EMTP Reference Models for Transmission Line Relay Testing

1. Introduction

It is well known that in order to ensure a protective relay will perform as expected; it must be tested under realistic power system conditions. This generally means that the relay must be tested with transient data generated from an electromagnetic transient simulation program. There are many such programs available – ATP (Alternative Transients Program), EMTP (Electromagnetic Transients Program) and PSCAD™ (EMTDC). In each of these programs, the power system that generates the transient data can be modeled in detail. It is also possible to easily simulate various fault scenarios and system configurations.

The purpose of this write-up is to provide a concept for a standard transmission line test model, its parameters, the operations that must be considered, and typical cases that are studied on the model so that a realistic testing of a protective relay can be carried out. This write-up is not intended to be a complete guide, but rather serve as a keystone from which to start building.

2. Basic System Model

The basic model of Fig. 1 is suitable for testing most transmission line protection applications. The model is made up of various components – lines, transformers, sources, etc. There are three sources in the network – S1, S2 and S3. The source angle can be varied to simulate power flows. The transmission lines consist of one pair of mutually coupled lines (between buses 1 and 2), out of which one is a three terminal line. Intermediate nodes are provided in the line models to enable application of faults at various locations. Breakers and switches are also included to simulate different configurations. This model can be expanded to include series capacitors, shunt reactors and capacitors etc.

The physical parameters of the components that make up the network are provided in Appendix A of this document. It is possible for the user to generate their own simulation files in the simulation program of their choice with the provided parameters. Alternatively, the user may use the ATP/EMTP files provided in Appendix B to simulate different configurations in the ATP/EMTP environment.
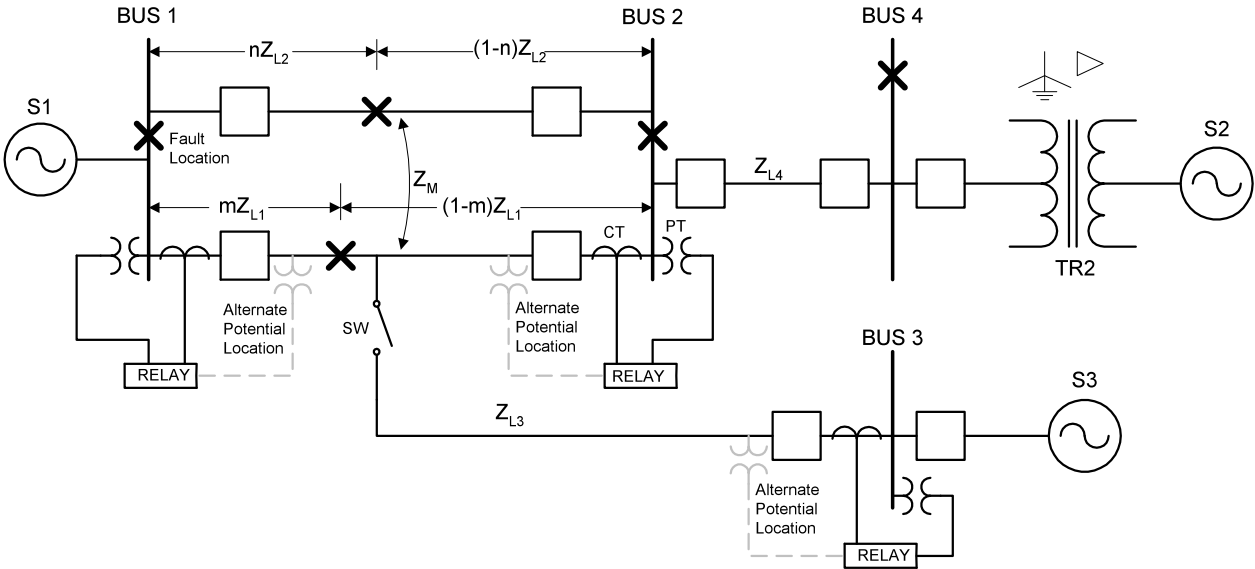
Fig. 1: Basic System Model for Testing Transmission Line Protection.

2.1 How to Use the EMTP Model and Test Results

A standard transmission line EMTP test model is provided that allows the user to define various system and fault parameters, and fault location. Depending on the functionality of the transients program employed, a number of options beyond the scope of the system model may be used. These generally include some level of breaker and fault control. The application of these functions will depend on what the user is trying to accomplish. One must keep in mind that a study of the type envisaged here, is not the same as a real-time digital simulation as there is no closed-loop control. That is, after the fault is applied the breaker simulation does not respond to the operation of the relays being tested and automatically reconfigure the power system (open the breaker). An EMTP study is a prerecorded event. Any simulated breaker operation or system reconfiguration is pre-programmed in the case setup. This limitation must be recognized and the impact on the relay performance understood.

In the event that an accurate relay model is available in the EMTP being used, then closed loop testing with the relay module might be considered.

An EMTP case generates one or more COMTRADE files of bus voltage and line current signals for playback to the protective relays being tested through any of a number of relay test devices. For example, consider a phase A-to-ground fault on line L1 at mZ_{L1} where m is equal to 0.25 and switch SW is open. At Bus #1 the bus voltages and line L1 currents flowing out of Bus #1 are recorded. Also recorded at Bus #2 are the bus voltages and line L1 currents flowing out of Bus #2. This provides the data to test both line terminal relays as a system for this case within the limitations of an EMTP study mentioned above.

2.2   EMTP Case

The EMTP case may be as simple as applying an internal fault on the protected line of the system represented by Fig. 1 to see if the relays at each terminal trip. Generally the case is made up of a prefault period sufficient to reset all relay logic (i.e. loss-of-potential) and a fault period sufficient to assure relay operation. For a two terminal line, COMTRADE files are developed with PT and CT secondary quantities at the two line terminals.

2.3   COMTRADE Files

The COMTRADE files are digital fault records generated in a standard format that can be read by most test sets. They consist of sampled voltage and current data, and in some cases digital status data. The file consists of a defined pre-fault period and fault period defined by EMTP program parameters. Some relays can generate comtrade files.

2.4   Test Sets

The test set or fault playback device usually consist of three voltage and three current amplifiers, appropriately connected to the relay to represent the relay connection to the power system. It also consists of control, memory and communications to allow computer control. The test sets convert the digital sampled data to real secondary quantities that the relay would see. The COMTRADE files are loaded to the test set with a procedure specific to the test set. The case is played into the relay in real time and the relay is monitored for operation.

2.5   Test Results

EMTP cases can be developed for a number of internal and external fault conditions to verify relay performance for the model system developed within the study limitations. The cases from each terminal may be played into a relay separately or into two [or three] relays simultaneously from two [or three] test sets operating synchronously. The test results will confirm:

- Correct relay operation . . . trips, no trips, direction, timing, fault location, targeting, outputs, etc.
- Correct pilot system operation . . . pilot tripping, coordination of relay terminals, permissive, blocks, etc.
- Correct installation and wiring
- Correct system functioning
- Correct settings

EMTP cases may be:

- Applied in the test lab or in the field running end-to-end satellite testing,

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- Exchanged with the manufacturer or other users to facilitate the resolution of testing or application issues,
- Saved in a database to be used for product acceptance testing

EMTP is a powerful tool and can be used to test the relay for most applications. Its limitations, however, in representing the interaction between the physical relay and the power system simulator must be understood.

3.   Transmission Line Models

Transmission lines play a critical role in the generation of transients and the following discussion will cover a number of different transmission line models for use in different relaying studies.

The resistance, inductance and capacitance of overhead transmission lines are evenly distributed along the line length. Therefore, in general, they cannot be treated as lumped elements. In addition, some of the line parameters are also functions of frequency. For steady-state studies, such as load flow and short-circuit studies, the only parameters needed are the positive and zero sequence parameters calculated from tables and simple handbook formulas at the power frequency. For electromagnetic transient studies the parameters calculated from simple formulas are not adequate, and the line parameters must be computed using auxiliary subroutines available in different electromagnetic transients programs. Most electromagnetic transient programs contain two major categories of transmission line models:

1. Constant parameter models;
2. Frequency-dependent parameter models.

In the constant parameter model category, electromagnetic transients programs provide a variety of options such as:

- Positive and zero sequence lumped parameter representation.
- Pi-section representation.
- Distributed parameter (Bergeron model) transposed and untransposed line representation.

In the frequency-dependent model category, electromagnetic transients programs may provide:

- A frequency dependent line model for transposed and untransposed lines using a constant modal transformation matrix.
- A frequency-dependent line model for transposed and untransposed lines using a frequency-dependent modal transformation matrix.
- Phase domain frequency-dependent line model for transposed and untransposed lines (no modal transformation)

Since different electromagnetic transients programs have different line models available, it is not feasible to cover all available models in this report. Most of the discussion however, concerning

line modeling and which models are better suited for which application studies, holds true for all transient simulation programs.

3.1   Line Models for Steady State Studies

There are a large number of steady state applications where transmission lines need to be modeled correctly and for only one particular frequency. EMTP has a number of models that could be used for this purpose and one must know where each model is applicable.

3.1.1   Exact-pi Circuit Model

The exact-pi equivalent circuit of a single-phase transmission line is shown in Fig. 2.
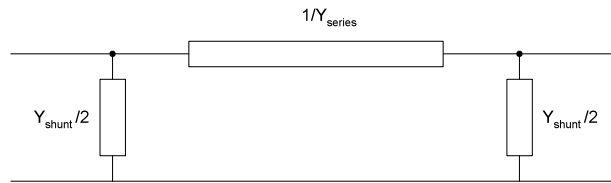
Fig. 2: Exact-pi Equivalent Circuit.

The series impedance and shunt admittance of the exact-pi equivalent circuit of a single-phase line are given below in Equations (1) and (2):

$$\frac{1}{Y_{series}} = (R' + j\omega L') \cdot l \cdot \sinh(\gamma \cdot l)/(\gamma \cdot l) \tag{1}$$

$$Y_{shunt/2} = \frac{(j\omega \cdot C'/2) \cdot l \cdot \tanh(\gamma \cdot l/2)}{(\gamma \cdot l/2)} \tag{2}$$

where, R', L', C' are the resistance, inductance, and capacitance per unit length, l is the line length, and γ is the propagation constant which is equals to

$$\gamma = [(R' + j\omega \cdot L') \cdot j\omega \cdot C']^{1/2} \tag{3}$$

Equations (1)-(3) show that the exact-pi circuit model can represent the line accurately at one specific frequency.

This model is a lumped parameter model and it is good for only one frequency of interest and one particular line length. This model includes the hyperbolic corrections with no approximations involved and is the best model for steady-state solutions and for frequency scans. This model takes into account the skin effect and ground return corrections. It is a multiphase

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model in the phase domain with constant R, L, C, and G of the line and it is correct for any number of circuits in the same right-of-way. This model is not adequate for transient studies.

3.1.2   Nominal-pi Circuit Model

This model is derived from the exact-pi model described by equation 1 if the frequency or line length is low. For overhead transmission lines this is typically the case if $l \leq 150$ Km at 60 Hz, or $l \leq 15$ Km at 600 Hz. This model takes into account the skin effect and ground return corrections. It is a multiphase model in phase domain with constant R, L, C, and G of the line and it is correct for any number of circuits in the same right-of-way. The line is automatically represented as untransposed, and the user could model particular transposition schemes in great detail by cascaded connection of nominal-pi circuit models.

This model has the same limitations as the exact-pi model in addition to being limited for short lines i.e., less than 150 kilometers at 60 Hz and less than 5 kilometers at 2 kHz. It cannot represent frequency dependence of line parameters in frequency scans, and it cannot be used for "electrically long" lines. This model is not good for transient studies. However, this it has been used for transient studies by connecting a number of cascaded nominal-pi models in series.

3.2   Line Models for Transient Studies

Distributed and frequency dependent parameter models are best for transient studies. They use traveling wave solutions, which are valid over a much wider frequency range than pi-circuit models.

3.2.1   Nominal-pi Model

This model is not a good choice for transient studies. However, it has been used for transient studies by connecting a number of cascaded pi-nominal models, similar to what was done in the past with transient network analyzers. When used as such, this model has a big disadvantage of producing reflections at the cascading points.

To adequately represent the line over various frequency ranges, a large number of nominal-pi cascaded sections should be used. As a rule of thumb, one should use one section to represent the line up to 100 Hz, eight sections to extend the range up to 700 Hz and 15-20 sections to extend the range up to 1-2 kHz or keep the section lengths between 5-10 kilometers (2 kilometers for frequency up to 5 kHz).

3.2.2   Constant-Parameter Distributed Line Model

This line model assumes that the line parameters R', L', and C' are constant. The L' and C' are distributed and the losses $R' \cdot l$ are lumped in three places, which is reasonable as long as

$R' \cdot l$ << Zsurge. The above conditions are met for positive sequence parameters to approximately 1-2 kHz, but not for zero sequence parameters. It is a good model only where the zero sequence currents are very small, or oscillate with a frequency close to the one at which the parameters were calculated. This frequency should not be very high to meet the condition $R' \cdot l$ << Zsurge, otherwise the line must be split into smaller sections. The transformation matrix to decouple the propagation modes is taken as real and constant and it is less valid as asymmetry gets stronger. The speed of execution of this model is much faster than the cascaded nominal-pi circuit models and there are no reflections within the line. Shunt losses are ignored in this model.

3.2.3   Frequency-Dependent Distributed Line Model

This model provides an accurate representation of the distributed nature of all line parameters, as well as their frequency dependence. Therefore, the line parameters for this model are not constant but functions of frequency, i.e., *R(ω), L(ω), C(ω)* and *G(ω)*. All parameters are distributed including R' and G'.

Most frequency-dependent models are based on the modal theory where multi-phase line equations are decoupled through modal transformation matrices, so that each mode can be studied separately as a single-phase line. The transformation matrices for untransposed or unbalanced lines are complex and frequency-dependent. It is possible however to obtain a good accuracy by using real and constant transformation matrices. Some programs may provide the option of using frequency-dependent transformation matrix. However, this option has a tendency to yield unstable solutions and should be used with diligence. The latest advancement in frequency dependent transmission line models is the frequency-dependent phase domain model. This model does not use the modal transformation matrix and hence does not have the inaccuracies associated with the frequency dependence of the transformation matrix. It provides better accuracy while dealing with asymmetrical lines.

In summary, use the pi-exact model for steady-state analysis. For transient analysis use the frequency dependent model for the lines of main interest, and the constant frequency distributed parameter (Bergeron) model for lines of secondary interest.

Pi-circuit model is not a good choice for transient studies. However, it has been used for transient studies by cascading a number of nominal-pi sections, similar to what was done in the past with transient network analyzers. When used in this way, this model has a big disadvantage of being computationally slow and requires additional network nodes.

4.   Generator Model

The following two source models are the most commonly used in the protective relaying studies:

Model 1:   Ideal sinusoidal sources behind sub-transient reactances or Thevenin impedances of the system

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Model 2:   Detailed synchronous machine model

The choice of a specific model in a study depends on system configuration and the objectives of study.

