k factor for the next line section) to calculate the apparent positive-sequence impedance from the fictitious bus to the fault or possibly into the third section.

3. If the fault is beyond the second section, then compute the voltage at the boundary between the second and third sections as follows:

$$VA'' = VA' - Z1' * (IA + k' * IR),$$

and find the apparent positive-sequence impedance into the third section, etc.

A <u>much</u> easier approach is to analyze the effects of the conductor changes. Often the size/spacing changes make insignificant changes to the line constants. If the changes are significant, then the short-circuit calculation procedures discussed earlier can be used to make nomographs for interpreting the readings of a standard fault locator.

Tapped Load

Tapped load seldom makes any significant difference in the fault location, since delta-wye connections of the transformers are usually used (no ground source), and since the impedances of the transformers are generally large compared to the line impedances. It does make a difference when the load current is near the short-circuit current, however.

One situation of practical interest having a rather simple theoretical solution is the case of tapped loads on radial circuits. Appendix I describes a solution which works as long as the tapped loads do not affect the zero-sequence network.

Three-Terminal Lines

Single-end fault locators indicate accurately up to the tap point. Beyond that point, infeed causes an excessive distance to fault indication.

The simplest way to handle a three-terminal line when substantial sources exist at each of the three terminals is to install a fault locator at each of the three terminals. When a fault occurs, obtain the readings from all three units, and accept the reading from the terminal showing the fault location short of the tap point.

Cogeneration

If a cogenerator is connected to the system at a tap point, then the fault locator indicates accurately up to the point of the tap, and indicates long beyond that point due to the infeed of unmeasured current from the cogenerator. If there are sources at both ends of the line, then a unit at each end of the line can be used, and the measurement short of the cogenerator tap is accepted as the more accurate indication.

Another approach is to only consider permanent faults. When a fault occurs, the cogenerator must also trip. If the utility reclose attempt results in a second (e.g. permanent) fault, then the fault location will be accurate, since the cogenerator would not be connected at the time of the reclose. Of course, an analysis of the amount of infeed the cogenerator can provide, compared to the utility source of fault current, may reveal that the cogenerator infeed can be neglected in some cases.

Short-Duration Faults

Impedance-based fault-locating techniques require that the system-frequency voltage and current quantities can be accurately measured. This requires filtering already mentioned, and signals of long enough duration to measure.

A two-cycle fault is probably the practical lower limit on fault duration for consistently reasonable results.

Travelling-wave relays and very fast breakers can provide clearing times of less than one cycle. Surge arresters may also operate fast enough to produce fault durations of less than one cycle.

For such short duration faults, the current never reaches its faulted steady state, and the voltage never drops to its faulted steady state, so the tendency is for the fault location to indicate long. Travelling-wave approaches may be the only solutions.

CCVT Transients

Capacitively-coupled voltage transformers delay the secondary voltages and create transients. Filtering in the fault locator must remove transient components created by the CCVTs. In the SEL equipment, a net band-pass filtering process is provided by an analog low-pass filter with a cutoff of 84 Hz, and by a digital filter which rejects DC. This combination has proven itself effective, as long as the fault duration is long enough to allow the 60 Hz component of the voltage to reach a steady state. The time this takes depends on the CCVT design.

CT Saturation

CT saturation robs the fault locator of current, making the measured impedance increase above its expected value without saturation, and the fault location indicates long. Fortunately, CT saturation is only likely to happen for very close-in faults, where the voltage is small. Although the percentage error in the distance calculation might be large, the absolute distance error probably will not be. For example, if CT saturation causes a 20% error in the current measurement, and the fault is only one mile away from the station, then a distance error of 0.2 miles would result, which is tolerable in a practical sense. If the fault is two miles away, the CT saturation error would probably drop to less than 10% in this case, corresponding to a distance error of less than 0.1 mile.

Delta-Connected PTs

At the outset, we assumed that phase-to-neutral voltages are available for all three phases. In some applications, only phase-to-phase voltages are available. Such is the case where two line-to-line voltage transformers are used instead of three phase-to-ground transformers.

Measurement of the line-to-line voltages denies the fault locator of any direct knowledge of the zero-sequence voltage component at the point of measurement, making ground-fault location more difficult. Phase-fault locating is not affected, since phase faults do not produce zero-sequence voltage.

Reference 5 describes a fault-locating relay which estimates the faulted phase-to-neutral voltage from the phase-to-phase voltage measurements and from an estimate of the zero-sequence bus voltage calculated from the zero-sequence current and a setting for the zero-sequence source impedance.

For an AG fault, the voltage VA can be calculated from the line-to-line voltages and the zero-sequence current using the following theory:

$$\begin{aligned} VA &= V1 + V2 + V0 \\ &= 1/3[VAB - VCA] + V0 \end{aligned}$$

Estimate V0 using V0 = - Z0 * I0, where Z0 is the zero-sequence source impedance, and I0 is the zero-sequence current.

Then, $$VA = 1/3[VAB - VCA] - Z0 * I0$$

Since VAB, VCA and I0 are available from the PTs and the CTs, all that is newly required is Z0, the zero-sequence source impedance.

This scheme has been in use for about three years, with good results. One theoretical limitation, which has not proven to be a practical limitation, is that the zero-sequence source impedance depends on the fault location, in a looped system.

Transmission Line Asymmetry

Does the fault location calculated by an impedance method vary from phase to phase, because of the asymmetrical construction of the line? To address this question, we analyzed two line configurations in Appendix II. One is a horizontal line configuration; the other is vertical. The following observations summarize the results of that study.

1. In the horizontal configuration, there is virtually no ground-fault phase dependency on accuracy, as long as the residual current and the faulted phase current are close together. (This condition minimizes the effects of the very different mutual impedances between the center phase and an outside phase, versus the coupling between the outside phases.) There is substantial phase-fault dependency; however. For the example configuration of Appendix II, a phase fault between two adjacent phases will indicate short, by several percent. A phase fault between the outside phases will indicate long.

2. In the vertical configuration, there is some ground-fault phase dependency, due to the differences between the self impedances, owing to the different conductor heights over ground. For the example, the dependency was about 0.3%, small enough to be neglected in most applications. The phase fault phase dependency is similar to the horizontal case.

3. The unequal mutual terms in the phase impedance matrices lead to load-current dependencies which affect fault locating. If the load current is similar to the fault current, then the errors due to load current can be several percent.

VALUE OF FAULT LOCATING TO PROTECTIVE RELAYING

Knowing the location of faults, especially permanent ones, is of obvious benefit in operating power systems. Several years of experience with fault-locating relays show that fault locating is also very valuable in the analysis of protective relaying schemes. Several examples follow.

1. A phase-to-phase fault occurred one substation away from a fault-locating relay: the distance-to-fault indication was incorrect. This led to the discovery that the positive-sequence impedance for the transmission line had been calculated wrong. (The wrong conductor spacing had been entered into the line constants program years before the application of the fault-locating relay.) The discovery was important in correcting the settings of the line protection.

2. When fault-locating relays are used at both line ends, or when a fault occurs at a known location, the line constants can be checked. In several cases, short distance-to-fault indications have revealed errors in the zero-sequence impedance for the line, most likely due to high estimates of the soil resistivity.

3. A fault on the first 80% of the line normally should operate the appropriate Zone 1 distance element. However, if enough fault resistance is present, the apparent impedance to the fault may be outside the Zone 1 circle, but still inside Zone 2 or 3. The fault locator indicates the distance to fault, not the apparent impedance, so it is easy to sort out faults in Zone 1 distance, which do not pick up the Zone 1 element, from faults beyond Zone 1 distance. A similar argument exists for better understanding high-resistance faults detected by ground-overcurrent elements.

4. In a trip-reclose-trip-lockout sequence, usually (but not always) the same fault is responsible for both trips. Fault locating makes it easy to determine if two faults or one fault actually occurred. For example, the first fault may be due to a tree branch. On reclose, say, with the remote end open, a weak insulator string could flash over on a transient overvoltage, at a location and phase different from the first fault. The fault locator must be able to respond to faults in rapid succession to be useful in this way. (The fault-locating relays of our manufacture save up to 12 events triggered in rapid succession, and satisfy this requirement.)

In the future, fault location may become a valuable input in reclosing schemes and automatic sectionalizing schemes.

TWO PRACTICAL EXAMPLES

Rochester Gas and Electric Multiple Circuit Application

Rochester Gas and Electric Company engineers have applied fault-locating relays at three installations, each of which uses a single digital fault-locating distance relay to locate faults on several 34.5 kV lines.

One installation (Station 216) uses the low side transformer current transformers, which provide the total current in four 34.5 kV circuits.

Another installation (Station 204) sums the currents from two transformers and an additional tie line to provide the fault-locating relay with the sum current into a total of six 34.5 kV circuits. RG & E developed nomographs for each of the individual circuits, since the circuits are different and inhomogeneous. One such nomograph is given in Figure 5, for Circuit 759 at Station 204.

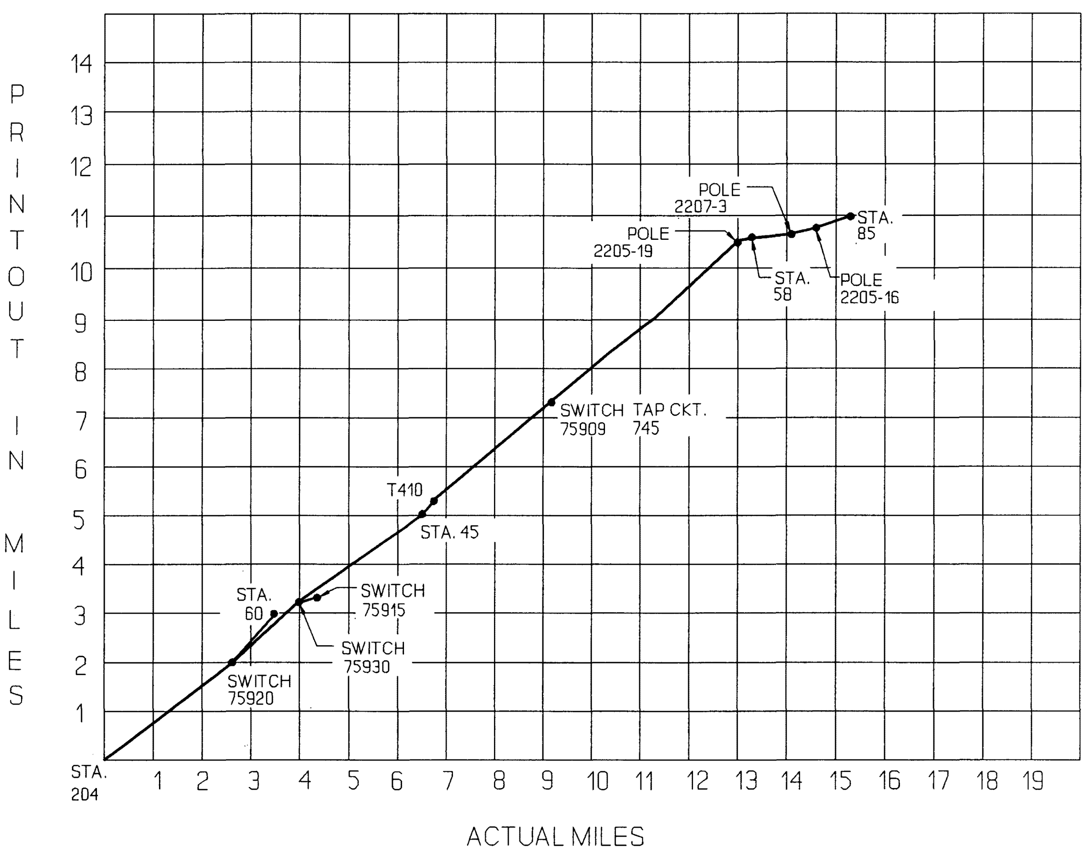

Figure 5: Nomograph - 34.5 kV Circuit 759 - Station 204

A third installation (Station 56) also sums the currents from two transformers and a tie line, to provide fault locating for four circuits using a single fault-locating relay.