Model 1: Ideal sources with sub-transient reactances model is used for representing large generating stations. The assumption is that the system inertia is infinite and the disturbance under study does not cause system frequency to change. The time frame of interest is small (approximately 10 cycles) and the machine controls such as excitation system and governor have not responded to the disturbance. The model is commonly used in transmission line primary relaying studies.

In a large integrated system, the system can be divided into few subsystems. Each subsystem then can be reduced to an ideal three-phase source and equivalent positive and zero sequence Thevenin impedances. These impedances can be calculated using a steady-state 60 Hz fault program by isolating the subsystem from the rest of the system at the common bus between them and then applying a fault at that bus. It is common practice to select the common buses, which are at least one line away from the line terminals where the relaying performance is being evaluated. Again the assumptions in using this representation are the same as those in case of ideal sources with sub-transient reactances. However the main advantage of this model is that the computation requirements are significantly reduced because all components within a subsystem are reduced to a simple representation using an ideal source and equivalent Thevenin impedances. The main disadvantage is that the Thevenin impedance represents the system equivalence at 60 Hz only. The transient response of the system using the reduced model is not as accurate as when the complete system is represented with all lines and sources.

Model 2: The detailed model is mostly used for representing small generating stations in non-integrated systems for applications where the system disturbance is likely to cause change in frequency and the relays are slow in responding to that disturbance. The model requires complete machine data including inertia, sub-transient, transient and steady-state reactances. Models of turbine and excitation system can also be included depending upon the time frame of study and their response time. The detail model represents complete machine behavior from sub-transient to steady-state time frames. Generally, the excitation and governing system are ignored for line relaying studies. The main disadvantage is the model is complex, it requires complete machine data, is computationally inefficient and my not provide any additional accuracy in the simulation. It is therefore not recommended for use in large integrated system.

In the test basic system shown in Fig. 1, Sources S1 and S3 are represented by ideal sources with Thevenin impedances behind them. Detailed model representation is used for Source S2. Model parameters of all three sources are given in Appendix A.

5.   Transformer Model

The transformer is one of the most familiar and well-known pieces of power system electrical apparatus. Despite its simple design, transformer modeling over a wide frequency range still

presents substantial difficulties. The transformer inductances are frequency and saturation dependent. The distributed capacitances between turns, between winding segments, and between windings and ground, produce resonances that can affect the terminal and internal transformer voltages.

Models of varying complexity can be implemented in emtp for power transformers using supporting routines or built-in models. However, none of the existing models can portray the physical layout of the transformer, or the high frequency characteristics introduced by inter winding capacitance effects. Although there is no single model, or supporting routine, that can be used to represent any power transformer at every frequency range, several emtp capabilities can be used to model any transformer type at a particular frequency range. Fundamentally power transformers can be represented in three different ways in the emtp. They are:

- The built-in ideal transformer model.
- The built-in saturable transformer model.
- Models based on mutually coupled coils, using supporting routines.

Ideal transformers ignore all leakage by assuming that all the flux is confined in the magnetic core. In addition they neglect magnetization currents by assuming no reluctance in the magnetic material. The saturable transformer model eliminates these two restrictions, by considering that around each individual coil a separate magnetic leakage path exists, and that a finite magnetic reluctance path exists as well. The models based on matrices of mutually coupled coils can represent quite complex coil arrangements but are somewhat more difficult to use.

The above basic transformer models do not represent saturation, eddy current, and high frequency effects with the exception of the saturable transformer model which has saturation built-in directly into the model. Saturation, eddy currents, and high frequency phenomena can be represented separately by increasing the complexity of the above basic models. The above models are used in studies where the user is interested at relatively low frequencies up to 2 kHz. At frequencies above 2 kHz the capacitances and capacitive coupling between windings become very important. In fact, at very high frequencies the transformer behavior is dominated by its capacitances. Complex and detailed model is needed if one is interested in the internal transient winding voltage distribution.

Usually transformer models are derived considering the behavior of the transformer from its terminals. However, in relaying studies, one might be interested in internal power transformer faults. Such a method, for the simulation of internal transformer faults, using emtp capabilities was presented in [1]. Sometimes, if explicit representation of transformers is not required, the user needs to model the effect of the transformer presence in the power system without the need of any details about the transformer itself. Thevenin equivalent representations in the sequence domain are well known and can be used in these situations.

5.1   Ideal Transformer Model

The equations that describe a single-core two winding ideal transformer are:

$$\frac{v2}{v1} = \frac{N2}{N1} = n \tag{4}$$

$$\frac{i2}{i1} = \frac{1}{n} \tag{5}$$

where $N1, N2$ are the turns of windings 1 and 2 respectively.

The assumption in modeling ideal transformers is that all the flux is confined in the magnetic core and that there is no reluctance in the magnetic material. The ideal transformer can be modeled in ATP by using the type 18 source, and by setting a voltage source to zero. This component has a very simple input format. One of its main advantages is that it can be used together with other emtp linear and nonlinear components to represent more complex power transformers not available in ATP.

5.2   Saturable Transformer Model

The saturable transformer model uses a star-circuit representation for single-phase transformers with up to three windings. Its extension to three-phase units is not as accurate. This model requires as a minimum the following information:

* The voltage rating of each winding.

* The leakage impedance of each winding, and

* The transformer connectivity information.

The leakage impedances are fixed inductances and resistances and are separated into individual elements for each winding. The representation of the magnetizing branch is optional and is discussed later. Impedance values in p.u. from short circuit or load flow data files, must be converted to actual units using the following equation:

$$Z_{\text{base}} = \frac{V^2}{S_{1\phi}} \tag{6}$$

V = voltage rating of the winding
$S_{1\phi}$ = single-phase power rating

The saturable transformer model is based on a classical textbook equivalent circuit of a single-phase transformer as shown in Fig. 3.
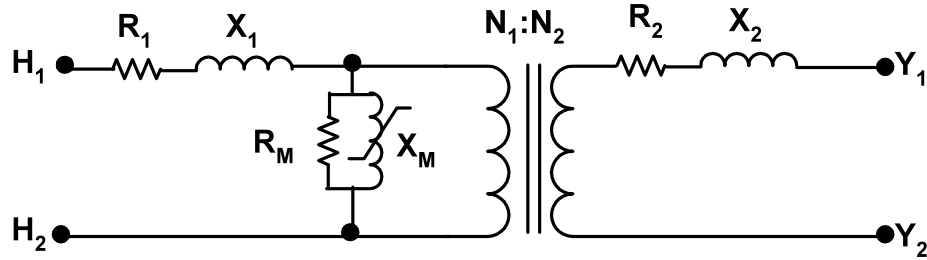
Fig. 3: Saturable Transformer Model.

In Fig. 3, H_1 and H_2 are the high voltage winding and Y_1 and Y_2 the low voltage winding. R_1 and R_2 are the resistances of the high and low voltage windings respectively. The transformer leakage reactance X_{12} is split between the high X_1 and low X_2 reactances. R_M represents the no-load losses and X_M the nonlinear magnetizing reactance. An ideal transformer with $N_1:N_2$ turns ratio is used between the primary and secondary side of the transformer. This model is good for low frequencies. The winding resistances are frequency dependent and need to be modified to reflect proper damping at higher frequencies. The turn's ratio cannot be dynamically changed during the simulation to reflect tap changer operation. Occasionally, numerical instability has occurred with this model.

5.3   Matrix Models

The modeling of three phase transformers is more complex than that of single-phase units. In a transformer bank of single-phase units, the individual phases are not magnetically coupled, and their operation is balanced assuming all three phases have equal parameters. In three phase transformers, there is direct magnetic coupling of one winding to the other two phase windings. Three phase transformers exhibit asymmetry of magnetic path lengths, which results in asymmetric flux densities in the individual legs of the transformer core. The core asymmetry effects are more noticeable for zero sequence or unbalanced operation. Common types of three phase transformers are:

- Three-legged core form.

- Five legged core form and

- Shell form.

Accurate representation of three phase transformers requires the use of a full matrix model that takes into consideration coupling of every winding of one phase with all other bank windings.

The following matrix gives the two-port admittance matrix that describes a non-ideal two winding transformer as seen from the primary side:

$$[Y] = [\omega L]^{-1} = \begin{bmatrix} Y & -tY \\ -tY & t^2 Y \end{bmatrix} \tag{7}$$

This admittance matrix represents a linear relationship between the primary and secondary side voltages and currents:

$$\begin{bmatrix} i_L \\ i_H \end{bmatrix} = [Y] \begin{bmatrix} V_L \\ V_H \end{bmatrix} \tag{8}$$

This representation uses essentially the same 2 x 2 matrix known from load flow studies, except that the complex admittance matrix must be separated into [R] and $[\omega L]^{-1}$ for transient studies. In load flow studies with $p.u.$ quantities, t would be the off-nominal turns ratio. Emtp studies are usually done with actual quantities. The branch equations associated with the above matrices are:

$$[L]^{-1}[V] = [L]^{-1}[R][I] + \begin{bmatrix} \dfrac{di}{dt} \end{bmatrix} \tag{9}$$

The matrix elements for transformers with any number of windings can be derived from the short-circuit impedances between pairs of windings. The calculations are rather involved, and support routine BCTRAN available in ATP should be used. BCTRAN produces the branch matrices from the positive and zero sequence short-circuit and excitation test data. It recognizes the fact that delta-connected windings provide a short circuit for zero sequence currents, as well as other intricacies, and works for single-phase units as well. BCTRAN requires separate test data for zero sequence short circuit leakage impedance and magnetizing currents. A model produced by BCTRAN is good from dc up to 2 kHz. It can take into account excitation losses, but nonlinear behavior is not represented and must be added externally.

Two matrix representations are possible for transformer modeling, the admittance and impedance matrix representation. The impedance matrix representation is only possible if the exciting current is nonzero, the matrices are else singular. These matrices can be read in directly as coupled R-L branch data.

5.4   Transformer Saturation

Transformer saturation characteristics should be modeled whenever it is anticipated that the flux will exceed the linear region, about 1.0 per unit. This occurs quite often and it must be considered in cases such as transformer energization, switching of transformer terminated lines, ferroresonance, load rejection and other studies. The most commonly used representation is the single-valued nonlinear inductor, which is an integral part of the saturable transformer model. The saturable transformer model allows for a nonlinear magnetizing inductance to be placed at the star point. With two and three winding transformers one can come up with an equivalent circuit for the transformer with a fictitious node where the magnetization branch could be placed.

In transformers with more than three windings, it is not quite possible to come up with a fictitious node to place the magnetization branch and the nonlinear branch is placed at the transformer terminals. This is also the case with the admittance and impedance models, where the saturable branch is placed at the terminals of one of the transformer windings. In the admittance and impedance matrix representation, adding any of the nonlinear inductance models as extra branches easily does this. If the matrix already contains the effect of the unsaturated exciting current, then the added nonlinear inductance model should only represent the difference between unsaturated and saturated exciting current.

In the unsaturated region, it makes little difference where the magnetizing inductance is connected. In the saturated region, where the slope of the flux-current curve becomes comparable to the short-circuit inductance (typically 1 to 2.5 times L_{short} for transformers with separate windings, or 4 to 5 times L_{short} for autotransformers), it may make a difference where it is placed. Comparisons of field tests and emtp simulations on three-legged core-type transformers have shown that results are matched best if the nonlinear inductance is connected across the winding closest to the core (usually the tertiary winding or winding with the lowest voltage rating).

The ATP program has auxiliary routines to calculate the magnetization branch saturation parameters. This is performed using the supporting saturation routine SATURATION in ATP. The resulting characteristic can be used in the saturable transformer component built-in model, or in a pseudo-nonlinear inductor Type-98 element. The generated saturation curve is single valued (without hysterisis). All it is needed is a few RMS values of the transformer open circuit excitation test data. The supporting saturation routine generates the data for the piecewise linear inductance by converting the RMS voltage and current data into peak flux, peak current data.

The nonlinear inductor model, Type-93 element, which has the same format as the Type-98 pseudo-nonlinear reactor model, works well for a number of simulations, however, a number of limitations exist. This model does not represent hysteresis effects, which means that remnant flux in the core cannot be represented. As a result, inrush currents during energization cannot be modeled accurately if the transformer had some level of remanent flux in the core before it was energized. This model is also frequency independent.

ATP provides another model, the Type-96 pseudo-nonlinear hysteretic reactor, which could overcome some of the limitations of the Type-98 model. Data for the Type-96 model can be obtained using the supporting saturation routine HYSDAT. The only information that needs to be supplied by the user is the scaling, that is the location of the positive saturation point. This is the point of the first quadrant where the hysteresis loop changes from being multi-valued to being single-valued. The Type-96 model has its own limitations and sometimes numerical difficulties. Some of the Type-96 limitations include initialization problems outside the major hysteresis loop and the choice of only one core material [ARMCO M4].

For protection studies such as current transformer saturation, which involve "deep saturation", the simpler model (Type-98) that does not represent hysteresis produces very satisfactory results [2]. However, with this model, remanance in the CT core cannot be taken into consideration.

5.5   Eddy Currents

Eddy currents in the core of a transformer have two major effects: they introduce core losses, and they delay flux penetration into the core. Modeling of eddy currents is not an easy task since data are not readily available. The no load losses include the hysteresis and eddy current losses and can be represented by *Rm* in parallel with the magnetizing inductance branch where

$$Rm = \frac{V^2}{Pnl} \tag{10}$$

and *Pnl* is the no-load loss.

5.6   High Frequency Transformer Models

At frequencies above 2 kHz capacitances and capacitive coupling among windings become important. For frequencies of up to 30 kHz, the simple addition of total capacitances of windings to ground and between windings is sufficient for most purposes. For frequencies above 30 kHz, a more detailed representation of the internal winding arrangement is required and capacitances between winding and among winding segments must be modeled. The manufacturer does not typically provide the capacitances of transformers. The values of terminal to ground capacitance including bushing capacitance vary considerably with typical values in the range of 1 to 10 nF. This is due mainly to the physical arrangement of the transformer windings and the overall transformer design. The user should consult the manufacturer for such data. New high frequency transformer models have been developed in recent years and are implemented in some versions of emtp. These models could be useful for power line carrier attenuation applications in the protective relaying area.

5.7   Conclusions

The ATP has a built-in saturable component transformer model and a supporting routine, BCTRAN, for transformer parameter calculations. The BCTRAN supporting routine derives matrix parameters for modeling transformer windings as mutually coupled branches. When these matrix models are used, the magnetic core of the transformer is typically represented with a non-linear reactance or a hysteretic reactance branch connected externally to the terminals of the windings.

The built-in saturable transformer component is simpler to use than the matrix models. However, if zero sequence behavior of three-phase core-type transformers must be modeled, then the auxiliary program that derives matrix parameters must be used. The transformer models discussed here are valid only at moderate frequencies. In general, these models are accurate enough for fault and switching studies.

6. Current Transformer Digital Model

Current transformer (CT) equivalent circuit is shown in Fig. 4. For protection system studies, the circuit can be simplified as shown in Fig. 5, [3]. CT parameters Rp, Lp, and inter-winding capacitance can be neglected. Ls can also be neglected, although in some cases it may be taken into consideration. Rb represents combined CT secondary winding resistance, lead resistance, and the CT burden. The magnetizing branch can be located on the CT primary or secondary. Simulation results are identical in both cases. Location on the secondary is preferred because V-I curve measurements are regularly performed from the CT secondary and therefore, there is no need to refer the results to the primary side [4,5].
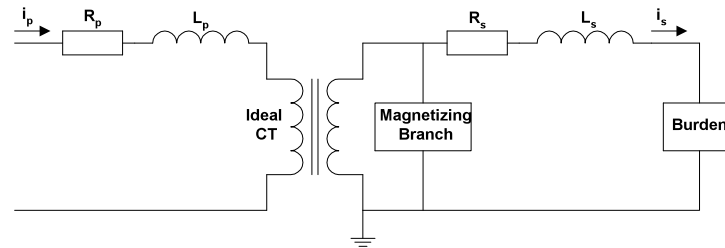
R_p, L_p - primary winding resistance and leakage inductance
R_s, L_s - secondary winding resistance and leakage inductance

Fig. 4: CT Equivalent Circuit.
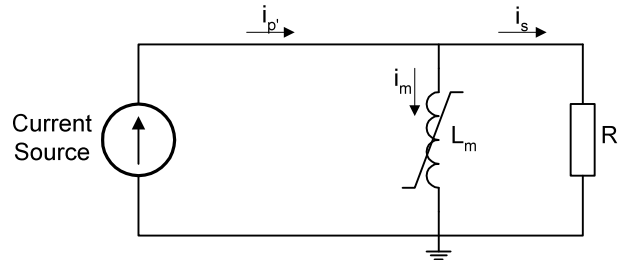
L_m - magnetizing inductance

Fig. 5: CT Representation for Transient Analysis.

All CT models developed using one of electromagnetic transient programs are based on the CT equivalent circuit and can be built using component-models available in the programs. The magnetizing branch Lm is represented by a nonlinear inductor element whose characteristic is specified in piecewise linear form by the user. Since the Ψ-I data points are not readily available, these programs provide a routine to convert the more commonly available V_{rms}-I_{rms} characteristics into an equivalent Ψ-I set.

Electromagnetic transient programs have component-models to represent the magnetizing branch. Some magnetizing branch models are integral part of a transformer model; whereas others are stand alone nonlinear inductance models that can be added to the linear transformer

model. When using magnetizing branch (Lm) models external to the transformer model, the CT secondary winding resistance must be connected on the burden side of Lm. This will mean that it is necessary to set the winding resistance in the transformer model to almost zero (e.g. $1\mu\Omega$), and to include the correct winding resistance in the connected burden [4].

The hysteresis effect may or may not be important in a particular study. However, it is more important to include the effect of remanence on the CT performance, which is easily studied if the magnetizing branch model can represent hysteresis. If the model cannot represent the hysteresis, it may still allow the specification of a steady state flux level at the beginning of a study. Specification of an initial value of flux will simulate the presence of remanent flux, similar to using hysteresis model.

As mentioned earlier, the V-I curve is not directly used in electromagnetic transient program simulations. For instance, EMTP/ATP provides a routine to convert the V-I curve into an equivalent Ψ-I data set, which is then used by EMTP/ATP. The EMTP/ATP extrapolates the Ψ-I curve using the slope defined by the last two points of the Ψ-I data set. If V-I curve data are such that the slope is not monotonically decreasing (contain "noise"), then the Ψ-I curve may get extrapolated at a higher slope (Fig. 6). This may result in incorrect CT transient response. The problem may be solved by adding an additional point to the V-I curve to ensure that the Ψ-I curve slope appropriately represents deep saturation region [5].
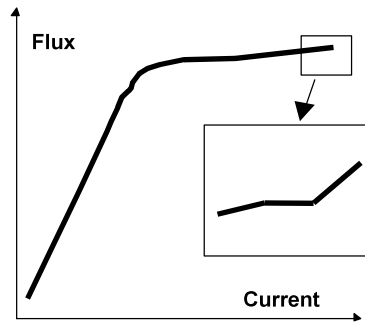
Fig. 6: Flux-Current Characteristic Representing the Noise.

Measured V-I characteristics for a 2000/5, C800 CT and an 800/5, C400 CT are shown in Fig. 7.
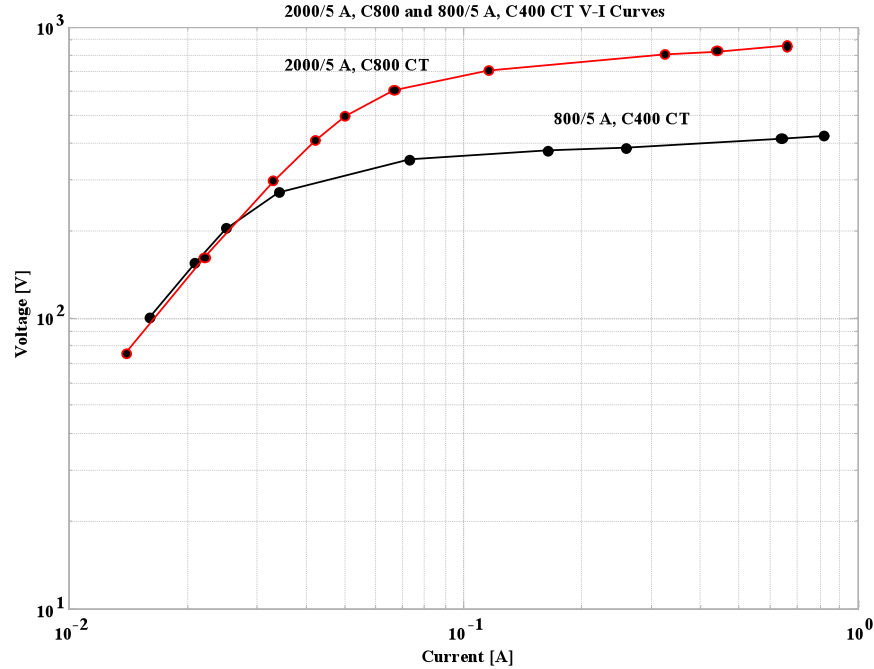
Fig. 7: Measured 2000/5, C800 and 800/5, C400 Current Transformer V-I Curve Characteristics.

6.1   Validation of the V-I Curve Model

After the Ψ-I curve data have been included in the CT model, it can be verified by simulating the conditions under which the actual V-I curve was measured. A circuit diagram that can be used for EMTP/ATP simulation of the V-I curve measurement is given in Fig. 8. Steady state simulations should be run for each voltage point selected from the V-I curve by varying source voltage E. Current I is measured through the resistor R and voltage V recorded at node A2. The duration of each simulation can be several cycles. RMS values for current and voltage are then calculated to obtain pairs of voltage and current points. If the V-I characteristic is properly modeled, the measured and simulated curves will overlap each other. This method can be used for the V-I curve verification of any transformer model.
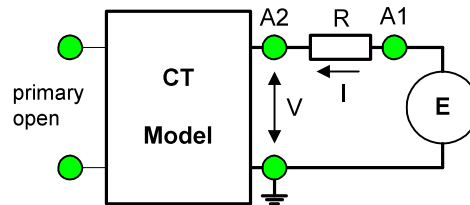
Fig. 8: Computer Simulation of the CT V-I Curve Measurement.

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7. Digital Models of Coupling Capacitor Voltage Transformers

Coupling capacitor voltage transformers (CCVT) are widely used in high voltage power systems to obtain standard low voltage signals for protective relaying and measuring instruments. They are usually designed as stand-alone single-phase units. A typical CCVT includes the following components (Fig. 9): capacitor stack (C1, C2); drain coils (Ld); compensating inductor (Rc, Lc, Cc); step-down transformer (Rp, Lp, Cp, Cps, Rs, Ls, Cs, Lm, Rm); ferroresonance suppression circuit (Rf, Lf, Cf); and other circuits with L, C elements and gaps which in many cases are non-linear. Components C1, C2, Lc and Lp make a parallel resonant circuit tuned to the fundamental frequency to obtain high measurements accuracy.

The generic CCVT model appropriate for relaying studies does not need to include all the above components and can be simplified as given in Fig. 10. The existing ATP component-model "TRANSFORMER" can be used to represent the step-down transformer. Its use also requires selection of values for Rs and Ls. The influence of these elements is small, and some small values ($\mu\Omega$) can arbitrarily be adopted [6].
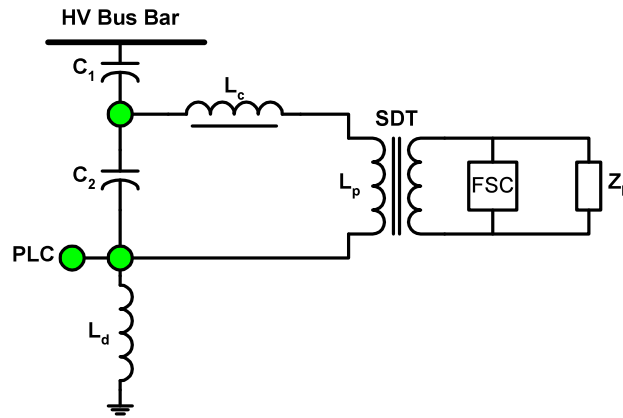
C2   Capacitor Stack
PLC -   Power Line Carrier C1, Interface
Lc -   Compensating Inductor
Ld -   Drain Coil
SDT -   Step Down Transformer
Lp -   Primary Winding Leakage Inductance
FSC -   Ferroresonance Suppression Circuit
Zb -   Burden

Fig. 9: A CCVT Circuit Connection.
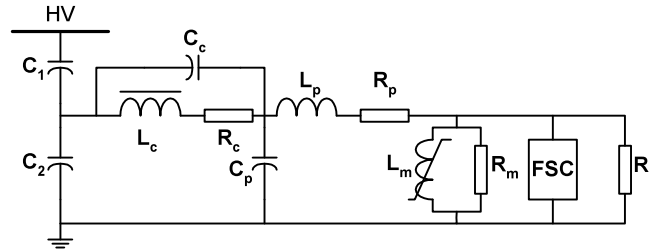
Fig. 10: Generic CCVT Model.

The Ferroresonance Suppression Circuit (FSC) has considerable effect on the transient response of the CCVT. There are two main FSC designs. The first FSC design includes capacitors and iron core inductors connected in parallel and tuned to the fundamental frequency. They are permanently connected on the secondary side and affect the CCVT's transient behavior (Fig. 11a). Capacitor Cf is connected in parallel with an iron core inductor Lf tuned to the fundamental frequency. Resistor Rf is a damping resistor designed to damp ferroresonance oscillations within one cycle. The circuit is tuned with a high Q factor in order to attenuate ferroresonance oscillations at any harmonic except the fundamental. The FSC can be modeled using two different Lf representations as shown in Fig. 11b and Fig. 11c, [7]. FSC model with Lf represented as an air core inductance (Fig. 11b) uses components Cf and Lf tuned to 60 Hz. Fig. 11c shows Lf represented as a non-saturable transformer. The calculated Lf value needs to be incorporated in the transformer model as a self-inductance. Primary and secondary windings are connected in such a way that parallel resonance occurs only at the fundamental frequency. At other frequencies, only the leakage inductance is involved so the damping resistor is the one which attenuates ferroresonance oscillations. FSC simulation using the transformer representation of Lf is more accurate.
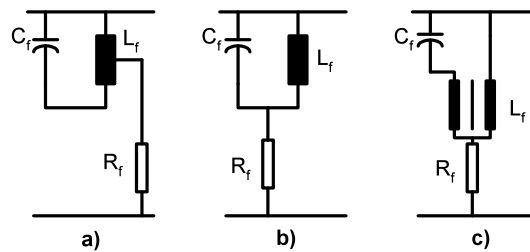
Fig. 11: FSC actual design (a), FSC digital models - Lf simulated using inductor model (b), and using transformer model (c).

The second FSC design includes a resistor connected on the SDT secondary side. This resistor can be permanently connected. Another option is to have a gap or an electronic circuit connected in series with the resistor, which is activated whenever an over voltage occurs. This FSC design does not affect transient response unless an overvoltage occurs.

Reference [8] describes a method for the CCVT frequency response measurements performed from the CCVT secondary side. The method is suitable for field measurements since it does not require any internal CCVT disassembly. The CCVT parameters can be estimated and used to develop computer models.

8.   Voltage Transformer Model

Modeling of magnetic voltage transformers (VTs) is, in principal, similar to modeling any other power transformer. Fig. 12 shows the model needed to accurately simulate the transient response of VTs.
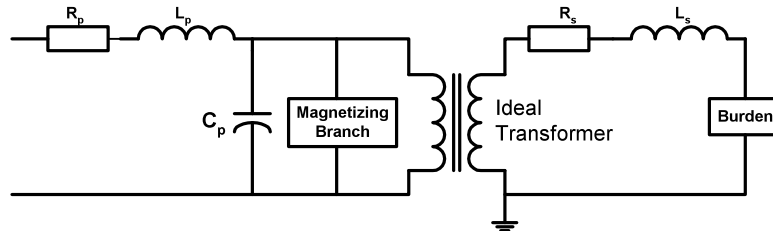
Fig. 12: VT Model.

9.   Breaker Model

The purpose of this write up is to provide basic information on the concept of Breaker Control as it is applicable to transmission line protective relays. At the outset it must be mentioned that in this Guide the term Breaker Control is essentially switch control, i.e., the switch opens at a current zero there is no modeling of the breaker nonlinear arc dynamics and losses. The separate EMTP model of the circuit breaker can be employed for detailed arc models [12]. The time step involved in circuit breaker simulations is typically of the order of nanoseconds or lower, whereas for relay simulations time steps of the order of microseconds (depending upon line length) or shorter are adequate. This write-up is not intended to be a complete guide, but rather serve as a starting point from which to start building mainly determined by the details of the particular transients program being employed [9], [11].

9.1   Types of Switches

There are three types of switches that are applicable for Transmission Line Relay Testing:

1. Time controlled switch – In this type of switch the Time at which it is close is specified and also the time at which it is to open is specified. The actual switch opening time will occur at the next current zero after the time at which it is required to open. Sometimes to simulate current chopping a current margin is also specified and the switch actually opens at the instant the current magnitude falls below the current margin and the time is greater than the time at which it is to open.
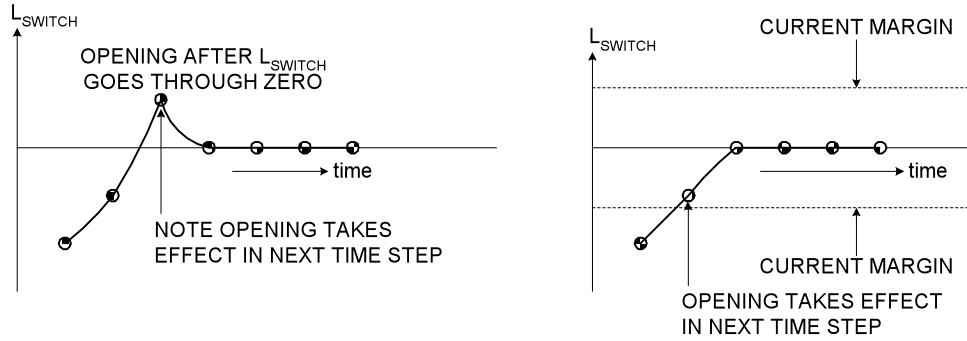
Fig. 13: Basic Switch Simulations.