Since these are radial feeders, the currents in the unfaulted circuits are load currents. Experience has shown that the load currents usually have little effect on the fault locating accuracy, and Line Operations personnel have developed confidence in the indications. For example, when a tree fault occurred on a line fed by Station 204, Operations obtained the fault location by interrogating it remotely, and then dispatching line crews to isolate the faulted section. The unfaulted sections were restored to service by connecting them to adjacent circuits, and service was restored in 33 minutes.

Sharing one fault-locating relay amongst four to six radial circuits provides very economical fault locating at voltages where fault locating could never be considered before. When load currents are important, they may be handled by the method of Appendix I.

Otter Tail Power Company Impedance Study

The reactance and Takagi fault locating algorithms used by the fault-locating relays depend on accurate values of the positive and zero-sequence impedances to determine locations of faults on the transmission line. Proper operation of the line protection also depends on these impedances.

The positive- and zero-sequence impedances of the transmission line can be verified when a fault locating relay is installed at each end of the transmission line. The positive-sequence impedance can be checked when the location of the fault is known. Once the positive-sequence impedance has been verified it can be used to check the value of the zero-sequence impedance of the line as used by each relay.

A permanent fault occurred on the Jamestown-Center 345 kV line in North Dakota on May 10, 1985, when fault-locating relays were in service at both ends of the line. The permanent fault was located 110.6 miles from the Center substation. The fault was the result of a tornado passing through the line causing two structures to be damaged.

With the data from the fault-locating relays and the known location of the fault, checks can be made on the positive-sequence impedance of the transmission line by calculating the distance to the fault and comparing the calculated distance with the actual distance to the fault.

Reference 2 describes a method to accomplish this comparison, and Reference 3 gives the details of the calculation procedure. A short summary follows:

The distance to the fault from one end of the line can be verified using the positive-sequence impedance of the transmission line using the two-end fault-locating equations given in Reference 2

Let:

V_F = The positive-sequence voltage at the fault

$V_{1C,J}$ = The positive-sequence voltages at Center and Jamestown respectively

$I_{1C,J}$ = The positive-sequence current at Center and Jamestown respectively

m = The per unit distance from Center to the fault. (i.e., fault at Center m=0, fault at Jamestown m=1)

Z_{1L} = The positive-sequence impedance of the transmission line

The two equations for the positive-sequence voltage at the fault (one written using the data from each end) can be set equal to each other and solved for the distance m:

$$V_{1C} - I_{1C}(mZ_{1L}) = V_{1J} - I_{1J}[(1-m)Z_{1L}]$$

$$m = \frac{V_{IC} - V_{IJ} + I_{1J}\,Z_{1L}}{Z_{1C}\,(I_{1C} + I_{1J})}$$

Positive-sequence quantities from each end of the line, calculated from the event report data saved by the fault-locating relays, are entered into this equation. The resultant value of m, which is a complex number, for the May 10 fault is 0.9112 -7.3°. Using this magnitude of m gives a distance to the fault from Center of 110.7 mi. This value compares very favorably with the actual value of 110.6 miles. This calculation shows that confidence can be placed in the positive-sequence impedance of the transmission line.

With the value of the positive-sequence impedance known, the zero-sequence impedance of the line as used by each relay to locate the fault can be calculated using the data from only one end of the line. The results of these calculations yield impedances which can be directly entered into the relay settings.

When measuring the distance to the fault from one end of the transmission line, all sequence components must be taken into account. If the positive-sequence impedance of the transmission line is equal to the negative-sequence impedance (i.e., $Z_{1L}=Z_{2L}$) and the resistance of the fault is near zero then an impedance to the fault can be calculated using the voltage and current measurements from one end of the line.

An apparent impedance to the fault can be calculated from the faulted phase voltage and a compensated phase current which allows for the impedance of the zero-sequence network to the fault:

$$mZ_{1L} = \frac{V_F}{I_F + KI_0}$$

Where:

m = The per unit distance from the relay to the fault

Z_{1L} = Positive-sequence impedance of the transmission line

V_F = The faulted phase to neutral voltage at the relay

I_F = The faulted phase current at the relay

I_O = The zero-sequence current at the relay

The compensation factor K is defined by the following equation:

$$K = \frac{Z_{0L} - Z_{1L}}{Z_{1L}}$$

When the fault location and positive-sequence impedance of the transmission line is known, these two equations can be combined and solved for m Z_{0L} as follows:

$$m\ Z_{0L} = \frac{V_F - m\ Z_{1L}(I_F - I_0)}{I_0}$$

Utilizing currents and voltages from Center and a value of m=0.91, the apparent zero-sequence impedance of the transmission line as seen by the Center relay becomes:

Z_{0L} from Center = 71.7 + j206.3 ohms primary

The same procedure is performed with the Jamestown quantities using a value of m=0.09. This yields an apparent zero-sequence impedance of:

Z_{0L} from Jamestown = 52.2 + j205.6 ohms primary

These two line impedances will not necessarily be equal. The differences between these two numbers can be attributed to items such as changes in soil resistivity along the line as well as errors associated with sampling devices supplying quantities to the relays. The latter is especially true in this case where different types of potential devices at Center (CCVT's) and Jamestown (PT's) are used.

These new values for Z_{0L} are substantially lower than the design value of 65.70 + j254.59 from the line constants program. This fact seems to indicate that the actual zero-sequence impedance of the transmission line is less than anticipated. Since these new values are lower, other relay systems utilizing the design value of Z_{0L} will be adversely affected. These new values can be used by the fault locating relay at each end to more accurately determine the location of the transient faults where very little physical evidence of the fault remains to determine the exact location.

Using these new values of zero-sequence impedances, new compensation factors can be calculated and applied to other faults previously recorded. Table 1 shows fault locations calculated by the relay located at each substation using previously estimated values of Z_{0L}.

Table 1: Fault Locations Calculated by Relay with Old Z_0 Values					
Date	**Fault Type**	**Center**	**Jamestown**	**Total**	**% of Line Length**
04/08/85	B-G	27.36 mi*	81.28 mi*	108.64 mi	89.4%
04/19/85	C-G	14.51 mi	112.77 mi	127.28 mi	104.7%
04/19/85	C-G	26.19 mi	99.17 mi	125.36 mi	103.1%
05/10/85	B-G	123.75 mi	11.76 mi	135.51 mi	111.5 %
05/30/85	C-G	50.48 mi	78.74 mi	129.22 mi	106.3%
06/25/85	C-G	122.63 mi	4.27 mi	126.90 mi	104.4%

***Note:** These mileages used Z_{0L} = 65.70 + j254.59 ohms primary. Others used Z_{0L} = 55.48 + j215.0 ohms primary.

The fault locations shown in Table 2 below were developed using the re-calculated values of Z_{0L} for each respective relay.

Table 2: Fault Locations Calculated with Corrected Z_0					
Date	**Fault Type**	**Center**	**Jamestown**	**Total**	**% of Line Length**
04/08/85	B-G	30.42 mi	93.91 mi	124.33 mi	102.3%
04/19/85	C-G	13.39 mi	112.83 mi	126.22 mi	103.9%
04/19/85	C-G	25.28 mi	98.11 mi	123.39 mi	101.5%
05/10/85	B-G	110.69 mi	10.97 mi	121.66 mi	100.1%
05/30/85	C-G	48.35 mi	77.93 mi	126.28 mi	103.9%
06/25/85	C-G	115.99 mi	3.68 mi	119.67 mi	98.5%

As can be seen from the results, the new measurements from Table 2 are more accurate in terms of the total line length than those measured by the relay without the modified zero-sequence impedance. This is particularly true when comparing the results for the fault on April 8, 1985, where the total line length went from 108.64 miles to 124.33 miles.

The corrected value of Z_0 should be used in adjusting the settings of the distance relays at Center and Jamestown, since the value from the line constants program could result in significant overreaching, as explained below. A residual-current compensated ground-distance relay measures the positive-sequence impedance to the fault, by comparing the faulted phase-to-neutral voltage with a resultant current, which is the faulted phase current plus a constant times the residual current. In equation form, for an A-G fault, this is:

$$Z_1 = \frac{V_A}{I_A + K * I_R} = \text{The positive-sequence impedance to the fault}$$

Where:

$$K = 1/3 \; (Z_0/Z_1 - 1)$$

Since K depends on Z_0, an error in Z_0 causes an error in the resultant current.

If we assume that the current distribution factors for the positive, negative and zero-sequence networks are the same, then IA = IR, and we can rewrite the above equation as:

$$Z_1 = \frac{VA}{(1 + K) * I_A}$$

For the same fault, but different values of K, the ratio of reaches is:

$$\frac{1 + K}{1 + K'}$$

Using the calculated and measured values of Z_0 given earlier, this ratio is 1.14, meaning that ground distance relays set with the calculated value of Z_0 would reach 14% farther than their setting. For example, for a Zone 1 setting of 85%, the overreach is 12%, for a total reach of 97%, leaving little margin for other possible sources of error.

Although this example considers distance relay settings, similar conditions hold for the effects of the Z_0 error on the setting of residual overcurrent relays, especially the instantaneous elements.

CONCLUSIONS

Fault-locating relays have demonstrated their ability to do much more than provide protection and fault locating. As the last example shows, for instance, their data have been used to verify line constants.

Many simple techniques have been applied to overcome sources of error in fault locating. Correction tables and charts, used to compensate for conductor changes, etc. are examples.

On radial systems, one fault-locating relay has been applied to cover several feeders, making fault locating available at low voltages, where it was unaffordable before the advent of fault-locating relays.

These contributions to the operation of the electric power system stem from the need in utilities to solve practical problems, the creativity of utility engineers applied to those problems, and the availability of fault-locating relays.

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APPENDIX I - USING ONE FAULT-LOCATING RELAY ON A RADIAL CIRCUIT WHERE SHUNT LOAD CURRENT IS PRESENT

General Description

One fault-locating relay can be used to locate ground faults on several radial distribution circuits, by using the total current into the group of feeders.