2. "STATISTICS" Switch – A STATISTICS switch can be used to open or close the circuit breaker randomly with predetermined distribution functions such as Gaussian or uniform. Thus, the user will need to specify the mean closing time and the standard deviation in addition to the type of distribution. The "STATISTICS" Switch can be employed to determine the maximum peak currents that can flow through a relay when closing into a fault. Also the overvoltages on the system that occur due to current chopping and pole span of the breaker and line mutual induction can be analyzed.

The STATISTICS switch performs the same close or open operation repetitively according to the specified distribution characteristics. Usually 100 or 200 simulations are run to determine the statistical distribution of interest such as the maximum relay currents or the maximum overvoltages on the system.
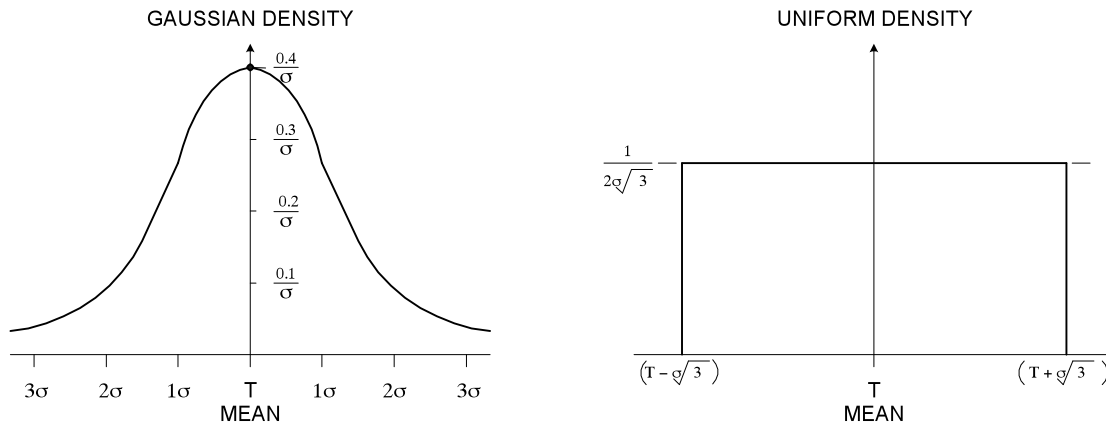
Fig. 14: Distribution Densities for "STATISTICS" Type Switches.

3. "TACS" Switch – Within EMTP there is an analog computer equivalent system, called "Transient Analysis of Control Systems", which provides the control signal to open the switch. Thus, for example a simple distance relay model could be implemented in TACS which would control the switch in the network model. Again, the switch would behave similarly to the description before for a Time controlled switch. For example, assume the switch is initially closed and a fault occurs. As the voltage decreases and the current

increases the impedance relay algorithm implemented in TACS will measure a fault. If the algorithm determines the fault impedance is within the zone of operation a TACS trip signal can be issued to the network switch. The switch will then open at the next current zero in the circuit. After a time delay a reclose operation can be simulated by closing this switch or another switch in parallel.
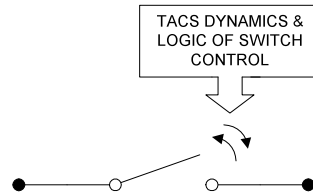
Fig. 15: TACS Controlled Switch Operation.

9.2   Single Pole and Three Pole Operation of Circuit Breakers

The operation of all the above switches is inherently single phase, i.e., each switch of each phase operates independently. Therefore, it is possible to set up an EMTP data case to simulate single pole opening and reclosing after a time delay.

To setup three pole operation of a circuit breaker with a Time controlled switch, it is sufficient to input the same opening time on all three phases which will result in the phase opening at the next available current zero of the particular phase. To setup three pole operation of a circuit breaker with a STATISTICS switch, it is sufficient to input on each phase STATISTICS switch the same mean closing time and the same standard deviation. To setup three pole operation of a circuit breaker with a TACS controlled switch, it is sufficient to drive each phase TACS switch by the same named TACS control variable.

9.3   Closing Resistors

On some high voltage transmission lines, circuit breakers are employed with pre-insertion resistors usually with a value equal to the surge impedance of the line (approximately 250-400 ohms). There is an auxiliary contact which closes first and inserts a resistor in series with the transmission line for about one cycle. Then the circuit breaker main contact closes and bypasses the auxiliary contact and the resistor. The auxiliary contact then opens to avoid overheating the resistor. This procedure results in a lowering of the surges impressed upon the system particularly at the receiving end where a doubling of the impressed surge occurs.

The present trend is to apply metal oxide surge arresters on transmission lines at the two ends of the line and also at other points along the line to limit the surge overvoltages. The reasons for this trend are the better V-I characteristics, higher energy capability of metal oxide arresters, and also the inherent complexities of having a breaker design with a main contact, an auxiliary

contact, and a high wattage resistance. An excellent reference for simulating closing resistors is [11].

9.4   Data Parameters Required for Switch Input

This section identifies some of the generic data required of the user to implement the switch model within the various transients program. It is of course imperative to consult with the manual of the particular version of transients program being employed.

1. Node names between which the switch is connected to in the circuit. Note that it is not advisable to connect two switches in parallel, due to difficulties with current division between two shorted nodes.
2. Time at which the switch is to be closed. (for Time controlled switch)
3. Time at which the switch is to be opened. (for Time controlled switch)
4. The current margin at which the switch can be forced to open. . (for Time controlled switch)
5. The mean closing time or the time at which it is aimed to close the circuit breaker (for STATISTICS switch only)
6. The standard deviation – this can be calculated as the pole span divided by 6. The factor six represents the Gaussian normal distribution of the circuit breaker from-3σ to +3σ. (for STATISTICS switch only)
7. OPEN/CLOSE signal identified within TACS as a variable which controls whether switch is open or closed depending upon the signal value. (for TACS switch only). This TACS signal could serve as the relay output to operate the circuit breaker.

10. Test Procedure

The basic EMTP network model of Fig. 1 allows to simulate the transient and steady states of the events the relay under testing might get across in real life applications. The line to be protected is line 1 and a number of fault characteristics and conditions should be tested in order to evaluate the internal relay functions and algorithms.

The thorough evaluation of a relay by a manufacturer could result in the application of thousands of cases given the practically infinite numbers of varying conditions that its various customers could meet in real life applications. A user perspective could be different in the sense that he should normally concentrate on the conditions that he is most likely to meet on his network.

10.1   Fault Characteristics

The relay should be tested for various fault characteristics the most important of which are fault location, type, resistance, evolving, inception angle, and load.

10.1.1 Fault Location

The purpose of varying the fault location is to test the relay functions related to directionality and mho and quadrilateral reach accuracy.

Faults are applied internally and externally to Line 1 of the basic system model in Fig. 1. At a minimum, internal faults on Line 1 should be at m = 0, 0.5 and 1.0 to test tripping dependability and speed of each line terminal used in either pilot or non-pilot schemes. (ATP/EMTP model files in Appendix B allow fault application at 33% and 66% of the line length). Additional internal faults may be applied to test zone-1 speed and accuracy. Faults external to Line 1 should be applied at each line terminal bus to test the security of the pilot system against tripping and to test zone-2 coordination for non-pilot [or disabled pilot] systems. Additional fault locations may be tested to evaluate specific needs such as zone-2 and zone-3 coordination, fault location capabilities, loss-of-load tripping, close-into-fault and other special schemes.

10.1.2 Fault Type

The purpose of varying the fault type is to test the relay internal functions related to fault- type selection and targeting. These tests are paramount for the purpose of testing the relay in applications like Single-Pole Tripping.

There are 10 basic fault types that involve all combinations of phases A, B and C and ground (G). These are shown in the following table. All fault types must be applied to test the relay ability to make the correct faulted phase selection and operate correctly at each fault location defined above.

	Single-phase-to-ground			Two-phase-to-ground			Phase-to-phase			Three Phase
Phase A	X			X		X	X		X	X
Phase B		X		X	X		X	X		X
Phase C			X		X	X		X	X	X
Ground	X	X	X	X	X	X				
Fault Type	AG	BG	CG	ABG	BCG	CAG	AB	BC	CA	ABC

Table 1: Fault Type Combinations.

10.1.3 Fault Resistance

Fault resistance has a direct impact on the sensitivity of the mho and quadrilateral elements for ground faults. It is important particularly for single-phase-to-ground faults to measure the sensitivity limits of the relay. The sensitivity limit can be defined as the maximum fault resistance above which no detection occurs. The fault resistance has also a direct effect on functions like single-ended fault location.

Fault resistance for ground faults consist of the arc resistance and ground loop (ground return path) impedance. Again arc resistance is generally negligible. Tower footing resistance and ground-wire shielding impact the impedance of the ground loop. These factors, however, are reflected in the transmission line model. Other faults, such as those involving trees, may also result in high resistance at the faults.

10.1.4 Evolving Faults

There are a number of ways for evolving faults to occur. The simplest is the fault evolving to include more phases in the fault. For example: single-phase-to-ground to two-phase-to-ground and two-phase-to-ground to three-phase. These faults should be applied internal and external to the protected line to insure correct pilot operation and step distance coordination. Other types of evolving faults to be tested are those that occur external and evolve to an internal fault. For example: a reverse bus fault evolving to a forward line fault, and an external parallel circuit fault flashing over to the protected line. These fault types affect dependable pilot operation. Evolving faults have a direct impact on internal relay functions like fault-type selection, targeting and directionality.

10.1.5 Fault Inception Angle

The fault inception angle defines the angle of the voltage at the instant of the fault. This angle is referenced to a phase voltage, generally phase-A. The phase currents will lead or lag their respective phase voltages prior to the fault based on load conditions and will lag during the fault based on fault impedance. The fault inception angle, therefore, controls the amount of asymmetrical transient current generated in the fault current. These transient currents affect the operating speed security of the protection. The fault inception angle should be varied over 360^0 to reflect real-life operation or to find worst-case conditions.

10.1.6 Pre-Fault Loading

Pre-fault loading refers to the amount of current that flows into the line prior to the fault. It impacts the sensitivity of mho and quadrilateral elements particularly when the faults are resistive.

10.1.7 Variation of the System Parameters

Although the system model in Fig. 1 has been designed to provide a relatively generic test bench for transmission line protection relays, variation of the parameters of its components should also be considered when preparing the realistic test scenarios. By adjusting some or all of the transmission line impedances, generator constants, transformer parameters, etc. the basic system architecture in Fig. 1 can be tuned to the specific needs of the network operator. The ranges (min and max values) of the relevant parameters should be selected based on the local network data.

These ranges define a series of alternative network variations representing the differences of the power system constants within the customer's actual network.

10.1.7.1 Line Parameters' Variation

The customer should look for the lines of minimum, medium and maximum length in the transmission system and include the impedances of these lines in the preparation of the simulation case scenarios.

10.1.7.2 Generator Parameter Variation

With regard to generators' constants the customer should look for the parameters of the generators of minimum, medium and maximum installed capacity.

10.1.7.3 Transformer Parameter Variation

Similarly, the transformer parameters should include extreme MVA cases.

In some transmission system architectures the parameters of certain components (e.g. transformers) may vary only within a narrow range. In such cases it is reasonable to use the average constant values rather than varying system parameters.

10.2 Communication-Assisted Schemes

Communication assisted or pilot schemes allow two relays installed at the extremities of a line to exchange information and therefore to define the protected zone boundaries without any ambiguity. These schemes allow for the implementation of directionality-based protection .
The most popular schemes are POTT, PUTT, DCB, DCUB, Transient Block (Power Reversal) and Weakfeed (12).

10.3 Fault Test Cases

10.3.1 Internal Faults

Purpose: Verify the relay is successful to detect internal faults (Dependability).

Test Conditions:
Line 2 breakers open in order to remove any parallel line effect
Switch SW open

Test Variations:

Fault type: all
Fault locations on line 1: distributed along the line at various locations. The line model in Appendix B will allow fault applications at 0%, 33%, 66% and 100% of the line length.
Protection Schemes: applied to pilot and non-pilot
Loading conditions: Pre-fault load and no-load
Fault resistance: From zero ohm to limit for ground faults
Evolving faults: Yes
Incident angles from 0° to 180° in 30° increments

Comments: These test cases should be the first to be applied and simply test the primary function of the relay, which is to detect internal faults or dependability of the relay.

10.3.2 External Faults

Purpose: Verify the relay is not tripping for a fault outside the protected zone (Security)

Test Conditions:
Line 2 breakers closed
Switch SW open

Test Variations:

Fault type: all
Fault locations: For a zone 1 element, this will include buses 1, 2 and 4. Also, on line 2 faults can be applied at 33% and 66% of line length.
Communications assisted: applied to pilot and non-pilot
No load conditions
No fault resistance
Incident angles from 0° to 180° in 30° increments

Comments: These test cases supplement the first series and verify the relay security.

10.3.3 One End Open Internal Faults

Purpose: Verify the ability of the relay to detect a fault with no infeed

Test Conditions:
Line 2 open
Switch SW open

Test Sequence:

Open circuit breaker of Line 1 at Bus 2.

Test Variations:

Fault type: all
Fault locations on line 1: At 33%, 66% and 100%.
Communications assisted: applied to pilot and non-pilot
No pre-fault load
No fault resistance
Incident angles from 0° to 180° in 30° increments

10.3.4 Loss of Load Tripping

Purpose: Verify the ability of the relay to detect a fault with varying loss of load conditions

Test Sequence:
- Apply fault on Line 1: At 33%, 66% and 100%.
- Open breaker at Bus 2 on Line 1 in 2 cycles

Test Variations:
Fault type: all
Fault locations on line 1: m= 0.95
Pre-fault load
No fault resistance
Incident angles from 0° to 180° in 30° increments

10.3.5 Closing into Faults

Purpose: Verify the relay ability to detect a fault immediately after closing the line

Test Conditions:
Line 2 open
Switch SW open

Test Sequence:
- Open the breakers of line 1 at buses 1 and 2
- Apply a permanent fault
- Close Line 1 circuit breakers at buses 1 and 2 in succession.

Test Variations:

Fault type: all
Fault locations on line 1: m= 0%, 33%, 66%
No pre-load

No fault resistance
Incident angles from 0° to 180° in 30° increments

10.3.6 Power Swing

Purpose: Verify the relay ability to trip properly when a fault occurs during a power swing

Test Sequence:
- Apply a three-phase fault at bus 1 and remove the fault before generator losses synchronism
- Following the fault at Bus 1, a power swing condition should appear
- Apply various fault on the line during the power swing condition

Test Variations:

Fault type: all
Fault locations on line 1: m= 0%, 33%, 66%
Pre-Load applied
No fault resistance
Incident angles from 0° to 180° in 30° increments

Comments: These test cases require the complete model of at least one generator in order to simulate the change in phase angle that causes the power swing.

10.4 Non-Fault Test Cases

10.4.1 Line Closing

Purpose: Verify the relay ability not to trip when line closing occurs

Test Sequence:
- Line 1 open
- Close Line 1 breakers simultaneously

10.4.2 Loss of Potential

Purpose: Verify the relay ability not to trip in case of loss of phase voltage input(s)

Test Sequence:
- Remove one or more phase voltage input(s)
- Restore voltage input(s) after 10 cycles

Test Variations:

- All single phase interruptions
- All combinations of two phase interruptions
- Interruption of all three phases voltages
- Pre-load Load applied

10.4.3 Power Swing

Purpose: Verify the relay ability not to trip during a power swing condition

Test Sequence:
- Apply a three-phase fault at bus 1 and remove the fault before generator losses synchronism
- Following the fault at Bus 1, a power swing condition should appear
- Apply various fault on the line during the power swing condition

10.5 Special Applications

Particular line or network issues in special applications will affect the operation of a line relay. Each particular situation could require additional and special testing. Some examples of special applications follow.

10.5.1 Parallel Lines

Correspond in Fig. 1 to the condition where breakers of line 2 are closed. Line 1 single-phase-to-ground zone 1 elements reach is directly affected by the current flowing into the adjacent line.

Current reversal in line 1 should also be tested: faults should be applied on Line 2, followed by appropriate Line 2 breaker clearing, to test the security of Line-1' pilot scheme against tripping for current reversals in the Line-1 relays.

10.5.2 Short Lines

Short lines exhibit very often a very high source to line impedance ratio with the consequence that the fault current will be limited to some low values with the voltage undergoing a small change. This has a direct effect on the speed of the relay.

10.5.3 Single-pole Tripping Applications

Single-pole tripping applications require a very reliable fault-type selection. After the faulty line phase has been opened, operation of the relay during the open pole condition, before reclosing takes place, has to be tested for the same conditions found in a normal operation.
As an example, a power swing condition could occur during the open pole and capacity either to trip and to block tripping should be tested.

10.5.4 Three Terminal Applications

In Fig. 1, three terminal application corresponds to the condition where switch SW is closed. Require communication assisted schemes by definition.

10.5.5 Series Compensation

Series compensated lines are among the most complex to protect with distance elements. Most of the time, protection of this type of line requires special studies (13).

10.5.6 CVT Response

When capacitive-coupled voltage transformers are being used, it is necessary to verify the amount of overreach and the measures to mitigate this effect for zone 1 elements and close in faults in the reverse direction.

10.5.7 CT Saturation

The most common effect of a CT saturation is a slowing down of the relay operation. Some particular functions like directional elements or fault-type selection could be affected by CT saturation.

10.5.8 Untransposed Lines

Untransposed lines exhibit a high level (up to 10%) of current and voltage negative and zero sequence quantities. Some polarizing elements based on the measurement of these quantities could have their sensitivities affected.

11. Case File Nomenclature

11.1   Introduction

Relay testing with emtp generated transient data is very common nowadays. The engineer involved in generating the emtp data cases, or testing the relays using COMTRADE files must be able to easily identify the type of fault or event studied during testing so that he can quickly anticipate the relay response and relay targeting during testing. This section presents a system that enables the engineer involved to easily name and later identify the cases he will be using to test the relay systems.

11.2   File Naming

The information one must convey with the emtp and COMTRADE file names used for relay testing consists of a number of important attributes that are shown below and are discussed in more detail later on in this section of the report.

- System conditions.
- Fault type(s).
- Fault incidence angle.
- Fault resistance.
- Fault location.
- File extension.

An attempt has been made here to come up with an easy way to name emtp and COMTRADE files, using a short file name, that describe the fault conditions one might consider while testing a relay system with emtp generated transient data. Since it is not possible to describe all possible scenarios with a limited number of file name characters, we decided to cover the most important attributes of fault events.

The proposed file name consists of eighteen characters for the main name and three characters for the file name extension. An example of a file name is listed below and the underscore character, for ease of readability, separates each main attribute:

S01_TT3_A10_R00_F07.atp

The meaning of this file is as follows and each attribute will be discussed in more detail in the next paragraphs:

S01   Describes system condition 01.
TF3   Stands for C-G fault.
A10   Stands for incidence angle of 0 degrees.
R00   Stands for zero ohm fault resistance.
F07   Stands for fault location 07.

Fig. 16 shows a system diagram of a test system with node naming for EMTP use and the locations in the network where faults were placed. This system has no connection with the basic model system of Fig. 1, although some of the node names used might be similar.
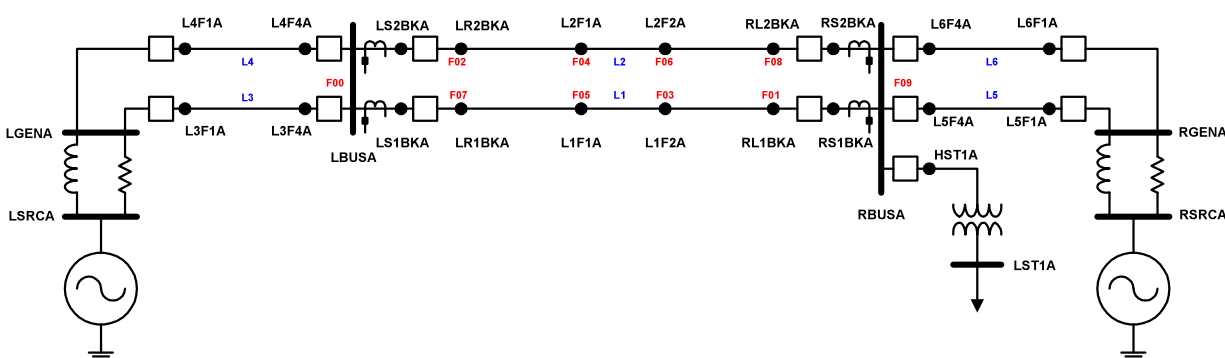
Fig. 16: System Used for Explaining Case File Nomenclature.

11.2.1   System Conditions – Sxx

System conditions attribute of the file name starts with the letter S and is followed by a two digit number xx covering up to 100 different system conditions, i.e., from 00 –99. Here the user can describe a number of different system conditions, with a few examples shown below:

S01   Describes an unloaded normal system.
S02   Describes a loaded system with load from LBUS to RBUS.
S03   Describes a loaded system with load from RBUS to LBUS.
S04   Describes a system where the left side source is strong and the right side source is weak.

The user is free to create a text file describing each system condition for his own future use and to share with other colleagues involved in a particular test evaluation project, for example, a relay manufacturer.

11.2.2   Fault Type Description – Txy

The fault type description starts with the letter T, followed by the letter F if the fault is not an evolving type of fault, and a numeric character from 0-9 describing the fault type as shown below:

0   A-B-C
1   A-G
2   B-G
3   C-G

4	A-B
5	B-C
6	C-A
7	A-B-G
8	B-C-G
9	C-A-G

Evolving type faults are described using the letter T followed by two numeric characters each one describing the fault sequence. For example, T13 indicates that the fault started as an A-G fault and evolved into a C-G fault.

11.2.3 Fault Incidence Angle – Axy

The fault incidence angle description starts with the letter A and is followed by two numeric characters. The first numeric character takes the numbers 1 through 4 describing the four 90 degree quadrants. For example, 1 is the first quadrant from 0 – 90 degrees, 2 is the second quadrant from 90 – 180 degrees and so on.

The second numeric character takes the numeric values for 0-6 with each one of them indicating the multiplication factor of a 15-degree angle step. For example, 0 means 0 x 15 = 0 degrees, and a 3 means 3 x 15 = 45 degrees. We can use the two numeric characters to describe any fault incidence angle from 0 – 360 degrees in 15-degree increments. A few examples are shown below:

A10   Indicates a fault incidence angle of 0 degrees since 1 indicates the first quadrant and 0 indicates 0 x 15 = 0 degrees.

A23   Indicates a fault incidence angle of 135 degrees since 2 indicates the second quadrant and 3 indicates 3 x 15 = 45 degrees. Therefore, the fault incidence angle is 90 + 45 = 135 degrees.

A43   Indicates a fault incidence angle of 315 degrees since 4 indicates the fourth quadrant and 3 indicates 3 x 15 = 45 degrees. Therefore, the fault incidence angle is 270 + 45 = 315 degrees.

11.2.4 Fault Resistance – Rxy

The majority of power system faults involve ground and some degree of fault resistance. Therefore, we included the fault resistance as an attribute of the file naming. The fault resistance attribute starts with the letter R and is followed by two numeric characters. The first numeric character takes on the numeric values from 0-3, i.e., 2, and represents a multiplication factor of ten to the power of 2 (10^2). The second numeric character takes the values from 0-9. The combination of the two numeric characters can represent the following fault resistance values:

1. x = 0 and y = 0 – 9   0, 1, 2, 3, 4, 5, 6, 7, 8, 9 Ohms
2. x = 1 and y = 0 – 9   10, 20, 30, 40, 50, 60, 70, 80, 90 Ohms

3. x = 2 and y = 0 – 9   100, 200, 300, 400, 500, 600, 700, 800, 900 Ohms
4. x = 3 and y = 0 – 9   1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 Ohms

The following examples show how to decipher the fault resistance value from the file name:

R05   Indicates a 5 Ohm resistance since $10^0 = 1$ and 1 x 5 = 5 Ohms.
R15   Indicates a 50 Ohm resistance since $10^1 = 10$ and 10 x 5 = 50 Ohms.
R23   Indicates a 300 Ohm resistance since $10^2 = 100$ and 100 x 3 = 300 Ohms.

11.2.5 Faulted Location – Fxyvw

The faulted location in a network is an important attribute of the file naming convention. The faulted location starts with the letter F and is followed by two numeric characters. Each numeric character can take the values from 0-9 and we can represent up to 100 faulted locations in a power system. The user must provide a one-line diagram as shown in Fig. 16 where the faulted locations are indicated very clearly.

Evolving faults typically would involve two different faulted network locations. For those faults, we use two additional numeric characters indicating the second in a sequence-faulted location. For example, F0105 would indicate a fault at location 01 evolving into a second fault in location 05.

11.2.6 File Extensions

The following file extensions are suggested:

ATP data files: Typically use .atp extension
ATP output files: Typically use .pl4 extension
COMTRADE files: Typically use three different extensions per COMTRADE standard, .cfg, .hdr, .dat

12. Modifying EMTP Data Files

The table below is intended to assist the user in modifying the reference model data files (included in Appendix B) for the purposes of defining user specific fault scenarios. The table includes fault characteristics listed in section 10.1 and directs the user to the relevant location of the EMTP input data file (line and column). Additionally, a short comment is also given on how to modify the parameters in order to implement the relevant fault characteristic. As this document is not intended to replace the EMTP user manual it is assumed that the user has a good understanding of the program operation. The file names that appear in the "Filename" column are identified in Appendix B.

Fault	Filename	Line No	Required Modifications

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characteristic			
Fault Location	*Main.dat*	134-137	Bus name(s) should be given in columns 3-8 and 9-14 of the time controlled switches to define fault location.
Fault Type	*Main.dat*	134-137	Individual phase and earth switches should be configured by adjusting closing times in columns 15-24 to define required fault connection.
Fault Resistance	*Main.dat*	72-74	Fault resistances of individual phases are defined in columns 27-32.
Evolving Faults	*Main.dat*	134-137 72-74	Appropriate number of switches and resistances should be added to define required evolving fault configuration and sequence of events.
Fault Inception Angle	*Main.dat*	134-137	Fault inception angle is set by adjusting the closing time instant in columns 15-24.
Pre-Fault Loading	*Main.dat*	146-148 152-154	Pre-Fault loading can set by adjusting the angles of the sources S1 and S3 as well as the generator S2 in columns 31-40.
	Machine_Data.pch	26	
Line parameters' variation	*L1L2_Full_Line.pch* *L3_Full_Line.pch* *L4_Full_Line.pch*	-	The user can provide alternative line data by modifying or replacing the line parameter files: *L1L2_Full_Line.pch*, *L3_Full_Line.pch* and/or *L4_Full_Line.pch*.
Line 3 connection node	*Main.dat*	105-107	Required node names should be given in columns 3-8.
Generator Parameter Variation	*Machine_Data.pch*	-	The user can provide alternative generator data by modifying or replacing *Machine_Data.pch* file.
Transformer Parameter Variation	*BUS2_XFMR.pch*	-	The user can provide alternative unit transformer data by modifying or replacing *BUS2_XFMR.pch* file.

Table 2: Modifying EMTP Data Files.

References

[1] P. Bastard, P. Bertrand and M. Meunier, "A transformer model for winding fault studies", *IEEE Trans. on Power Delivery*, vol. 9, no. 2, pp. 690-699, April 1994.

[2] "Mathematical Models for Current, Voltage, and Coupling Capacitor Voltage Transformers", IEEE Power System Relaying Committee, *IEEE Transactions on Power Delivery*, Vol. 15, No. 1, January 2000, pp. 62-72.

[3] Lj. A. Kojovic, "Guidelines for Current Transformers Selection for Protection Systems", IEEE/PES Summer Meeting, Vancouver, Canada, July 2001.

[4] M. Kezunovic, Lj. A. Kojovic, C. W. Fromen, D. R. Sevcik, F. Phillips, "Experimental Evaluation of EMTP-Based Current Transformer Models for Protective Relay Transient Study", IEEE Transactions on Power Delivery Vol. 9, No. 1, pp. 405-413, January 1994.

[5] Lj. A. Kojovic, "Comparison of Different Current Transformer Modeling Techniques for Protection System Studies", IEEE/PES Summer Meeting, Chicago, Illinois, July 2002.

[6] M. Kezunovic, Lj. A. Kojovic, V. Skendzic, C. W. Fromen, D. R. Sevcik, S. L. Nilsson, "Digital Models of Coupling Capacitor Voltage Transformers for Transients Protective Relaying Studies", IEEE Transactions on Power Delivery Vol. 7, No. 4, pp. 1927-1935, October 1992

[7] Lj. A. Kojovic, M. Kezunovic, S. L. Nilsson, "Computer Simulation of a Ferroresonance Suppression Circuit for Digital Modeling of Coupling Capacitor Voltage Transformers", ISMM International Conference, Orlando, Florida, March 1992.

[8] Lj. A. Kojovic, M. Kezunovic, V. Skendzic, C. W. Fromen, D. R. Sevcik, "A New Method for the CCVT Performance Analysis using Field Measurements, Signal Processing and EMTP Modeling", IEEE Transactions on Power Delivery Vol. 9, No. 4, pp. 1907-1915, October 1994.

[9] ATP Manual.

[10] EMTP Manual.

[11] EMTP Primer, EPRI EL-4202, 1985.

[12] V. Phaniraj and A.G. Phadke, "Modelling of Circuit Breakers in the EMTP", IEEE Trans. On Power Systems, Vol. 3, No. 2, pp. 799-805, May 1988.