Load currents on the faulted feeder and the other feeders in that group are included in the measured currents. When the load currents are appreciable, errors result. This note shows a simple way to minimize the effects of load currents when locating faults on radial feeders.

Background

The sequence network drawing on the following page is for a radial network with a ground fault on the reference phase.

The positive- and negative-sequence networks include shunt branches at the bus, which represent the net load effects on all of the feeders. No shunt branch is included in the zero-sequence network, as the common assumption is made that the load stations are not zero-sequence sources to the feeders.

Arrows next to the source impedances indicate the assumed point of measurement of the currents. I1 and I2 include the load current. I0 does not. I1 and I2 are not the same as I1F and I2F, respectively. However, it is clear from the drawing that:

$$I0F = I1F = I2F = 1/3\ IR = 1/3\ IAF. \qquad (1)$$

Only I0F is observable under the assumptions made here.

Normally we would calculate the positive-sequence impedance to the fault using:

$$Z1 = VA/(IA + k * IR), \quad \text{where } k = 1/3(Z0/Z1 - 1) \qquad (2)$$

Because of the load currents being measured during the fault, which do not flow in all of the faulted line, if at all, IA is not accurate. In our picture, IA is not equal to IAF. The solution is to use the residual current for phase A, as suggested by equation (1), as follows:

$$Z1 = VA/(IR + k * IR) = VA/(IR*(1 + k)) \qquad (3)$$

Practical Considerations

Data from an event report generated by a fault is easily processed by hand using equation (3), or a short program can be written for that purpose.

A fault-locating relay could be connected so that IA=IB=IC=IR, and then the calculation would be performed directly in the relay; however, this destroys the phase information, which may be useful in identifying trouble.

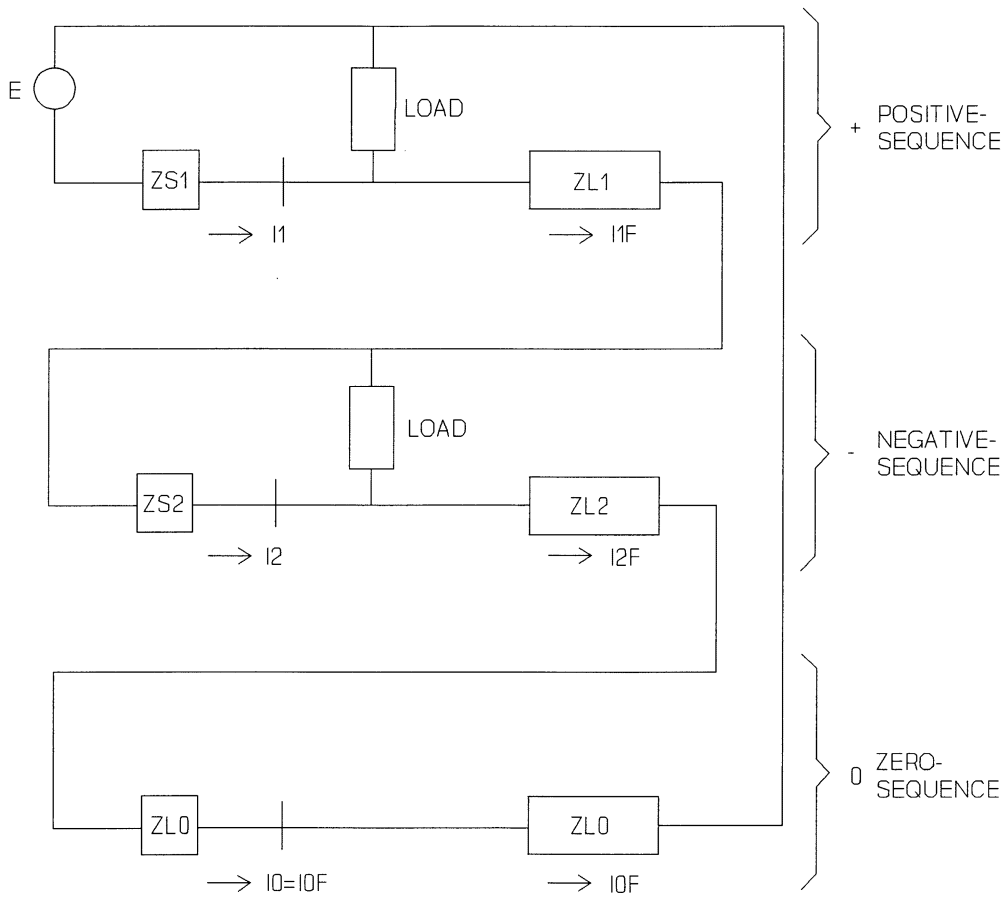


Figure 5: Sequence Network Drawing for Radial System with Tapped Load

APPENDIX II - COMPARISON OF IMPEDANCE MATRICES FOR TWO 100-MILE LINE CONFIGURATIONS

The purpose of this Appendix is to illustrate the dependence of fault locating on the construction of the transmission line. Since it is not possible to build a transmission line where the phase conductors are symmetrically located with respect to each other and with respect to earth and possible ground wires, neither the self impedances (Zaa, Zbb, and Zcc) nor the mutual impedances (Zab, Zbc, Zca, Zba, and Zac) are the same. Because of this, the transformation of the phase impedance matrix to the symmetrical component domain does not yield a diagonalized symmetrical component impedance matrix.

Therefore, the sequence networks, which we normally assume are independent, are in fact not, but are coupled by mutual impedances between them.

For two examples, consider a transmission line with a horizontal (flat) conductor configuration, and with two shield wires. Also consider for comparison a line with a nearly vertical conductor configuration, and a single shield wire. A 10 ohm-meter value of earth resistivity is used for both.

A line constants program was used to find the self and mutual resistances and inductances for the two transmission lines. The matrices are ZH and ZV for the horizontal and vertical configurations.

Average values of the self and mutual impedances are calculated, and the symmetrical component impedance matrices are found by transformations.

Begin by defining the system frequency, a unit conversion relationship between radians and degrees, and the 120° operator.

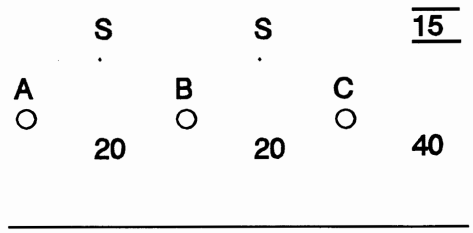
$w := 377 \qquad rad \equiv 1 \qquad a := 1 \cdot e^{j \cdot 120 \cdot deg} \qquad a = -0.5 + 0.866i$

$$degree \equiv \frac{\pi}{180} \cdot rad$$

Let the matrix A be the relationship between the phase voltages (Va, Vb, and Vc) and the symmetrical component sequence voltages (V0, V1, and V2). Its inverse (matrix AS) returns phase quantities from sequence quantities.

$$A := \tfrac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \qquad AS := A^{-1} \qquad I := \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

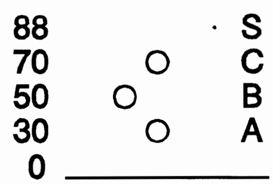
From the line constants program, we obtained the resistance and reactance data contained in matrix ZH, for the horizontal transmission line configuration, where the conductors are 40 feet above the earth, and spaced 20 feet apart. Two shield wires are centered 15 feet above the plane of the phase conductors.



$$ZH := \begin{bmatrix} 22.95 + w \cdot .3248j & 10.15 + w \cdot .1226j & 10.01 + w \cdot .1004j \\ 10.15 + w \cdot .1226j & 23.18 + w \cdot .3246j & 10.15 + w \cdot .1226j \\ 10.01 + w \cdot .1004j & 10.15 + w \cdot .1242j & 22.95 + w \cdot .3248j \end{bmatrix}$$

$$ZH = \begin{bmatrix} 22.95 + 122.45j & 10.15 + 46.22i & 10.01 + 37.851i \\ 10.15 + 46.22i & 23.18 + 122.374i & 10.15 + 46.22i \\ 10.01 + 37.851i & 10.15 + 46.22i & 22.95 + 122.45i \end{bmatrix}$$

From the line constants program, we similarly obtained the matrix ZV for the vertical configuration, with horizontal offsets of 0 for the shield, 16 for A, 20 for B and 16 for C. This is one side of a double circuit line.



$$ZV := \begin{bmatrix} 22.17 + w \cdot .3253j & 9.14 + w \cdot .1231j & 9.05 + w \cdot .1019j \\ 9.14 + w \cdot .1231j & 21.92 + w \cdot .3264j & 8.95 + w \cdot .1242j \\ 9.03 + w \cdot .1019j & 8.95 + w \cdot .1242j & 21.81 + w \cdot .3274j \end{bmatrix}$$

$$ZV = \begin{bmatrix} 22.17 + 122.638i & 9.14 + 46.409i & 9.05 + 38.416i \\ 9.14 + 46.409i & 21.92 + 123.053i & 8.95 + 46.823i \\ 9.03 + 38.416i & 8.95 + 46.823i & 21.81 + 123.43i \end{bmatrix}$$

Transform the phase impedance matrices into sequence impedance matrices, by pre-multiplying by matrix A and post-multiplying by AS.

$$ZSH := A \cdot ZH \cdot AS$$
$$ZSV := A \cdot ZV \cdot AS$$

$$ZSH = \begin{bmatrix} 43.233 + 209.285i & 2.333 - 1.489i & -2.456 - 1.276i \\ -2.456 - 1.276i & 12.923 + 78.994i & -4.846 + 2.817i \\ 2.333 - 1.489i & 4.862 + 2.788i & 12.923 + 78.994i \end{bmatrix}$$

$$ZSL = \begin{bmatrix} 40.053 + 210.806i & 2.342 - 1.729i & -2.055 - 1.614i \\ -2.045 - 1.608i & 12.923 + 79.163i & -4.715 + 2.766i \\ 2.352 - 1.735i & 4.732 + 2.714i & 12.923 + 79.152i \end{bmatrix}$$

In these matrices, the diagonal contains Z00, Z11 and Z22, and the off-diagonal terms are the mutual impedances between the sequence networks. Because the matrices did not diagonalize by the sequence transform, we know that the sequence networks are not independent.

Define a matrix function to find the average of the diagonal elements.

$$DIAG(MAT) := \tfrac{1}{3} \cdot tr(MAT)$$

Define a matrix function to find the average of the off-diagonal elements.

$$OFFDIAG(MAT) := 1/6 \cdot tr(MAT \cdot (1-I))$$

Define a matrix function to calculate the magnitude of each element of MAT, normalized by scalar SF:

$$MAG(MAT, SF) := \left[\left| \frac{MAT}{SF} \right| \right]$$

Using these functions makes it easy to find the average self and mutual impedances from the phase impedance matrices, and to normalize any matrix for comparison purposes.

Beginning with the vertical configuration, find the average self impedance per phase, the average mutual impedance per phase, and find the average mutual impedance per phase normalized to the average self impedance.

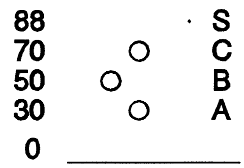
ZSSV: = DIAG(ZV)	ZSSV	= 21.967 + 123.04i	Average self impedance
ZMMV: = OFFDIAG(ZV)	ZMMV	= 9.043 + 43.833i	Average mutual impedance

MAG(ZMMV, ZSSV) = 0.358 — Magnitude of mutual impedance, normalized by self impedance.

This factor of 0.358 indicates that each of the currents in the other phases has about one-third of the effect on the voltage drop in the phase under consideration, as does the current in that phase itself.

Now normalize the matrix ZV by the average self impedance:

$$MAG(ZV,\ ZSSV) = \begin{bmatrix} 0.997 & 0.378 & 0.316 \\ 0.378 & 1 & 0.381 \\ 0.316 & 0.381 & 1.003 \end{bmatrix}$$



The self impedances of the three phases are nearly equal; however, the mutual impedances differ substantially from the average value found earlier (0.358).

Using the fact that Z11=Z22=ZSS-ZMM, normalize the sequence matrix by the positive sequence impedance and find the magnitude of each term in the matrix.

$$MAG(ZSV,\ ZSSV - ZMMV) = \begin{bmatrix} 2.675 & 0.036 & 0.033 \\ 0.032 & 1 & 0.068 \\ 0.036 & 0.068 & 1 \end{bmatrix}$$

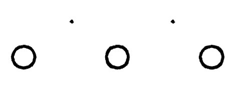
We observe there are several percent of coupling between the sequence networks, owing to the assymetry of the conductor configuration.

Repeating the process for the horizontal configuration gives the results below:

ZSSH	:	DIAG(ZH)	ZSSH	=	23.027 + 122.424i
ZMMH	:	OFFDIAG(ZH)	ZMMH	=	10.103 + 43.43i
Z1	:	ZSSH - ZMMH	Z1	=	12.923 + 78.994i
Z0	:	ZSSH + 2 · ZMMH	Z0	=	43.233 + 209.285i

$$MAG(ZMMH,\ ZSSH) = 0.358$$

$$MAG(ZH,\ ZSSH) = \begin{bmatrix} 1 & 0.38 & 0.314 \\ 0.38 & 1 & 0.38 \\ 0.314 & 0.038 & 1 \end{bmatrix}$$



$$MAG(ZSH,\ ZSSH - ZMMH) = \begin{bmatrix} 2.67 & 0.035 & 0.035 \\ 0.035 & 1 & 0.07 \\ 0.035 & 0.07 & 1 \end{bmatrix}$$

Similar off-diagonal terms exist, as compared to the vertical configuration. One difference is that the phase impedance matrix self impedance terms are nearly the same, as the only assymetry of these conductors with respect to ground is the closer relationship of the center phase (B) to the two ground wires. The difference shows up only in the fourth decimal place.

To further analyze the effects of line unbalance, form a matrix ZHBAL to represent a balanced line, which a fault locator set with Z0 and Z1 would assume exists.

$$ZHBAL := \begin{bmatrix} ZSSH & ZMMH & ZMMH \\ ZMMH & ZSSH & ZMMH \\ ZMMH & ZMMH & ZSSH \end{bmatrix}$$

To see the difference between the actual line and the balanced approximation, take the difference between matrices ZHBAL and ZH, and normalize the matrix elements by the magnitude of the nominal self impedance.

$$DZH := \left[\frac{1}{|ZSSH|} \right] \cdot (\mathrm{ZHBAL} - \mathrm{ZH}) \quad \text{... balanced vs unbalanced representations}$$

$$DZH := \begin{bmatrix} & 0.001 & -0.022i \ \ 0.001 & +0.045i \\ & -0.0221i & -0.001 & -0.022i \\ 0.001 & +0.045i & -0.022i & 0.001 \end{bmatrix}$$

The very small diagonal elements reconfirm our earlier observation that the self impedances are very close together. The off-diagonal elements are two to four percent, meaning that one unit of current in one phase indices a voltage difference of two to four percent between the actual line and its balanced model, and that voltage is induced in a different phase.

Consider an AG fault, with no load flow, on a radial system driven by an infinite bus. IB=IC=0, and IA=VA/ZSS=1.

$$IA := e^{-j \cdot 79.3\ \mathrm{deg}} \qquad IB := 0 \qquad IC := 0$$

$$\begin{bmatrix} DVA \\ DVB \\ DVC \end{bmatrix} := DZH \cdot \begin{bmatrix} IA \\ IB \\ IC \end{bmatrix} \qquad DVA = -8.398 \cdot 10^{-5} - 0.001i$$

The very small difference between the voltages calculated with the unbalanced and balanced models indicates that virtually no error will result from using the balanced model instead of the unbalanced model in this special case.

Next, we try the case of just balanced load, to determine the voltage difference between the unbalanced and balanced representations.

Balanced load:

$$\begin{bmatrix} DVA \\ DVB \\ DVC \end{bmatrix} := DZH \cdot \begin{bmatrix} 1 \\ a^2 \\ a \end{bmatrix} \qquad \begin{aligned} DVA &= -0.058 - 0.01i \\ DVB &= 0.02 - 0.011i \\ DVC &= -0.019 + 0.057i \end{aligned}$$

The balanced model produces a six percent less voltage drop in the outside phase (A and C) than the unbalanced model. The sources of these differences are the large differences in the "a-c" mutual elements.

The center phase is not as affected by phase a and phase c currents, as we might expect, since a and c are symmetrical with respect to b.

This balanced load analysis is important, because it shows that load currents flowing in the uninvolved phases induces voltages in the faulted phase, which are not accounted for by the balanced model. When load flows outward, a fault on either of the outside phases tends to look closer in, and a fault on the inner phase tends to look farther away.

Repeating the calculations for the vertical configuration yield the results below:

$$ZVBAL := \begin{bmatrix} ZSSV & ZMMV & ZMMV \\ ZMMV & ZSSV & ZMMV \\ ZMMV & ZMMV & ZSSV \end{bmatrix}$$

$$DZV := \left[\frac{1}{|ZSSV|} \right] \cdot (ZVBAL - ZV)$$ ... balanced vs unbalanced representations

$$\begin{bmatrix} DVA \\ DVB \\ DVC \end{bmatrix} := DZV \cdot \begin{bmatrix} IA \\ IB \\ IC \end{bmatrix} \qquad DVA = 0.003 + 0.002i$$

The 0.003 pu larger voltage for the balanced case maps into a 0.3% increase in the indicated distance to fault, and is due to the very slightly lower self impedance of the lowest conductor, as compared to the average. If we were to fault phase B, the error would be almost zero, and the phase c error is about 0.3% short.

The load case is very similar to the horizontal configuration, and the same comments hold.

$$\begin{bmatrix} DVA \\ DVB \\ DVC \end{bmatrix} := DZV \cdot \begin{bmatrix} 1 \\ a^2 \\ a \end{bmatrix} \qquad \begin{aligned} DVA &= -0.057 - 0.008i \\ DVB &= 0.019 - 0.008i \\ DVC &= -0.019 + 0.057i \end{aligned}$$

Phase-to-phase faults are measured by the loop impedances, which average out to the positive-sequence impedances. However, there is substantial difference between the loop impedances A-B and A-C, for example. For the horizontal line configuration, consider the impedance ZAA-ZAB, which should be used to locate an AB fault, and compare it to the positive-sequence impedance. Do the same for the ac loop.

$$ZAA := ZH_{0,0} \qquad ZAB := ZH_{0,1} \qquad ZAC := ZH_{0,2}$$

$$\frac{ZAA - ZAB}{ZSSH - ZMMH} = 0.966 - 0.004i$$

$$\frac{ZAA - ZAC}{ZSSH - ZMMH} = 1.069 + 0.011i$$

This shows that the correct loop impedance for an AB fault is about three percent less that the positive-sequence impedance, so that a fault locator scaling on the basis of the positive-sequence impedance will indicate short by several percent.

On the other hand, a fault between the outside phases will indicate long, since the actual value of impedance is greater than the positive-sequence impedance.

Conclusions

1. The horizontal line configuration offers little ground fault error, when the unfaulted phase currents are small.

2. The vertical line configuration offers a small ground fault error even when the currents are zero in the uninvolved phases, since the conductors have different self impedances.

3. Load currents or faults currents in the uninvolved phases can induce voltages several percent different than predicted by the balanced model. These differences can cause significant fault-locating errors.

4. Phase fault locating accuracy depends significantly on the involved loop. Errors of several percent are possible, due to the substantial differences in the loop impedances.

FIELD EXPERIENCE WITH FAULT LOCATING RELAYS

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13TH ANNUAL WESTERN PROTECTIVE

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INTRODUCTION

As transmission line structures become more compact and clearances between phases become less, the occurrence of a transmission line fault is likely to increase. This is particularly true in areas where unanticipated external factors result in these faults. Such has been the case with the Center to Jamestown 345 kV line in central North Dakota. This transmission line has faulted excessively since it was uprated from 230 kV to 345 kV in 1981.

Many theories for the frequent faults have been proposed, including underinsulation and birds. (Reference 1)

In order to determine where these faults were occurring, fault locating relays were installed first at Jamestown and then later at Center. These relays, manufactured by Schweitzer Engineering Laboratories (SEL) in Pullman, Washington, provide valuable information about the location of the faults. In addition, the data saved by the relays permit us to calculate the actual line constants.

This paper discusses the application of the relays to the power system, and presents some fault data obtained from the relays. It also provides the computations used to calculate the transmission line constants for the Jamestown-Center line. The results clearly show that the actual positive-sequence impedance of the line agrees well with the value determined from the conductor and tower data, but that a significant difference exists between the measured and calculated values of the zero-sequence impedance. The error in the zero-sequence impedance calculated from conductor, tower and earth data results in a calculated value of overreach of 14 percent for ground faults, which is sufficient to compromise the security of zone 1 ground distance relays set to reach 85-90 percent of the line.

An introduction to the fault locating relays is offered first, followed by their application to the Jamestown-Center line, and the calculations of transmission line impedance.

FAULT LOCATING RELAYS

The relay provides three zones of MHO-circle directional distance protection and locates all fault types. Fault location is determined from prefault and fault measurements at one end of the line.

A detailed event report containing the prefault, fault, and postfault voltages and currents includes the distance to the fault, the type of fault, and the state of all relay units, inputs and outputs during the event.

Phasors representing the voltages and currents are easily obtained from the event report data. The information is useful in verifying short-circuit and load-flow calculations, verifying transmission line constants, and measuring voltage and current unbalance. The phasor data are used later to calculate transmission line constants.

Three-phase voltages and currents are input to small transformers, which step down the instrument transformer secondary quantities to levels compatible with electronic processing. The transformers also provide galvanic isolation between the instrument transformer secondaries and the electronics.