[13] IEEE Guide for Transmission Line Protection

[14] IEEE Guide for Protective Relay Application of Transmission-Line Series Capacitor Banks

Appendix A – Physical Parameters of the Components Used in the Basic System Model

The physical parameters of the various components that make up the basic system model of Fig. 1 are provided here. With this information, it will be possible for the user to perform the transient simulation in their own simulation programs. The ATP/EMTP reference model files are provided in Appendix B. This model is also available in PSCAD simulation program. Both ATP/EMTP and PSCAD files are available on the website at http://www.ieee.xxx.

The frequency used is 60Hz.

A.1 Ideal Sources

Sources S1 (connected to Bus #1) and S3 (connected to Bus #3) are modeled as ideal sources. These consist of a sinusoidal source behind a Thevenin impedance.

A.1.1   Source S1 (230kV)

Positive-sequence impedance Z_1: $6.1 + j16.7\Omega$.
Zero-sequence impedance Z_0: $2.7 + j8.37\Omega$

A.1.2   Source S3 (230kV)

Positive-sequence impedance Z_1: $0.69 + j4.12\Omega$
Zero-sequence impedance Z_2: $0.34 + j4.77\Omega$

A.2 Synchronous Machine (Source S2)

The source S2, connected to Bus #4 through a step-up transformer is modeled as a synchronous machine. Exciter and governor dynamics are not modeled. The machine parameters are:

Rated kV:	24 kV
Rated MVA:	830 MVA
Armature dc resistance Ra:	$0.00199\ \Omega$
Positive-sequence reactance Xl:	0.15 pu
Zero-sequence reactance X0:	0.145 pu
Direct-axis synchronous reactance Xd:	1.89 pu
Quadrature-axis synchronous reactance Xq:	1.8 pu
Direct-axis transient reactance X'd:	0.23 pu
Quadrature-axis transient reactance X'q:	0.435 pu
Direct-axis sub-transient reactance X"d:	0.1775 pu

Quadrature-axis sub-transient reactance X"q: 0.177 pu
Direct-axis transient open-circuit time constant T'do: 4.2s
Quadrature-axis transient open-circuit time constant T'qo: 0.589s
Direct-axis transient open-circuit time constant T"do: 0.031s
Quadrature-axis transient open-circuit time constant T"qo: 0.063s
WR^2:   678,000 lb-ft^2

The actual machine has 6 masses. However, individual inertia, damping etc. were not available. Hence, it is modeled as a single mass machine.

All per-unit impedance values are on the machine base (830 MVA, 24 kV).

Where both saturated and unsaturated reactance values were available, the average of the two is used.

A.3 Unit Transformer (Connected to Source S2)

The transformer is a grounded Y - Δ two-winding transformer with the following parameters:

H.V. Winding:

Voltage: 229.893kV
MVA: 725MVA
Resistance: 0.1469Ω

L.V. Winding:

Voltage: 22.8kV
MVA: 725MVA
Resistance: 0.0044Ω

% Excitation current at 100% rated voltage: 0.706
No Load Losses at 100% rated voltage: 466.303kW

Short-circuit Test:

229.893kV to 22.8kV @ 725MVA:

%Z: 9.21
Losses: 1333.689kW

Zero-sequence quantities are assumed to be the same as positive-sequence quantities.

A.4 230kV Transmission Lines

There are essentially three 230kV transmission lines in the model system of Fig. 1. The first is a double-circuit line between Bus #1 and Bus #2. A second line is tapped off from Line 1 of the double-circuit line, and terminates at Bus #3. A third line connects Bus #2 to Bus #4.

Each line is 45 miles long, and there are three sections per line, each section being 15 miles in length. This allows the user to apply faults at the section junctions.

The double-circuit line is modeled using a constant parameter line model, while the other two lines are modeled as lumped parameter sections.

The line conductor is a Marigold 1113 Kcmil AA with a 1.216-inch diameter and a dc resistance of 0.09222Ω/mile at 50°C. The line parameters are calculated at 60Hz with an earth resistivity of 50Ω-m.

A.4.1   Tower Configuration for 230kV Double-Circuit Line

Conductor	Horizontal Separation from Reference (ft)	Height at Tower (ft)	Height at mid span (ft)
1	0.0	100.0	73.0
2	0.0	83.5	56.5
3	0.0	67.0	40.0
4	29.0	67.0	40.0
5	29.0	83.5	56.5
6	29.0	100.0	73.0

Table 3: Tower Configuration for 230kV Double-Circuit Line.

A.4.2   Tower Configuration for the other 230kV Lines

Conductor	Horizontal Separation from Reference (ft)	Height at Tower (ft)	Height at mid span (ft)
1	0.0	100.0	73.0
2	0.0	83.5	56.5
3	0.0	67.0	40.0

Table 4: Tower Configuration for 230kV Single-Circuit Lines.

A.5 Current Transformers (CT)

CTs are applied at those locations where relays are to be connected. Please see Fig. 1 for exact locations.

The following figure (Fig. 17), shows the CT equivalent circuit, with the values of the various parameters shown in the figure.
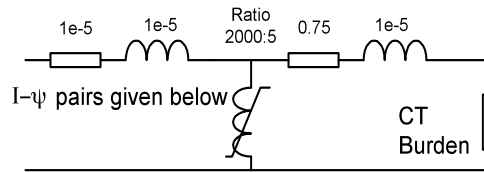
Fig. 17: Current Transformer Equivalent Circuit with Data.

The CT ratio is 2000:5, the CT wire resistance is 0.75Ω. The current vs. flux table is given below:

Current	Flux
0.0198	0.2851
0.0281	0.6040
0.0438	1.1141
0.0565	1.5343
0.0694	1.8607
0.1025	2.2771
0.2167	2.6522
0.7002	3.0234
1.0631	3.1098
15.903	3.2261

Table 5: Current-Flux Table for CT.

A.6 Coupling-Capacitor Voltage Transformers (CCVT)

The CCVT equivalent circuit is shown below in Fig. 18.

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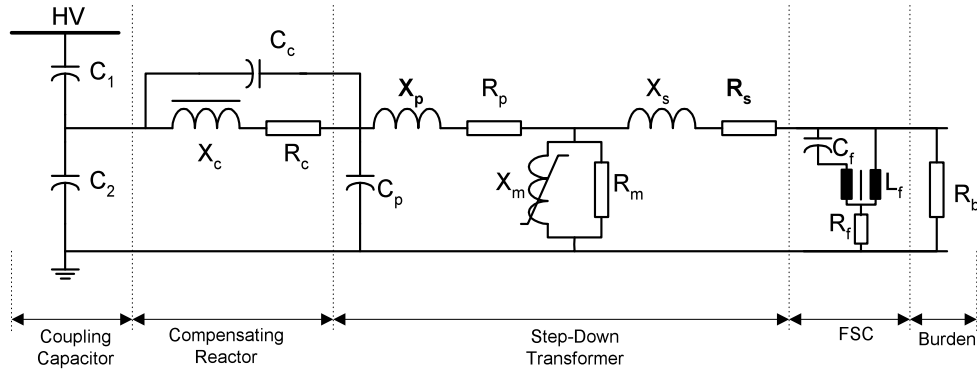
Fig. 18: CCVT Equivalent Circuit.

The data corresponding to the equivalent circuit is shown in the table below.

Capacitor Stack	C1 = 2.43 nF, C2 = 82 nF
Compensating Inductor	Rc = 228 [Ω], Xc = 58 [kΩ], Cc = 100 pF
Step Down Transformer	Cp = 150 pF, Rp = 400 [Ω], Xc = 2997 [Ω], Rs = 0.001 [Ω], Xs = 0.001 [Ω], ratio = 6584/115 Winding coupling (magnetizing slope): I = 0.001421 [A], Ψ = 13.7867 [Vs]
Ferroresonance Suppression Circuit (FSC)	Rf = 40 [Ω], Cf = 9.6 [µF]
FSC Transformer (representing reactance)	Winding coupling (representing Lf): I = 0.1 [A], Ψ = 0.035 [Vs]
FSC Transformer (winding leakage reactance and resistance	Rp = 0.02 [Ω], Xp = 0.02 [Ω], Rs = 0.001 [Ω], Xs = 0.001 [Ω], ratio = 1.98/1

Table 6: 230kV CCVT Data.

Appendix B – ATP/EMTP Reference Files for Simulating the Basic System Model

The ATP/EMTP files used for simulating the basic system model of Fig. 1 are provided here. The user can use these files directly in ATP/EMTP and obtain simulation results. Different fault scenarios and configurations, as described in Sections 10 and 12 can be simulated, with suitable changes to the ATP/EMTP files provided below.

First, a more detailed version of the basic system model is shown below in Fig. 19. The actual node names, as used in the ATP/EMTP reference files are indicated in the figure.
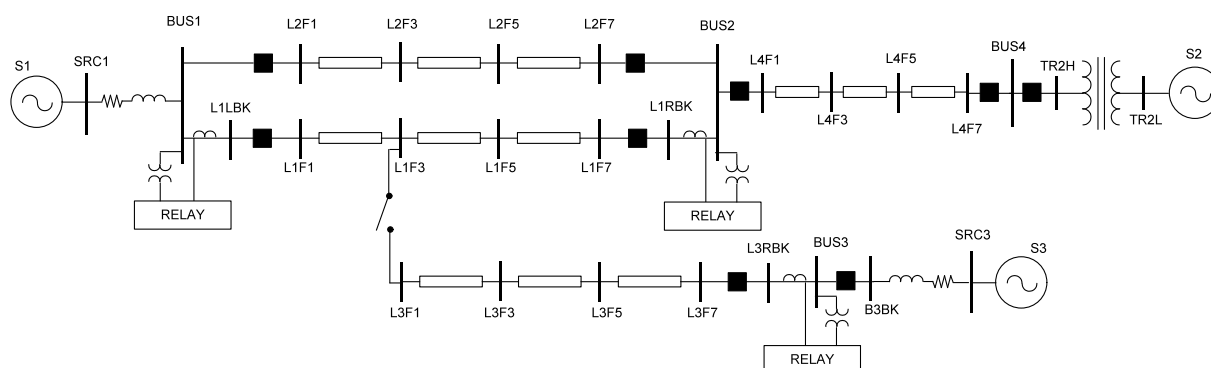
Fig. 19: Detailed Version of Basic System Model with ATP Node Names.

Each of the lines in the above figure consists of three sections, 15 miles each. This gives the user a large number of nodes at which to apply faults.

A number of files are used in the simulation. These are listed below.

B.1 File "Main.dat"

This file is the main input file. The fault related characteristics are specified in this file. Also specified here is the point of connection of the tapped line to Line 1 of the double-circuit line. Voltage outputs, from the secondaries of the CCVTs are also specified here. The file listing follows.

```
C ---------------------------------------------------------------------------
C Main Input file for EMTP reference model.
C
BEGIN NEW DATA CASE
C ==========================================================================
C
C First Misc. Data Card
C
C DELTAT  TMAX     XOPT     COPT    EPSILN   TOLMAT   TSTART
C (SEC)   (SEC)   (0=mH)   (0=uF)
C  1-8    9-16     17-24   25-32   33-40    41-48    49-56
C -----><------><------><------><------><------><------>
```

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```
   5.0E-5  0.2000    60.0        0        0        0        0
C
C ================================================================================
C Second Misc. Data Card
C
C  IOUT    IPLOT   IDOUBL   KSSOUT   MAXOUT   IPUN    MEMSAV    ICAT   NENERG   IPRSUP
C  1-8     9-16    17-24    25-32    33-40    41-48   49-56    57-64   65-72    73-80
C -----><------><------><------><------><------><------><------><------><------>
        5       5       0        0        0        1        0        1
C
C ================================================================================
C Now start the branch cards.
C
C ================================================================================
C Source impedance for source at Bus 1. Connected between SRC1 and BUS1
C
C Bus-->Bus-->===========<-R--><----L----->
51SRC1A BUS1A             6.10       16.70
52SRC1B BUS1B             2.70        8.37
53SRC1C BUS1C
C
C Source impedance for source at Bus 3. Connected between SRC3 and B3Bk
C
C Bus-->Bus-->===========<-R--><----L----->
51SRC3A B3BKA             0.69        4.12
52SRC3B B3BKB             0.34        4.77
53SRC3C B3BKC
C
C Instrument Transformer Branch data. Required on lines L1 and L3.
C
C CT on Line 1, connected between BUS1 and L1LBK
$INCLUDE L1LCT.PCH
C VT on Line 1, connected to BUS1
$INCLUDE L1LVT.PCH
C
C Double Circuit Line L1-L2
$INCLUDE L1L2_FULL_LINE.PCH
C
C CT on Line 1, far end, connected between BUS2 and L1RBK
$INCLUDE L1RCT.PCH
C VT on Line 1, far end, connected to BUS2
$INCLUDE L1RVT.PCH
C
C Line L3
$INCLUDE L3_FULL_LINE.PCH
C
C CT and VT at far end of Line L3.
C CT between BUS3 and L3RBK, VT at BUS3
$INCLUDE L3RCT.PCH
$INCLUDE L3RVT.PCH
C
C Line L4
$INCLUDE L4_FULL_LINE.PCH
C
C Two winding transformer between TR2H and TR2L
$INCLUDE BUS2_XFMR.PCH
C
C ================================================================================
BLANK ENDS BRANCH DATA
C ================================================================================
C Begin Switch Data
C ================================================================================
C
```

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```
C Line L1 local breaker L1LBK to L1F1
C Bus-->Bus--><-Tclose-><--Topen-><--Nstep-><-Vflash-><Request->Bus-->Bus-->***I
  L1LBKAL1F1A       -1.0      10.0
  L1LBKBL1F1B       -1.0      10.0
  L1LBKCL1F1C       -1.0      10.0
C Line L1 far end breaker L1RBK to L1F7
  L1RBKAL1F7A       -1.0      10.0
  L1RBKBL1F7B       -1.0      10.0
  L1RBKCL1F7C       -1.0      10.0
C
C Line L2, local breaker BUS1 to L2F1
  BUS1A L2F1A       -1.0      10.0
  BUS1B L2F1B       -1.0      10.0
  BUS1C L2F1C       -1.0      10.0
C Line L2, far end breaker BUS2 to L2F7
  BUS2A L2F7A       -1.0      10.0
  BUS2B L2F7B       -1.0      10.0
  BUS2C L2F7C       -1.0      10.0
C
C jumper between Line L1 and Line L3. First node on Line L3 is L3F1.
C L3F1 is connected to L1F3, which is at 15 miles from Bus1.
C Connect L3F1 to L1F5 for 30 miles from BUS1 or
C connect L3F1 to L1F7 for 45 miles from BUS1.
  L1F3A L3F1A       -1.0      10.0
  L1F3B L3F1B       -1.0      10.0
  L1F3C L3F1C       -1.0      10.0
C Breaker at Far end of Line L3, L3RBK to L3F7
  L3RBKAL3F7A       -1.0      10.0
  L3RBKBL3F7B       -1.0      10.0
  L3RBKCL3F7C       -1.0      10.0
C Breaker between BUS3 and B3BK (to which SRC3 is connected)
  BUS3A B3BKA       -1.0      10.0
  BUS3B B3BKB       -1.0      10.0
  BUS3C B3BKC       -1.0      10.0
C
C Breaker between BUS2 and First node of L4, L4F1
  BUS2A L4F1A       -1.0      10.0
  BUS2B L4F1B       -1.0      10.0
  BUS2C L4F1C       -1.0      10.0
C Breaker between BUS4 and Last node of L4, L4F7
  BUS4A L4F7A       -1.0      10.0
  BUS4B L4F7B       -1.0      10.0
  BUS4C L4F7C       -1.0      10.0
C
C Breaker between BUS4 and Transformer High side TR2H
  BUS4A TR2HA       -1.0      10.0
  BUS4B TR2HB       -1.0      10.0
  BUS4C TR2HC       -1.0      10.0
C
C Fault Switch. Applied at L1F1 which is close-in to BUS1, line side of
C breaker. Fault is applied at 0.05 sec. Permanent fault.
C Bus-->Bus--><-Tclose-><--Topen-><--Nstep-><-Vflash-><Request->Bus-->Bus-->***I
  L1F1A             0.05      10.0
C
C ==========================================================================
BLANK ENDS SWITCH DATA
C ==========================================================================
C Begin Source Cards
C
C SRC1
C Bus--><I<Amplitude<Frequency<- Angle-><-------A1<-------T1<---Tstart<----Tstop
14SRC1A   194367.         60.0      31.8                          -1.0
14SRC1B   194367.         60.0     -88.2                          -1.0
```

```
14SRC1C   194367.        60.0    151.8                                  -1.0
C
C SRC3
C Bus--><I<Amplitude<Frequency<- Angle-><-------A1<-------T1<---Tstart<----Tstop
14SRC3A   175024.        60.0     40.0                                  -1.0
14SRC3B   175024.        60.0    -80.0                                  -1.0
14SRC3C   175024.        60.0    160.0                                  -1.0
C
C Type 59 SM at SRC2
$INCLUDE MACHINE_DATA.PCH
C
BLANK ENDS SOURCE DATA
C ==============================================================================
C Begin Output Requests
C ==============================================================================
C Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->Bus-->
C BUS1A BUS1B BUS1C BUS3A BUS3B BUS3C
C TR2LA TR2LB TR2LC
  L1LVTAL1LVTBL1LVTCL1RVTAL1RVTBL1RVTCL3RVTAL3RVTBL3RVTC
C
C ==============================================================================
BLANK ENDS OUTPUT REQUESTS
BLANK ENDS PLOT REQUEST
BEGIN NEW DATA CASE
BLANK CARD TO END RUN
```