The six analog channels are filtered by two-pole low-pass filters to prevent possible aliasing errors in the subsequent sampling process. The three filtered current signals are summed to provide the zero-sequence current. The filtered data are presented to the inputs of sample/hold amplifiers.

Once all quantities are sampled, the analog-to-digital conversion process begins. The microcomputer controls the analog multiplexer, and the A/D converter. Each of the seven sampled inputs is selected by the multiplexer, one at a time, then scaled by a programmable-gain amplifier and converted to a binary number by the A/D converter. After all channels are converted and read into the computer, the computer proceeds with the execution of the digital filter and relay algorithms.

The sampling period is 4167 usec, corresponding to a sampling rate of 240 Hz, or four samples per power system cycle.

The requirements for the digital filters include elimination of dc offsets introduced by the analog electronics, reduction of the decaying exponential offset present on the current data following a fault, and passing the power-system frequency information. The digital filters must be simple, so that a minimum burden of computation is placed on the microprocessor.

A very simple and effective digital filter which has the properties of a double-differentiator smoother, and which requires only addition and subtraction of data samples is employed. Let the latest four samples of one channel of information be X_1, X_2, X_3, and X_4. Then the filter is defined by:

$$P = X_1 - X_2 - X_3 + X_4.$$

This filter has the desired property of eliminating dc offsets, as can be seen by setting all the samples to the same value and noting that the filter output is zero. It also eliminates ramps, as can be seen by setting the samples equal to, say, 1, 2, 3, 4, and again noting that the resulting output is zero.

A new value of P for each input is computed every one-fourth cycle. The latest value of P and the value of P one-fourth cycle earlier (renamed Q) form a Cartesian-coordinate pair representing the input signal as a phasor (P, Q). The phasor representations of the input signals are processed in the relay and fault-locating algorithms. In addition, they are available as part of the system output in response to an event.

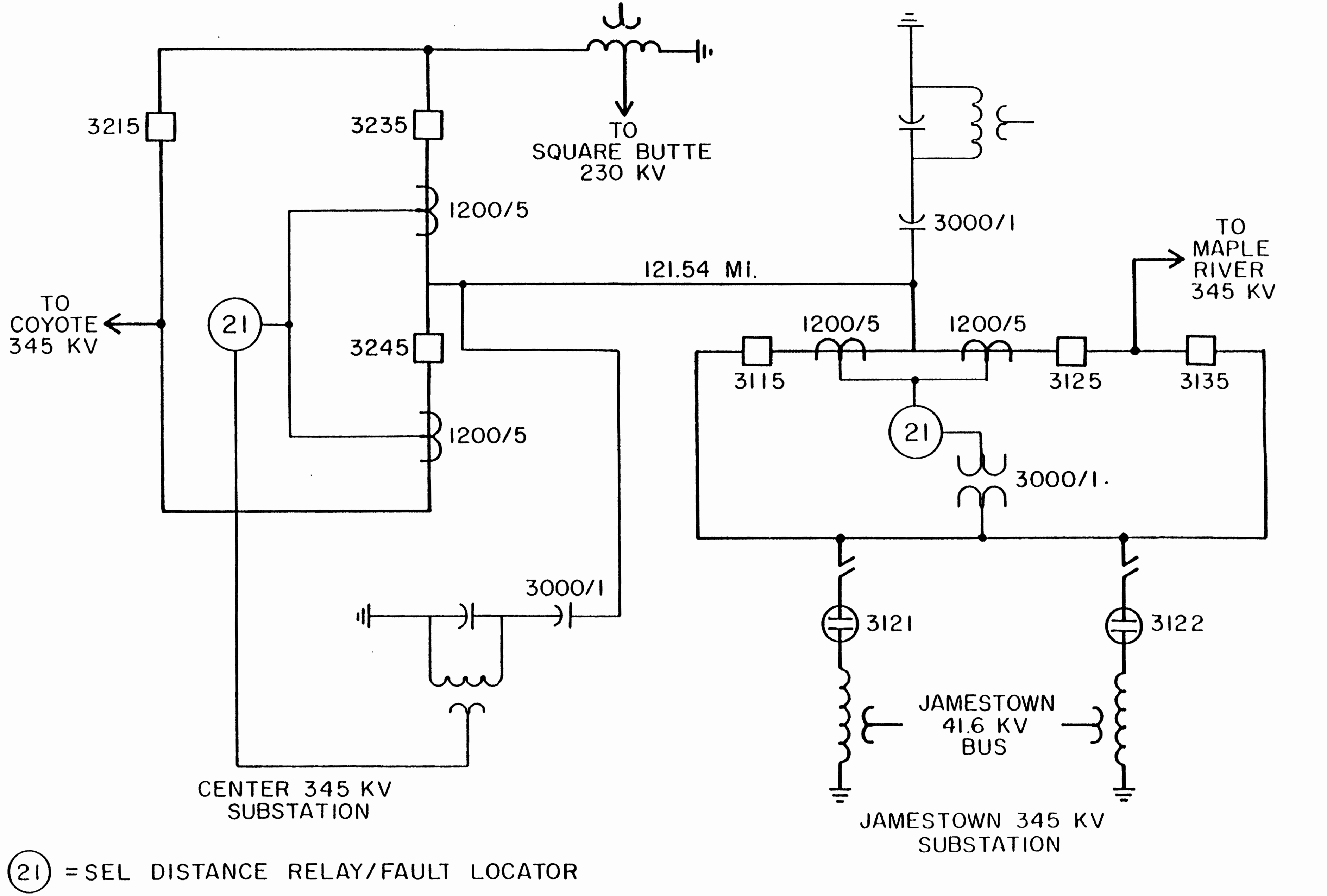
Six MHO relay algorithms are executed every one-fourth cycle. These encompass all possible fault types in the third zone. Line-to-line voltages and the current difference between associated phases are processed for each three types of phase faults. Line-to-ground voltages and residual-compensated line currents are used for the three types of ground faults. Zones 2 and 1 execute as required when any zone 3 element operates.

In each case, the MHO relay algorithm determines the difference between the selected voltage and the current times the relay impedance. This difference is compared in phase with the voltage. For impedances inside the circle, the angle between these quantities is acute. For impedances outside the circle, the angle is obtuse. If the impedance is on the circle, then the angle is 90 degrees. The phase comparison process is performed by computing the dot product of the difference voltage phasor and the voltage phasor. If the dot product is positive, then the impedance is inside the circle. If it is negative, then the impedance is outside the circle. If it is zero, then the impedance is on the relay boundary. This product principle of phase comparison is very similar to that implemented using an induction cylinder unit.

Four cycles of prefault data and seven cycles of fault and postfault data are stored in response to detection of an event. When the event is a fault, as indicated by operation of one or more MHO elements, the data are processed using the Takagi algorithm to determine the location of the fault. The algorithm is much less sensitive to fault resistance and load flow than a direct reactance computation, since it takes into account load flow conditions prior to the fault. No communications schemes are required for this fault locator algorithm. Reference 2 documents the development of the algorithm, and Reference 3 analyzes its performance under various system conditions.

The fault location is automatically computed after each fault occurs, and is included in the fault report, along with fault type and the time of its occurrence.

It is possible to use two-end algorithms for fault location, using the data available in the event reports from units located at both ends of the line. These schemes require additional data processing and communications, but do not need to depend on the zero-sequence parameters of the transmission line. The communications requirement is only to report the event-report voltage and current data from both line ends to the point of processing by the two-end algorithm. Details are given in Reference 3 and an example is included in the next section. Other important features of the fault locating relays include automatic self-testing, remote setting, and metering.



CENTER-JAMESTOWN 345 KV LINE
FIGURE 1

RELAY APPLICATION

The fault locating relays were applied on a 345 kV transmission line between the Center 345 kV substation located near the Milton R. Young generating station near Center, North Dakota, to the Jamestown 345 kV substation located 12 miles north of Jamestown, North Dakota. The line was originally constructed at 230 kV and was uprated to 345 kV when the Coyote Plant was brought on line in 1981. Since the line was energized at 345 kV the frequency of temporary single line-to-ground faults increased dramatically. Figure 1 shows a one-line diagram of the transmission line and pertinent substation apparatus at the two ends.

The parameters of the transmission line, developed from a transmission line impedance program is as follows in Table 1.

TABLE 1

CENTER-JAMESTOWN 345 KV LINE
IMPEDANCE DATA
LINE LENGTH = 121.54 MI.

	per unit	(100 MVA base)			primary	
Sequence	R(ohms)	X(ohms)	Yc(mhos)	R(ohms)	X(ohms)	Yc(mhos)
pos.	0.0043	0.0589	1.05033	5.12	70.11	$8.82X10^{-4}$
zero	0.0552	0.2139	0.64779	65.70	254.59	$5.44X10^{-4}$

The first relay was installed at Jamestown using existing relaying class 1200/5 current transformers (CT's) and 3000/1 capacitive coupled voltage transformers (CCVT's) to provide signals to the relay. This installation was completed in August 1984. In an effort to improve the accuracy of the fault locating algorithm and maintain voltage to the relay during interruption of the fault, the potential source for the relay was moved to a set of 345 kV metering potential (wound type) transformers (PT's) located on the bus side of the circuit breakers with a 3000/1 ratio. This change was made in October 1984.

As research continued, it was felt that a relay should be installed at the Center 345 kV substation to provide verification of the measurements from Jamestown. Signals were provided to the relay via existing 1200/5 relaying class CT's and 3000/1 CCVT's on the line side of the circuit breakers. This was done because no metering, bus side potential was available at the site. The relay was installed in April of 1985 and removed in July 1985 for use at another location.

Fault locations as well as event records such as those shown in Figures 2 and 3 are obtained from the relays via existing telephone communications systems through 300 Baud auto-answer modems located at the substation site. This ability to communicate with the relay provides swift timely information for both System Operations and Engineering personnel.

Engineers and System Dispatchers are able to request information from each relay via a local modem and interface to a Prime 750 computer. The relay is interrogated and provides the date, time, faulted phase(s) and distance to the fault for the five most recent faults.

Engineers can also use a portable personal computer with a built-in modem to communicate with each relay and obtain the printouts shown in Figures 2 and 3. The data can be translated into vector quantities of the three phase voltages and currents which can be used to evaluate the performance of the relay. Data are also provided about how the various functions of the relay responded to the particular fault. The data are output to a printer for evaluation and retention.

IMPEDANCE VERIFICATION

The fault locating algorithm used by the relay depends on accurate values of the positive and zero sequence impedances to determine locations of faults on the transmission line. With these impedance values, the relay computes the distance to the fault using voltages and currents supplied to the relay at the substation.

The positive and zero sequence impedances of the transmission line can be verified when a fault locating relay is installed at each end of the transmission line. The positive sequence impedance can be checked when the location of the fault is known. Once the positive sequence impedance has been verified it can be used to check the value of the zero sequence impedance of the line as used by each relay.