B.2 File "L1L2_Full_Line.pch"

This file contains the constant parameter line model for the double-circuit line.

```
C     **** UNTRANSPOSED K.C. Lee line calculated at   6.000E+01 HZ. ****
C     The transformation matrix was calculated at  6.00000000E+01 Hz.
C     Section 1 - 15 miles
C
$VINTAGE, 1
-1L1F1A L1F3A             6.11029E-01 1.30049E+03 1.28660E+05-1.50000E+01 1  6
-2L1F1B L1F3B             9.58016E-02 4.54611E+02 1.82388E+05-1.50000E+01 1  6
-3L1F1C L1F3C             9.59887E-02 4.21643E+02 1.82529E+05-1.50000E+01 1  6
-4L2F1C L2F3C             9.52755E-02 3.70705E+02 1.82544E+05-1.50000E+01 1  6
-5L2F1B L2F3B             9.54029E-02 3.36217E+02 1.82226E+05-1.50000E+01 1  6
-6L2F1A L2F3A             9.54567E-02 3.43427E+02 1.82321E+05-1.50000E+01 1  6
$VINTAGE, 0
  0.34248435  0.37686792 -0.51222924 -0.49786925 -0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195  0.46772318 -0.01991821  0.00334012  0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723  0.37310266  0.48705695  0.50211060 -0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723 -0.37310266  0.48705695 -0.50211060  0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195 -0.46772318 -0.01991821 -0.00334012 -0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34248435 -0.37686792 -0.51222924  0.49786925  0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
C
C     **** UNTRANSPOSED K.C. Lee line calculated at   6.000E+01 HZ. ****
C     The transformation matrix was calculated at  6.00000000E+01 Hz.
C     Section 2 - 15 miles
C
$VINTAGE, 1
```

```
-1L1F3B L1F5B                 6.11029E-01 1.30049E+03 1.28660E+05-1.50000E+01 1  6
-2L1F3C L1F5C                 9.58016E-02 4.54611E+02 1.82388E+05-1.50000E+01 1  6
-3L1F3A L1F5A                 9.59887E-02 4.21643E+02 1.82529E+05-1.50000E+01 1  6
-4L2F3A L2F5A                 9.52755E-02 3.70705E+02 1.82544E+05-1.50000E+01 1  6
-5L2F3C L2F5C                 9.54029E-02 3.36217E+02 1.82226E+05-1.50000E+01 1  6
-6L2F3B L2F5B                 9.54567E-02 3.43427E+02 1.82321E+05-1.50000E+01 1  6
$VINTAGE, 0
  0.34248435  0.37686792 -0.51222924 -0.49786925 -0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195  0.46772318 -0.01991821  0.00334012  0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723  0.37310266  0.48705695  0.50211060 -0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723 -0.37310266  0.48705695 -0.50211060  0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195 -0.46772318 -0.01991821 -0.00334012 -0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34248435 -0.37686792 -0.51222924  0.49786925  0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
C
C     **** UNTRANSPOSED K.C. Lee line calculated at   6.000E+01 HZ. ****
C     The transformation matrix was calculated at  6.00000000E+01 Hz.
C     Section 3 - 15 miles
C
$VINTAGE, 1
-1L1F5C L1F7C                 6.11029E-01 1.30049E+03 1.28660E+05-1.50000E+01 1  6
-2L1F5A L1F7A                 9.58016E-02 4.54611E+02 1.82388E+05-1.50000E+01 1  6
-3L1F5B L1F7B                 9.59887E-02 4.21643E+02 1.82529E+05-1.50000E+01 1  6
-4L2F5B L2F7B                 9.52755E-02 3.70705E+02 1.82544E+05-1.50000E+01 1  6
-5L2F5A L2F7A                 9.54029E-02 3.36217E+02 1.82226E+05-1.50000E+01 1  6
-6L2F5C L2F7C                 9.54567E-02 3.43427E+02 1.82321E+05-1.50000E+01 1  6
$VINTAGE, 0
  0.34248435  0.37686792 -0.51222924 -0.49786925 -0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195  0.46772318 -0.01991821  0.00334012  0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723  0.37310266  0.48705695  0.50211060 -0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.51218723 -0.37310266  0.48705695 -0.50211060  0.33184337 -0.28275890
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34694195 -0.46772318 -0.01991821 -0.00334012 -0.53205266  0.57852453
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
  0.34248435 -0.37686792 -0.51222924  0.49786925  0.32680261 -0.29215880
  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000  0.00000000
```

B.3 File "L1L2CT.pch"

This file contains the CT model for the local end of Line L1.

```
C 2000/5 Current transformer.
C TYPE 98 Element on the CT secondary side
C CT Primary terminals are BUS1A,B,C to L1LBKA,B,C
C CT Secondary terminals: L1LCTA,B,C
C
C Current ratio
C        1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890123456789 0
  TRANSFORMER                     CT2000
          9999
01BUS1A L1LBKA             1.E-5 1.E-5  5.
```

```
02CTSC0A                      1.E-5 1.E-5 2000.
C
  TRANSFORMER                            CT2000
          9999
01BUS1B L1LBKB                1.E-5 1.E-5  5.
02CTSC0B                      1.E-5 1.E-5 2000.
C
  TRANSFORMER                            CT2000
          9999
01BUS1C L1LBKC                1.E-5 1.E-5  5.
02CTSC0C                      1.E-5 1.E-5 2000.
C
C CT Wire resistance
C       1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
  CTSC0AL1LCTA                .75
  CTSC0BL1LCTB                .75
  CTSC0CL1LCTC                .75
C
C Nonlinear magnetizing inductance:
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
98CTSC0A                      0.01980.2851
C Current ----->Flux ---------->
          0.0198              0.2851
          0.0281              0.6040
          0.0438              1.1141
          0.0565              1.5343
          0.0694              1.8607
          0.1025              2.2771
          0.2167              2.6522
          0.7002              3.0234
          1.0631              3.1098
          15.903              3.2261
    9999.
98CTSC0B      CTSC0A          0.01980.2851
98CTSC0C      CTSC0A          0.01980.2851
C
C Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  L1LCTA                      4.0000                                       1
  L1LCTB                      4.0000                                       1
  L1LCTC                      4.0000                                       1
C
```

Notice the "1" in the last column of the CT secondary. This generates a current output from the simulation.

B.4 File "L1LVT.pch"

This file contains the CCVT model for the local end of Line L1.

```
C CCVT Data.
C Line 1, Local End.
C Primary: BUS1A,B,C
C Secondary: L1LVTA,B,C
C
C Coupling Capacitors C1, C2:
C       1         2         3         4         5         6         7         8
```

```
C 3456789012345678901234567890123456789012345678901234567890123456789012345678 90
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  BUS1A DM002A                     .00243
  BUS1B DM002B                     .00243
  BUS1C DM002C                     .00243
  DM002A                           .08200
  DM002B                           .08200
  DM002C                           .08200
C
C Compensating Inductor:
C         1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678 90
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM002ADM003A          228.00 58.E3
  DM002BDM003B          228.00 58.E3
  DM002CDM003C          228.00 58.E3
  DM002ADM003A                     0.0001
  DM002BDM003B                     0.0001
  DM002CDM003C                     0.0001
C
C Ferroresonance Suppression Circuit:
C         1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678 90
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM005A                40.0
  DM005B                40.0
  DM005C                40.0
  L1LVTADM004A                     9.6
  L1LVTBDM004B                     9.6
  L1LVTCDM004C                     9.6
C
  TRANSFORMER                      FSCA
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM004ADM005A          0.02  0.02  1.98
02DM005AL1LVTA          0.01  0.01  1.
C
  TRANSFORMER                      FSCB
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM004BDM005B          0.02  0.02  1.98
02DM005BL1LVTB          0.01  0.01  1.
C
  TRANSFORMER                      FSCC
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM004CDM005C          0.02  0.02  1.98
02DM005CL1LVTC          0.01  0.01  1.
C
C Primary Side Stray Capacitor:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM003A                           .00015
  DM003B                           .00015
  DM003C                           .00015
```

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```
C
C Step-Down Transformer
C
C          1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
  TRANSFORMER                      CCVTA  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->=====================================I
01DM003A                   400. 2997. 6584.
02L1LVTA                   .001  .001  115.
C
  TRANSFORMER                      CCVTB  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
01DM003B                   400.  2997. 6584.
02L1LVTB                   .001  .001   115.
C
  TRANSFORMER                      CCVTC  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
C
01DM003C                   400.  2997. 6584.
02L1LVTC                   .001  .001   115.
C
C Secondary Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->==================================I
  L1LVTA                   100.00
  L1LVTB                   100.00
  L1LVTC                   100.00
C
```

B.5 File "L1RCT.pch"

This file contains the CT model for the remote end of Line L1.

```
C 2000/5 Current transformer.
C TYPE 98 Element on the CT secondary side
C CT Primary terminals are BUS2A,B,C to L1RBKA,B,C
C CT Secondary terminals: L1RCTA,B,C
C
C Current ratio
C          1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
  TRANSFORMER                      CT2000
           9999
01BUS2A L1RBKA             1.E-5 1.E-5  5.
02CTSC1A                   1.E-5 1.E-5 2000.
C
  TRANSFORMER                      CT2000
           9999
01BUS2B L1RBKB             1.E-5 1.E-5  5.
02CTSC1B                   1.E-5 1.E-5 2000.
C
```

```
    TRANSFORMER                       CT2000
            9999
01BUS2C L1RBKC            1.E-5 1.E-5  5.
02CTSC1C                  1.E-5 1.E-5 2000.
C
C CT Wire resistance
C         1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
  CTSC1AL1RCTA            .75
  CTSC1BL1RCTB            .75
  CTSC1CL1RCTC            .75
C
C Nonlinear magnetizing inductance:
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
98CTSC1A                  0.01980.2851
C Current ----->Flux ---------->
         0.0198           0.2851
         0.0281           0.6040
         0.0438           1.1141
         0.0565           1.5343
         0.0694           1.8607
         0.1025           2.2771
         0.2167           2.6522
         0.7002           3.0234
         1.0631           3.1098
         15.903           3.2261
    9999.
98CTSC1B      CTSC1A      0.01980.2851
98CTSC1C      CTSC1A      0.01980.2851
C
C Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->=============================I
  L1RCTA                  4.0000                                          1
  L1RCTB                  4.0000                                          1
  L1RCTC                  4.0000                                          1
C
```

B.6 File "L1RVT.pch"

This file contains the CCVT model for the remote end of Line L1.

```
C CCVT Data.
C Line 1, Remote End.
C Primary: BUS2A,B,C
C Secondary: L1RVTA,B,C
C
C Coupling Capacitors C1, C2:
C         1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->=============================I
  BUS2A DM006A                      .00243
  BUS2B DM006B                      .00243
  BUS2C DM006C                      .00243
  DM006A                            .08200
  DM006B                            .08200
  DM006C                            .08200
C
C Compensating Inductor:
C         1         2         3         4         5         6         7         8
```

```
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM006ADM007A            228.00 58.E3
  DM006BDM007B            228.00 58.E3
  DM006CDM007C            228.00 58.E3
  DM006ADM007A                          0.0001
  DM006BDM007B                          0.0001
  DM006CDM007C                          0.0001
C
C Ferroresonance Suppression Circuit:
C         1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM009A                  40.0
  DM009B                  40.0
  DM009C                  40.0
  L1RVTADM008A                          9.6
  L1RVTBDM008B                          9.6
  L1RVTCDM008C                          9.6
C
  TRANSFORMER                           FSCA
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM008ADM009A            0.02  0.02  1.98
02DM009AL1RVTA            0.01  0.01  1.
C
  TRANSFORMER                           FSCB
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM008BDM009B            0.02  0.02  1.98
02DM009BL1RVTB            0.01  0.01  1.
C
  TRANSFORMER                           FSCC
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
01DM008CDM009C            0.02  0.02  1.98
02DM009CL1RVTC            0.01  0.01  1.
C
C Primary Side Stray Capacitor:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===============================I
  DM007A                                .00015
  DM007B                                .00015
  DM007C                                .00015
C
C Step-Down Transformer
C
C         1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
  TRANSFORMER                           CCVTA  1.E+6
C Current ----->Flux ---------->
  0.001421      13.7867
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->===============================I
```

```
01DM007A                        400.  2997. 6584.
02L1RVTA                        .001  .001  115.
C
  TRANSFORMER                              CCVTB  1.E+6
C Current ----->Flux ---------->
  0.001421      13.7867
    9999.
C
01DM007B                        400.  2997. 6584.
02L1RVTB                        .001  .001   115.
C
  TRANSFORMER                              CCVTC  1.E+6
C Current ----->Flux ---------->
  0.001421      13.7867
    9999.
C
C
01DM007C                        400.  2997. 6584.
02L1RVTC                        .001  .001   115.
C
C Secondary Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->================================I
  L1RVTA                  100.00
  L1RVTB                  100.00
  L1RVTC                  100.00
C
```

B.7 File "L3_Full_Line.pch"

This file contains the lumped parameter model for Line L3, tapped off Line L1.