A permanent fault occurred on the line on May 10, 1985, when relays were in service at both ends of the line. The permanent fault was located 110.6 miles from the Center substation. The fault was the result of a tornado passing through the line causing two structures to be damaged. The data retrieved from the Center and Jamestown relays are shown in Figures 2 and 3 respectively.

With this data and the known location of the fault, checks can be made on the positive sequence impedance of the transmission line by calculating the distance to the fault and comparing the calculated distance with the actual distance to the fault.

Reference 3 describes a method to accomplish this comparison. The first requirement is to choose a reference bus and modify the phasor relationships of the remote bus to the reference bus. This is accomplised by using the prefault current from one phase at the reference bus and calculating the remote end current based on the following equation using the distributed parameters of the transmission line. With the Center 345 kV bus as the reference, the equation is:

$$I_{JC} = V_C Y_C - I_C \tag{1}$$

where

I_{JC} = the calculated value of load current at Jamestown based on Center end quantities.

791 CENTER-JAMESTOWN AT CENTER Date: 5/10/85 Time: 16:25:08

		Currents (amps)			Voltages (kV)			MHO	+Seq	-Seq	Outs	Ins
								ABCABC	iIv	ivV3	TCTA	5DBDTE
	*RES	A	B	C	A	B	C	GGGBCA		2	PLTL	2TTCTT
	-9	-420	441	-52	-137.8	198.3	-51.8	......	*.*	.*..	....	......
	9	-211	-257	497	-147.1	-41.4	193.2	......	*.*	.*..	....	......
Fig.	9	423	-437	49	137.7	-198.3	51.9	......	*.*	.*..	....	......
2a	-4	208	257	-501	147.1	41.2	-193.1	......	*.*	.*..	....	......
	-9	-420	441	-42	-137.5	198.3	52.1	......	*.*	.*..	....	......
	4	-201	-261	497	-147.2	-40.9	193.1	......	*.*	.*..	....	......
	14	416	-444	42	137.4	-198.3	52.2	......	*.*	.*..	....	......
	-9	208	264	-497	147.4	40.8	-193.1	......	*.*	.*..	....	......
	-24	-416	444	-42	-137.5	198.3	-52.4	......	*.*	.*..	....	......
	14	-211	-261	497	-147.4	-40.8	193.1	......	*.*	.*..	....	......
	24	416	-444	42	137.5	-198.3	52.5	......	*.*	.*..	....	......
	-19	215	268	-494	147.4	40.7	-193.0	......	*.*	.*..	....	......
	43	-444	589	-70	-136.2	191.7	-51.0	......	*.*	.*..	....	......
	330	-331	257	381	-145.7	-44.2	193.7	......	*.*	**..	....	......
	-77	473	-794	98	129.1	-165.1	44.6	......	*.*	**..	....	......
	-820	504	-1084	-211	145.6	41.9	-192.3	.2....	*.*	**.*	..*.	......
	0	-469	812	-98	-122.3	141.7	-39.1	.2....	*.*	**.*	..*.	......
	995	-568	1366	158	-147.3	-35.5	189.6	.2....	*.*	**.*	..*.	......
Fig.	29	466	-798	98	121.2	-137.8	38.6	.2....	*.*	**.*	..*.	......
2b	-1000	593	-1405	-148	147.1	34.6	-188.7	.1....	*.*	**.*	*.*.	......
	-82	-395	635	-84	-109.0	118.1	-38.8	.1....	*.*	**.*	*.*.	......
	757	-423	995	134	-105.8	-33.5	139.5	.2....	*.*	**.*	..*.	......
	116	173	-247	42	53.0	-59.0	28.6	.1....	*.*	**.*	*.*.	......
	-291	127	-307	-74	36.4	18.3	-46.1	.2....	*.*	**..	....	......
	-33	-17	28	-10	-4.8	10.2	-5.7	.2....	*.*	**..	....	......
	43	-7	42	7	-4.1	-2.5	4.1	.2....	*.*	**..	....	......
	-9	0	-3	0	1.2	-1.0	-1.9	.3....	..*	.*..	....	......
	-4	0	-7	0	1.1	0.5	-2.5	......	..*	....	....	......
	9	0	0	-3	-0.1	0.4	-1.2	......	...	....	....	......
	0	0	3	0	-0.1	0.1	-0.6	......	...	....	....	......
	0	0	-3	0	0.1	-0.1	-0.4	......	...	....	....	......
	0	0	0	0	0.1	0.1	-0.6	......	...	....	....	......
	0	3	0	0	-0.2	0.3	-0.3	......	...	....	....	......
	4	0	0	0	-0.5	0.0	-0.1	......	...	....	....	......
	0	0	0	-3	-0.1	-0.2	0.0	......	...	....	....	......
	0	0	-3	0	0.1	0.0	-0.1	......	...	....	....	......
	-4	0	0	0	-0.4	0.1	-0.2	......	...	....	....	......
	0	0	3	0	-0.5	-0.1	0.2	......	...	....	....	......
	0	0	-3	0	0.0	0.0	0.2	......	...	....	....	......
	0	0	0	0	0.0	0.0	0.0	......	...	....	....	......
	4	0	3	0	-0.3	-0.1	0.0	......	...	....	....	......
	-4	0	0	3	-0.3	0.0	0.4	......	...	....	....	......
	0	0	-3	0	0.0	0.0	0.3	......	...	....	....	......
	9	0	0	-7	0.2	-0.1	0.0	......	...	....	....	......

Event : 1BG Location : 123.75 mi 5.73 ohms sec
Duration: 3.00 Flt Current: 1181

R1 = 5.12	X1 = 70.11	R0 = 55.48	X0 = 215.00
CTR = 240	PTR = 3000	LL = 121.48	MTA = 80.0
Z1% = 90.0	Z2% = 150.0	Z2DG = 15.0	Z2DL= 20.0
Z3% = 200.0	Z3DG = 45.0	Z3DL = 60.0	46PH= 1000
TTI = 2	Z2E = Y	Z3E = Y	
32QE= Y	GSE = Y	BPFE = Y	

Figure 2

954 CENTER-JAMESTOWN AT JAMESTOWN Date: 5/10/85 Time: 16:25:16

		Currents (amps)			Voltages (kV)			MHO	+Seq	-Seq	Outs	Ins
								ABCABC	iIv	ivV3	TCTA	5DBDTE
	*RES	A	B	C	A	B	C	GGGBCA		2	PLTL	2TTCTT
	9	7	-416	416	15.1	169.3	-183.3	......	*.*	....	....	......
	33	444	-247	-180	-201.2	114.9	88.5	......	*.*	....	....	......
Fig. 3a	-14	-7	416	-416	-15.2	-169.4	183.3	......	*.*	....	....	......
	-29	-444	250	176	201.2	-115.0	-88.3	......	*.*	....	....	......
	14	7	-406	423	15.3	169.2	-183.4	......	*.*	....	....	......
	24	448	-254	-176	-201.1	115.3	88.0	......	*.*	....	....	......
	-14	-3	402	-427	-15.6	-168.9	183.6	......	*.*	....	....	......
	-29	-445	254	176	200.9	-115.4	-88.0	......	*.*	....	....	......
	19	0	-402	427	15.9	168.8	-183.4	......	*.*	....	....	......
	9	455	-247	-173	-201.1	115.4	87.8	......	*.*	....	....	......
	-14	0	402	-427	-16.0	-168.8	183.5	......	*.*	....	....	......
	-4	-452	250	169	201.1	-115.4	-87.8	......	*.*	....	....	......
	72	17	-328	441	15.3	165.9	-184.4	......	*.*	....	....	......
	534	522	233	-98	-200.4	72.7	87.9	......	*.*	**..	....	......
	500	45	579	-381	-14.5	-107.7	185.6	......	*.*	**..	....	......
	-1495	-667	-1108	-35	200.5	-24.4	-86.2	.1....	*.*	**.*	*.*.	......
	-1456	-155	-1062	286	14.4	36.6	-186.0	.1....	*.*	**.*	*.*.	......
	1932	741	1469	95	-200.8	18.4	83.6	.1....	*.*	****	*.*.	......
	1708	173	1204	-268	-15.3	-18.5	185.9	.1....	*.*	****	*.*.	......
Fig. 3b	-1966	-752	-1483	-102	200.5	-17.8	-82.6	.1....	*.*	****	*.*.	......
	-1752	-194	-1235	261	15.7	15.6	-184.3	.1....	*.*	****	*.*.	......
	1602	596	1207	49	187.8	53.1	75.9	.1....	*.*	****	*.*.	......
	1228	155	861	-187	-36.8	-44.0	180.5	.1....	*.*	****	*.*.	......
	-674	-247	-508	3	179.5	-117.1	-53.7	.1....	*.*	****	*.*.	......
	-349	-49	-240	70	63.7	95.7	-185.6	.2....	*.*	**.*	..*.	......
	82	35	67	0	-183.5	149.3	35.5	.3....	*.*	**.*	....	......
	43	7	24	-10	-70.5	-121.2	-194.8	......	*.*	**..	....	......
	-4	-7	-3	0	183.6	-154.2	-32.1	......	..*	.*..	....	......
	-9	0	0	0	71.8	125.0	-197.0	......	..*	....	....	......
	0	0	0	0	-183.6	155.5	30.9	......	..*	....	....	......
	0	0	0	0	-72.6	-125.4	197.8	......	..*	....	....	......
	0	0	0	0	184.0	-156.0	-30.5	......	..*	....	....	......
	0	0	0	0	73.0	125.3	-198.1	......	..*	....	....	......
	0	0	0	0	-184.4	156.5	30.3	......	..*	....	....	......
	-4	-3	-3	0	-73.2	-125.0	198.0	......	..*	....	....	......
	4	0	0	0	184.3	-156.8	-29.8	......	..*	....	....	......
	0	0	3	0	73.5	124.7	-198.0	......	..*	....	....	......
	-4	0	-3	-3	-184.2	157.1	29.6	......	..*	....	....	......
	9	0	0	0	-73.7	-124.8	198.2	......	..*	....	....	......
	4	0	0	0	184.1	-157.3	-29.6	......	..*	....	....	......
	-14	0	-3	0	73.9	124.9	-198.5	......	..*	....	....	......
	-4	-3	0	0	-184.0	157.4	29.4	......	..*	....	....	......
	9	3	3	0	-74.2	-124.9	198.7	......	..*	....	....	......
	4	3	3	0	184.1	-157.4	-29.3	......	..*	....	....	......

Event : 1BG Location : 11.76 mi 0.54 ohms sec
Duration: 2.75 Flt Current: 1728

R1 = 5.12	X1 = 70.11	R0 = 55.48	X0 = 215.00
CTR = 240	PTR = 3000	LL = 121.48	MTA = 80.0
Z1% = 90.0	Z2% = 150.0	Z2DG = 15.0	Z2DL= 20.0
Z3% = 200.0	Z3DG = 45.0	Z3DL = 60.0	46PH= 1000
TTI = 2	Z2E = Y	Z3E = Y	
32QE= Y	GSE = Y	BPFE = Y	

Figure 3

V_C = phase to neutral prefault voltage at Center.

Y_C = the positive sequence capacitive admittance of the transmission line.

I_C = the prefault load current measured at the Center end.

Using the data rows from Figure 2a and 3a, the angular difference between the calculated current for Jamestown and the actual current at Jamestown represents the time difference in angular degrees between the two buses. Using the phase B quantities from the last two rows of the first cycle, the calculated Jamestown current from Center using equation (1) is $488.2A \angle 100.5^{o}$. When compared to the Jamestown current, $485.3A \angle 59.0^{o}$, the Jamestown quantities lag the Center quantities by 41.5^{o}. To bring the Jamestown quantities in synchronism with Center, this angular difference must be added to all Jamestown quantities.

Once the data from both ends of the line have been referenced to the sending end quantities (ie., the Center substation), an accurate location of the known fault can be calculated and compared to the actual location. When the two locations agree, it can be assumed that the positive sequence impedance of the line is accurate.

Care must be taken in selecting the two rows of data to be used in the fault calculation. Values must be chosen such that the initial transients of the fault have decayed out (first two to three samples) and before the circuit breakers have begun to extinguish the fault current. This is particularly important for the Center end quantities where potential for the relay is taken from line side CCVT's. Values should also be chosen such that the fault currents are at a maximum and the fault voltage is at a minimum. Using these criterion on the phase B to ground fault on May 10, 1985, rows of data were chosen as indicated by Figure 2b for Center and Figure 3b for Jamestown.

With the data chosen, the distance to the fault from one end of the line can be verified using the positive sequence impedance of the transmission line using the two-end fault-locating equations given in Reference 3. Figure 5 shows the equivalent circuit for a phase-to-ground fault on the line using symmetrical components. In the positive sequence network, equations can be written for V_F in terms of the positive sequence quantities.

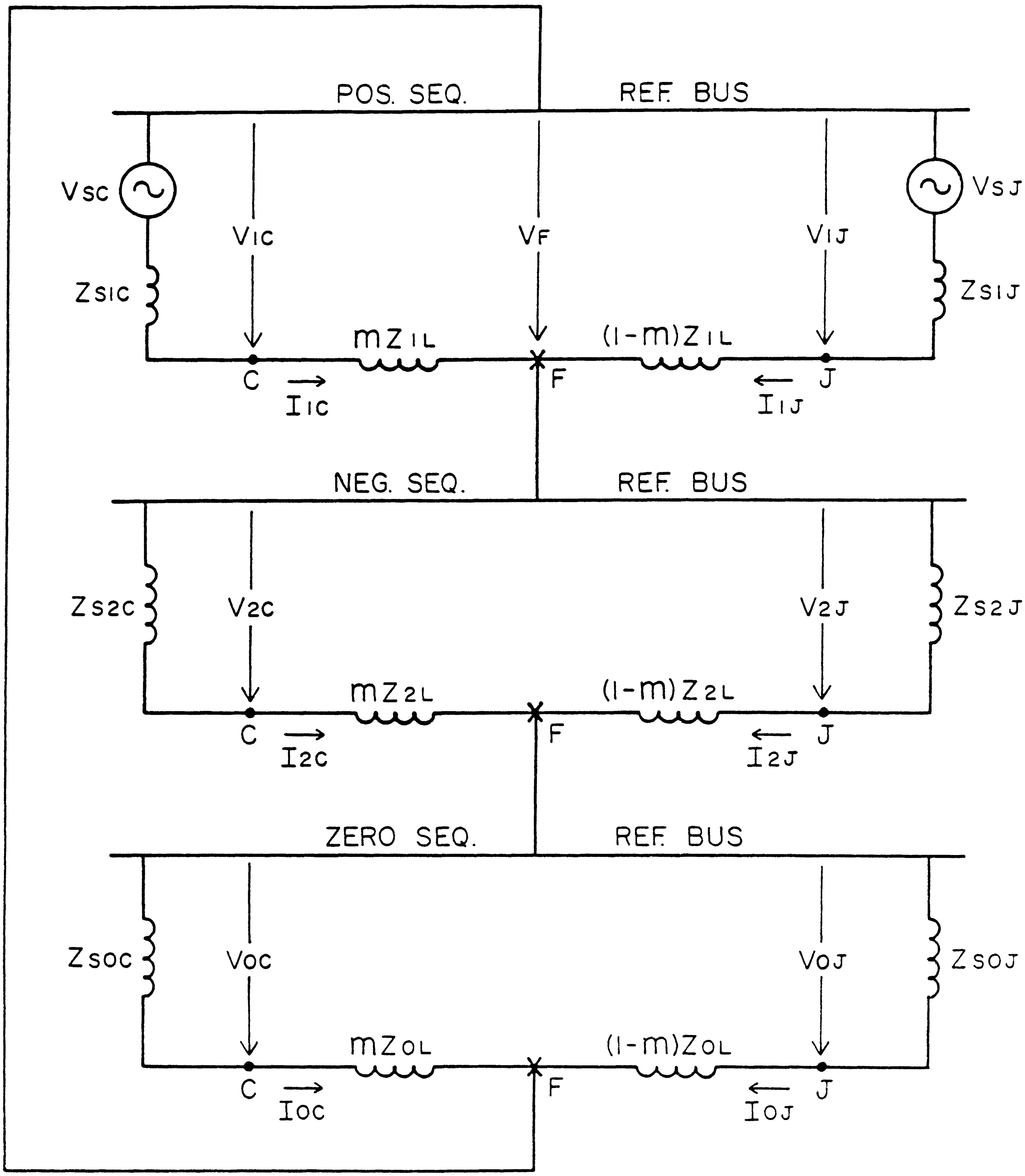
$$V_F = V_{1C} - I_{1C}(mz_{1L}) \tag{2}$$

$$V_F = V_{1J} - I_{1J}[(1-m)Z_{1L}] \tag{3}$$

where

V_F = the positive sequence voltage at the fault.

$V_{1C,J}$ = the positive sequence voltages at Center and Jamestown respectively to the fault.



SEQUENCE NETWORKS FOR PHASE-GROUND FAULT
CENTER-JAMESTOWN 345 KV LINE

FIGURE 5

$I_{1C,J}$ = the positive sequence current at Center and Jamestown respectively to the fault.

m = the per unit distance from Center to the fault. (ie., fault at Center m=0, fault at Jamestown m=1).

Z_{1L} = the positive sequence impedance of the transmission line.

These two equations can be set equal to each other and solved for the distance m the equation becomes.

$$V_{1C} - I_{1C}(MZ_{1L}) = V_{1J} - I_{1J}[(1-M)Z_{1L}] \tag{4}$$

$$m = \frac{V_{IC} - V_{IJ} + I_{1J} Z_{1L}}{Z_{1L} (I_{1C} + I_{1J})} \tag{5}$$

Positive sequence quantities from each end of the line and entered into equation (5). The resultant value of m, which is a complex number, for the May 10 fault is $0.9112\angle{-7.3^o}$. Using this magnitude of m gives a distance to the fault from Center of 110.7 mi. This value compares very favorably with the actual value of 110.6 miles. This calculation shows that confidence can be placed in the positive sequence impedance of the transmission line.

With the value of the positive sequence impedance known, the zero sequence impedance of the line as used by each relay to locate the fault can be calculated using the data from only one end of the line. The results of these calculations yield impedances which can be directly entered into the relay settings.

When measuring the distance to the fault from one end of the transmission line, all sequence components must be taken into account. If the positive sequence impedance of the transmission line is equal to the negative sequence impedance (ie., $Z_{1L}=Z_{2L}$) and the resistance of the fault is near zero ($R_F \cong 0$) then an impedance to the fault can be calculated using the voltage and current measurements from one end of the line.

An apparent impedance to the fault can be calculated from the faulted phase voltage and a compensated phase current which allows for the impedance of the zero sequence network to the fault. This equation, similar to those used in current compensated ground distance relays described in Reference 4, compensates the phase current with a portion of the zero sequence current as follows:

$$mZ_{1L} = \frac{V_F}{I_F + KI_0} \tag{6}$$

where

m = the per unit distance from the relay to the fault.

Z_{1L} = positive sequence impedance of the transmission line.

V_F = the faulted phase to neutral voltage at the relay.

I_F = the faulted phase current at the relay.

I_0 = the zero sequence current at the relay.

The compensation factor K is defined by the following equation:

$$K = \frac{Z_{0L} - Z_{1L}}{Z_{1L}} \tag{7}$$

When the fault location and positive sequence impedance of the transmission line is known, equation (6) and (7) can be combined and solved for m Z_{0L} as follows:

$$m\ Z_{0L} = \frac{V_F - m\ Z_{1L}(I_F - I_0)}{I_0} \tag{8}$$

Utilizing currents and voltages from Center and a value of m=0.91, the apparent zero sequence impedance of the transmission line as seen by the Center relay becomes:

Z_{0L} from Center = 71.7 + j206.3 ohms primary

The same procedure is performed with the Jamestown quantities using a value form of m=0.09. This yields an apparent zero sequence impedance of:

Z_{0L} from Jamestown = 52.2 + j205.6 ohms primary

These two line impedances will not necessarily be equal. The differences between these two numbers can be attributed to items such as changes in soil resistivity along the line as well as errors associated with sampling devices supplying quantities to the relays. The latter is especially true in this case where different types of potential devices at Center (CCVT's) and Jamestown (PT's) are used.

These new values for Z_{0L} are substantially lower than the design value of 65.70 + j254.59 given in Table 1. This fact seems to indicate that the actual zero sequence impedance of the transmission line is less than anticipated. Since these new values are lower, other relay systems utilizing the design value of Z_{0L} will be adversely affected. These new values can be used by the fault locating relay at each end to more accurately determine the location of the transient faults where very little physical evidence of the fault remains to determine the exact location.

Using these new values of zero sequence impedances, new compensation factors can be calculated using equation (7) and applied to other faults previously recorded using equation (6). Table 2 shows fault locations calculated by the relay located at each substation using previously estimated values of Z_{0L}.

TABLE 2

FAULT LOCATIONS CALCULATED BY RELAY
CENTER-JAMESTOWN 345 KV LINE

Date	Fault Type	Center	Jamestown	Total	% of Line Length
4/8/85	B-G	27.36 mi*	81.28 mi*	108.64 mi	89.4 %
4/19/85	C-G	14.51 mi	112.77 mi	127.28 mi	104.7 %
4/19/85	C-G	26.19 mi	99.17 mi	125.36 mi	103.1 %
5/10/85	B-G	123.75 mi	11.76 mi	135.51 mi	111.5 %
5/30/85	C-G	50.48 mi	78.74 mi	129.22 mi	106.3 %
6/25/85	C-G	122.63 mi	4.27 mi	126.90 mi	104.4 %

*NOTE: These mileages used Z_{0L}= 65.70 + j254.59 ohms primary. Others used Z_{0L}= 55.48 + j215.0 ohms primary.

The fault locations shown in Table 3 below were developed using the re-calculated values of Z_{0L} for each respective relay.

TABLE 3

FAULT LOCATIONS CALCULATED WITH COMPENSATED Z_{0L}
CENTER-JAMESTOWN 345 KV LINE

Date	Fault Type	Center	Jamestown	Total	% of Line Length
4/8/85	B-G	30.42 mi	93.91 mi	124.33 mi	102.3 %
4/19/85	C-G	13.39 mi	112.83 mi	126.22 mi	103.9 %
4/19/85	C-G	25.28 mi	98.11 mi	123.39 mi	101.5 %
5/10/85	B-G	110.69 mi	10.97 mi	121.66 mi	100.1 %
5/30/85	C-G	48.35 mi	77.93 mi	126.28 mi	103.9 %
6/25/85	C-G	115.99 mi	3.68 mi	119.67 mi	98.5 %

As can be seen from the above results, the new measurements from Table 3 are more accurate in terms of the total line length than those measured by the relay without the modified zero sequence impedance. This is particularly true when comparing the results for the fault on April 8, 1985, where the total line length went from 108.64 miles to 124.33 miles.

The corrected value of Z_0 should be used in adjusting the settings of the distance relays at Center and Jamestown, since the value from the line constants program could result in significant overreaching, as explained below.

A residual-current compensated ground-distance relay measures the positive-sequence impedance to the fault, by comparing the faulted phase-to-neutral voltage with a resultant current, which is the faulted-phase current plus a constant times the residual current. In equation form, for an A-G fault, this is:

$$Z_1 = \frac{V_A}{I_A + K * I_R} = \text{the positive sequence impedance to the fault}$$

where $K = 1/3\ (Z_0/Z_1 - 1)$.

Since K depends on Z_0, an error in Z_0 causes an error in the resultant current.

If we assume that the current distribution factors for the positive, negative and zero-sequence networks are the same, then IA = IR, and we can rewrite the above equation as:

$$Z_1 = \frac{V_A}{(1 + K) * I_A}$$

For the same fault, but different values of K, the ratio of reaches is:

$$\frac{1 + K}{1 + K'}$$

Using the calculated and measured values of Z_0 given earlier, this ratio is 1.14, meaning that ground distance relays set with the calculated value of Z_0 would reach 14 percent farther than their setting. For example, for a zone 1 setting of 85%, the overreach is 12%, for a total reach of 97%, leaving little margin for other possible sources of error.

Although this example considers distance relay settings, similar conditions hold for the effects of the Z_0 error on the setting of residual overcurrent relays, especially the instantaneous elements.

CONCLUSIONS

The experience with this type of fault locating relay on this application has been working out quite well. Operators appreciate the immediate availability of the fault location provided by the communications capabilities of the fault-locating relays.

By having relays at both ends of the transmission line, we performed calculations to determine transmission line parameters. From data recorded, we found that the zero sequence impedance of the line is noticeably less than that given by the design constants. Modifying the zero sequence impedances for each respective relay and applying them to past faults provides better accuracy for the single end locations given by each relay. The error we discovered could have caused ground distance relays to overreach by up to 14%.

In light of the apparent reduction of the zero sequence impedance, it would appear prudent to re-evaluate relay settings associated with other relays utilizing that impedance in the measuring process.

Although these relays were applied as fault locators their performance as distance relays has been sound. We have applied the fault locating relays as primary protection at 115kV.

REFERENCES

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2. T. Takagi, Y. Yamakoshi, M. Yamaura, R. Kondow, T. Matsushima, "Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 8, August, 1982.

3. E. O. Schweitzer III, "Evaluation and Development of Transmission Line Fault-Locating Techniques Which Use Sinusoidal Steady State Information", Ninth Annual Western Protective Relay Conference, October 26-28, 1982.

4. E. O. Schweitzer III, "Unified Protection, Monitoring and Control of Overhead Transmission Lines Achieves Performance and Economy", Minnesota Power Systems Conference, October 9-11, 1984.

5. J. V. Kresser and J. L. Blackburn, "Ch. 10 - Line and Circuit Protection", pg. 10-55,56, Applied Protective Relaying, Westinghouse Electric Corporation.

6. W. D. Stevenson, Jr., "Ch. 11 - Symmetrical Components", "Elements of Power System Analysis", Copyright 1975, McGraw Hill.

7. E. Clarke, "Circuit Analysis of A-C Power Systems", Copyright 1943 by General Electric Company, Seventh Printing, March 1961.

APPENDIX D: PROGRAM VERSIONS

This manual covers SEL-Profile Program versions listed below (most recent versions listed at top):

Firmware Part/Revision No.	Description of Firmware
Version 1.06 Oct. 1995	This firmware differs from previous versions as follows: - Added site license identification to the introduction screen.
Version 1.05 Aug. 1994	This firmware differs from previous versions as follows: - Added SEL-151/251, -C, -D, -CD, SEL-167D, SEL-121D, SEL-321, and Mehta-Tech event record compatibility.
Version 1.03 Nov. 1989	This firmware differs from previous versions as follows: - Added SEL-121B and SEL-121S event record compatibility.
Version 1.02	Original Release.

The revision number of your program displays on the screen when the program is started.

SEL-PROFILE TRANSMISSION LINE FAULT ANALYSIS PROGRAM COMMAND SUMMARY

TERSE MODE

D		Display previously accessed disk directory.
DD	directory	Display the named disk drive/directory.
DN		Display default directory N. N equals 1 - 4.
L	file	List contents of disk file to screen.
LL	directory/file	List the named file which resides in the named drive/directory.
LN	file	List the named file which resides in the default directory N. N equals 1 - 4.
R	file	Read named event report file into Data Set 1 or Data Set 2.
RR	directory/file	Read in the named event report file which resides in the named drive/directory.
RN	file	Read in the named event report file which resides in default directory N. N equals 1 - 4.
P		Print data set summary to screen.
PP		Print data set summary and contents to screen.
E	<Enter>	data set fault data manually.
ER		Erase both data sets, returning them to their startup states.
C	<Configure>	Modify/View/File line/terminal configuration settings: - line constant settings (X0,R0,X1,R1,X0S,R0S,LL,B0,B1,X0M,R0M) - line terminal settings (X0L,R0L,X1L,R1L,B0S,G0S,B1S,G1S) - analog channel permutation indices (IAP,IBP,ICP,VAP,VBP,VCP) - analog channel rescale factors (IAF,IBF,ICF,VAF,VBF,VCF) - analog channel deskew times (IASKW,IBSKW,ICSKW,VASKW,VBSKW,VCSKW)
S	<Schweitzer>	two-ended fault analysis method - view profile in phase quantities
X	<Reactance>	simple reactance fault analysis method - weighted - view profile in phase quantities
XX	<Reactance>	simple reactance fault analysis method - unweighted - fault location per data set row for six fault types
T	<Takagi>	single-end fault analysis method - weighted - view profile in phase quantities
TT	<Takagi>	single-end fault analysis method - unweighted - fault location per data set row for six fault types
M	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - compensates for mutual coupling from parallel line
MM	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - fault location per data set row for six fault types

VERBOSE MODE

(Toggle between VERBOSE and TERSE by typing V <CR>)
- all TERSE MODE commands are available in VERBOSE MODE

S	<Schweitzer>	two-ended fault analysis method - select fault type; select data rows; select alignment angle - view profile in phase or sequence quantities
X	<Reactance>	simple reactance fault analysis method - weighted - select fault type; select data rows - view profile in phase or sequence quantities
T	<Takagi>	single-end fault analysis method - weighted - select fault type; select data rows - view profile in phase or sequence quantities
M	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - compensates for mutual coupling from parallel line - select fault type; select data rows - view profile in phase or sequence quantities

MISCELLANEOUS COMMANDS

V	<Verbose>	toggles the menu screens between VERBOSE and TERSE modes.
U	<Start-up>	configures the default disk directories.
F1	<Help>	selects the help description for the current screen.
ESC	<Escape>	returns the cursor to the main menu or exits the SEL-PROFILE program when the main menu is displayed.

SEL-PROFILE TRANSMISSION LINE FAULT ANALYSIS PROGRAM COMMAND SUMMARY

TERSE MODE

D		Display previously accessed disk directory.
DD	directory	Display the named disk drive/directory.
DN		Display default directory N. N equals 1 - 4.
L	file	List contents of disk file to screen.
LL	directory/file	List the named file which resides in the named drive/directory.
LN	file	List the named file which resides in the default directory N. N equals 1 - 4.
R	file	Read named event report file into Data Set 1 or Data Set 2.
RR	directory/file	Read in the named event report file which resides in the named drive/directory.
RN	file	Read in the named event report file which resides in default directory N. N equals 1 - 4.
P		Print data set summary to screen.
PP		Print data set summary and contents to screen.
E	<Enter>	data set fault data manually.
ER		Erase both data sets, returning them to their startup states.
C	<Configure>	Modify/View/File line/terminal configuration settings: - line constant settings (X0,R0,X1,R1,X0S,R0S,LL,B0,B1,X0M,R0M) - line terminal settings (X0L,R0L,X1L,R1L,B0S,G0S,B1S,G1S) - analog channel permutation indices (IAP,IBP,ICP,VAP,VBP,VCP) - analog channel rescale factors (IAF,IBF,ICF,VAF,VBF,VCF) - analog channel deskew times (IASKW,IBSKW,ICSKW,VASKW,VBSKW,VCSKW)
S	<Schweitzer>	two-ended fault analysis method - view profile in phase quantities
X	<Reactance>	simple reactance fault analysis method - weighted - view profile in phase quantities
XX	<Reactance>	simple reactance fault analysis method - unweighted - fault location per data set row for six fault types
T	<Takagi>	single-end fault analysis method - weighted - view profile in phase quantities
TT	<Takagi>	single-end fault analysis method - unweighted - fault location per data set row for six fault types
M	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - compensates for mutual coupling from parallel line
MM	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - fault location per data set row for six fault types

VERBOSE MODE

(Toggle between VERBOSE and TERSE by typing V <CR>)
- all TERSE MODE commands are available in VERBOSE MODE

S	<Schweitzer>	two-ended fault analysis method - select fault type; select data rows; select alignment angle - view profile in phase or sequence quantities
X	<Reactance>	simple reactance fault analysis method - weighted - select fault type; select data rows - view profile in phase or sequence quantities
T	<Takagi>	single-end fault analysis method - weighted - select fault type; select data rows - view profile in phase or sequence quantities
M	<Mutual>	Takagi <T> or Reactance <X> fault analysis methods - compensates for mutual coupling from parallel line - select fault type; select data rows - view profile in phase or sequence quantities

MISCELLANEOUS COMMANDS

V	<Verbose>	toggles the menu screens between VERBOSE and TERSE modes.
U	<Start-up>	configures the default disk directories.
F1	<Help>	selects the help description for the current screen.
ESC	<Escape>	returns the cursor to the main menu or exits the SEL-PROFILE program when the main menu is displayed.