```
C
C Line 3, Section 1, 15 miles
C
$VINTAGE, 1
 1L3F1A L3F3A             2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L3F1B L3F3B             1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
 3L3F1C L3F3C             1.33607442E+00  7.54892738E+00 -2.15476823E-02
                          1.34686707E+00  8.79786722E+00 -4.13213989E-02
                          2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
C
C Line 3, Section 2, 15 miles
C
$VINTAGE, 1
 1L3F3B L3F5B             2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L3F3C L3F5C             1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
 3L3F3A L3F5A             1.33607442E+00  7.54892738E+00 -2.15476823E-02
                          1.34686707E+00  8.79786722E+00 -4.13213989E-02
                          2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
C
C Line 3, Section 3, 15 miles
C
$VINTAGE, 1
 1L3F5C L3F7C             2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L3F5A L3F7A             1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
```

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```
 3L3F5B L3F7B                     1.33607442E+00  7.54892738E+00 -2.15476823E-02
                                  1.34686707E+00  8.79786722E+00 -4.13213989E-02
                                  2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
```

B.8 File "L3RCT.pch"

This file contains the CT model for the remote end of Line L3.

```
C 2000/5 Current transformer.
C TYPE 98 Element on the CT secondary side
C CT Primary terminals are BUS3A,B,C to L3RBKA,B,C
C CT Secondary terminals: L3RCTA,B,C
C
C Current ratio
C        1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
  TRANSFORMER                     CT2000
          9999
01BUS3A L3RBKA            1.E-5 1.E-5  5.
02CTSC2A                  1.E-5 1.E-5 2000.
C
  TRANSFORMER                     CT2000
          9999
01BUS3B L3RBKB            1.E-5 1.E-5  5.
02CTSC2B                  1.E-5 1.E-5 2000.
C
  TRANSFORMER                     CT2000
          9999
01BUS3C L3RBKC            1.E-5 1.E-5  5.
02CTSC2C                  1.E-5 1.E-5 2000.
C
C CT Wire resistance
C        1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
  CTSC2AL3RCTA                .75
  CTSC2BL3RCTB                .75
  CTSC2CL3RCTC                .75
C
C Nonlinear magnetizing inductance:
C Bus-->Bus-->Bus-->Bus-->Is--->FLXs->=====================================I
98CTSC2A                  0.01980.2851
C Current ----->Flux ---------->
          0.0198         0.2851
          0.0281         0.6040
          0.0438         1.1141
          0.0565         1.5343
          0.0694         1.8607
          0.1025         2.2771
          0.2167         2.6522
          0.7002         3.0234
          1.0631         3.1098
          15.903         3.2261
     9999.
98CTSC2B      CTSC2A      0.01980.2851
98CTSC2C      CTSC2A      0.01980.2851
C
C Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->=============================I
```

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```
  L3RCTA                   4.0000                                                    1
  L3RCTB                   4.0000                                                    1
  L3RCTC                   4.0000                                                    1
C
```

B.9 File "L3RVT.pch"

This file contains the CCVT model for the remote end of Line L3.

```
C CCVT Data.
C Line 3, Remote End.
C Primary: BUS3A,B,C
C Secondary: L3RVTA,B,C
C
C Coupling Capacitors C1, C2:
C          1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===================================I
  BUS3A DM010A                        .00243
  BUS3B DM010B                        .00243
  BUS3C DM010C                        .00243
  DM010A                              .08200
  DM010B                              .08200
  DM010C                              .08200
C
C Compensating Inductor:
C          1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===================================I
  DM010ADM011A              228.00 58.E3
  DM010BDM011B              228.00 58.E3
  DM010CDM011C              228.00 58.E3
  DM010ADM011A                     0.0001
  DM010BDM011B                     0.0001
  DM010CDM011C                     0.0001
C
C Ferroresonance Suppression Circuit:
C          1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->===================================I
  DM013A                   40.0
  DM013B                   40.0
  DM013C                   40.0
  L3RVTADM012A                     9.6
  L3RVTBDM012B                     9.6
  L3RVTCDM012C                     9.6
C
  TRANSFORMER                            FSCA
C Current ----->Flux ---------->
  0.1           0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->=========================================I
01DM012ADM013A            0.02  0.02  1.98
02DM013AL3RVTA            0.01  0.01  1.
C
  TRANSFORMER                            FSCB
C Current ----->Flux ---------->
  0.1           0.035
   9999.
```

```
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->=====================================I
01DM012BDM013B              0.02  0.02  1.98
02DM013BL3RVTB              0.01  0.01  1.
C
   TRANSFORMER                        FSCC
C Current ----->Flux ---------->
  0.1          0.035
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->=====================================I
01DM012CDM013C              0.02  0.02  1.98
02DM013CL3RVTC              0.01  0.01  1.
C
C Primary Side Stray Capacitor:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->=====================================I
  DM011A                              .00015
  DM011B                              .00015
  DM011C                              .00015
C
C Step-Down Transformer
C
C         1         2         3         4         5         6         7         8
C 34567890123456789012345678901234567890123456789012345678901234567890
   TRANSFORMER                        CCVTA  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
C Bus-->Bus-->Bus-->Bus--><-R--><-L-->=====================================I
01DM011A                    400.  2997. 6584.
02L3RVTA                    .001  .001  115.
C
   TRANSFORMER                        CCVTB  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
01DM011B                    400.  2997. 6584.
02L3RVTB                    .001  .001   115.
C
   TRANSFORMER                        CCVTC  1.E+6
C Current ----->Flux ---------->
  0.001421     13.7867
   9999.
C
C
01DM011C                    400.  2997. 6584.
02L3RVTC                    .001  .001   115.
C
C Secondary Burden:
C Bus-->Bus-->Bus-->Bus--><-R--><-L--><-C-->=====================================I
  L3RVTA                    100.00
  L3RVTB                    100.00
  L3RVTC                    100.00
C
```

B.10 File "L4_Full_Line.pch"

This file contains the lumped parameter model for Line L4.

```
C
C Line 4, Section 1, 15 miles
C
$VINTAGE, 1
 1L4F1A L4F3A              2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L4F1B L4F3B              1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
 3L4F1C L4F3C              1.33607442E+00  7.54892738E+00 -2.15476823E-02
                          1.34686707E+00  8.79786722E+00 -4.13213989E-02
                          2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
C
C Line 4, Section 2, 15 miles
C
$VINTAGE, 1
 1L4F3B L4F5B              2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L4F3C L4F5C              1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
 3L4F3A L4F5A              1.33607442E+00  7.54892738E+00 -2.15476823E-02
                          1.34686707E+00  8.79786722E+00 -4.13213989E-02
                          2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
C
C Line 4, Section 3, 15 miles
C
$VINTAGE, 1
 1L4F5C L4F7C              2.74694761E+00  1.98137317E+01  1.82160275E-01
 2L4F5A L4F7A              1.32550570E+00  8.82314492E+00 -4.54680689E-02
                          2.76787292E+00  1.97886069E+01  1.93775227E-01
 3L4F5B L4F7B              1.33607442E+00  7.54892738E+00 -2.15476823E-02
                          1.34686707E+00  8.79786722E+00 -4.13213989E-02
                          2.78969566E+00  1.97631744E+01  1.91971527E-01
$VINTAGE, 0
```

B.11 File "BUS2_XFMR.pch"

This file contains the model for the two-winding unit transformer connected to source S2.

```
C  <++++++>  Cards punched by support routine on  31-Jul-03  12:57:31  <++++++>
C ACCESS MODULE BCTRAN
C $ERASE
C C Excitation Data
C C         1         2         3         4         5         6         7
C C 345678901234567890123456789012345678901234567890123456789012345678
C C <  FREQ  >< IEXPOS >< SPOS  >< LEXPOS >< IEXZERO>< SZERO  >< LEXZERO>NPITIW
C  2      60.0     0.706     725.0    466.603     0.706     725.0    466.603 0 2 2
C C         1         2         3         4         5         6         7
C C 345678901234567890123456789012345678901234567890123456789012345678
C C K< VRAT  ><   R   > <BUS1><BUS2><BUS3><BUS4><BUS5><BUS6>
C  1   132.729    0.1469 TR2HA      TR2HB      TR2HC
C  2     22.8     0.0044 TR2LA TR2LB TR2LB TR2LC TR2LC TR2LA
C C         1         2         3         4         5         6         7
C C 345678901234567890123456789012345678901234567890123456789012345678
C C J< Pij  >< ZPOSij >< SPOS  >< ZZEROij>< SZERO >IDIL
C  1 2 1333.689      9.21     725.0      9.21     725.0 0 0
C BLANK
$VINTAGE, 1,
 1TR2LA TR2LB              3342.8053097774
```

```
 2TR2LB TR2LC               0.0
                            3342.8053097774
 3TR2LC TR2LA               0.0
                            0.0
                            3342.8053097774
  USE RL
$UNITS, 0.60E+02 , 0.
 1TR2HA                                 .1469 10375.336358398
 2TR2LA TR2LB                             0.0 1781.1075402579
                                        .0044 305.95613556856
 3TR2HB                                   0.0          0.0
                                          0.0          0.0
                                        .1469 10375.336358398
 4TR2LB TR2LC                             0.0          0.0
                                          0.0          0.0
                                          0.0 1781.1075402579
                                        .0044 305.95613556856
 5TR2HC                                   0.0          0.0
                                          0.0          0.0
                                          0.0          0.0
                                          0.0          0.0
                                        .1469 10375.336358398
 6TR2LC TR2LA                             0.0          0.0
                                          0.0          0.0
                                          0.0          0.0
                                          0.0          0.0
                                          0.0 1781.1075402579
                                        .0044 305.95613556856
$VINTAGE, 0,
$UNITS, -1.,-1.
  USE RL
C ---------------- << case separator >>> -----------
```

B.12 File "Machine_Data.pch"

This file contains the model for source S2, modeled as a Type 59 S.M.

```
C Synchronous Machine Model Type 59 (SM)
C Rated kV: 24
C Rated MVA: 830
C Ra: 0.00199 pu
C Xl: 0.15
C Xd: 1.89
C Xq: 1.8
C X'd: 0.23
C X'q: 0.435
C X"d: 0.1775
C X"q: 0.177
C T'do: 4.2s
C T'qo: 0.589s
C T"do: 0.031s
C T"qo: 0.063s
C X0: 0.145 pu
C Rn: 0
C Xn: 0 solidly earthed.
C Machine includes 6 masses. However, individual inertia,
C damping etc. are not available. Hence, it is modeled below
C as a single mass machine with WR2 = 678,000 lb-ft^2.
C
C        1         2         3         4         5         6         7         8
```

58

```
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C <BUS > < VOLTS  >< FREQ  >< ANGLE  > Balanced Set
59TR2LA   18616.122     60.0      30.0
59TR2LB
59TR2LC
C          1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C          < EPSUBA >< EMPMEG >< EPOGEL >           < NIOMAX >
TOLERANCES     200.                                   20
C          1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C                            <  FM  >
PARAMETER FITTING            1.0
C
C          1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C KMKE  NP< SMOUTP >< SMOUTQ >< RMVA  >< RKV   >< AGLINE >< S1   >< S2   >
 1 1     2      1.0        1.0      830.0     24.0     600.0      600.0     720.0
BLANK card for quadrature axis of machine.
C Machine data, time-constants
C          1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C  Ra   ><  Xl   ><  Xd   ><  Xq   >< X'd   >< X'q   >< X"d   >< X"q   >
   0.00199     0.15      1.89      1.80      0.23     0.435     0.1775      0.177
C  0.0014     0.175      1.85      1.76     0.2575      1.76      0.18       0.18
C  T'do >< T'qo  >< T"do  >< T"qo  ><  X0   ><  Rn   ><  Xn   >
      4.2     0.589     0.031      0.063      0.16
C  5.74757           0.051142  0.382609  0.197985
C Mass Data Cards
C          1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C          < EXTRS >< HICO  >< DSR   >< DSM   >< HSP   >< DSD   >
 1            1.0     0.678                                      1.0
BLANK card ending all (here, just one) mass cards.
BLANK card terminating all (here, zero) S.M. output requests.
  FINISH
```

Appendix C – ATP/EMTP Auxiliary Program Input Files

In Appendix B, the actual model files that one can use to run ATP/EMTP studies were provided. For example, the file "L1L2_Full_Line.pch" is the constant parameter model of the double-circuit 230kV line. It is important to note that the constant parameter model was generated by running the auxiliary line constants program on a separate input file. The auxiliary program, although part of ATP/EMTP, will still need a file in a specific format, to actually generate the model. In the ATP reference model

For the model in Fig. 1, auxiliary input files were used to generate the transformer, and transmission line models. These input files are listed below.

C.1   Input File for 230kV Double-Circuit Line (first 15 mile section)

```
C CONDUCTOR: Marigold 1113 Kcmil AA, 1.216 inch dia.
C dc resistance 0.09222 ohms/mile at 50 deg. C.
C
C 230kV Constant Parameter Line Model.
C Section 1
C
BEGIN NEW DATA CASE
LINE CONSTANTS
$ERASE
C        1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
BRANCH  L1F1A L1F3A L1F1B L1F3B L1F1C L1F3C L2F1C L2F3C L2F1B L2F3B L2F1A L2F3A
ENGLISH
C        1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
  1 0.50 0.09222 4          1.216    0.00  100.00   73.0    0.00  0.00       0
  2 0.50 0.09222 4          1.216    0.00   83.50   56.5    0.00  0.00       0
  3 0.50 0.09222 4          1.216    0.00   67.00   40.0    0.00  0.00       0
  4 0.50 0.09222 4          1.216   29.00   67.00   40.0    0.00  0.00       0
  5 0.50 0.09222 4          1.216   29.00   83.50   56.5    0.00  0.00       0
  6 0.50 0.09222 4          1.216   29.00  100.00   73.0    0.00  0.00       0
BLANK
C        1         2         3         4         5         6         7         8
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
   50.0      60.0          1 000111 111000 1    15.00     0           1
C
C 3456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
BLANK
$PUNCH
BLANK
BEGIN NEW DATA CASE
BLANK
```

Notice the highlighted keyword "BRANCH" in the file above. Following this keyword, the node names to which the conductors in this section are connected are listed. In this case, the first conductor connects nodes "L1F1A" and "L1F3A"; the second conductor connects nodes "L1F1B" and "L1F3B" and so on.

Also highlighted is the number "15.00" towards the end of the file. This corresponds to the length of the section being 15 miles.

Please remember that to generate the complete 45-mile line model, you will require the auxiliary input files for the other two sections. They are not listed here, but can be obtained by simply changing the node names to which the conductors in that section are connected.

The reference model provided includes three 15-mile sections. Thus, faults can be applied at 0, 33 and 66% of the line length. If you need additional intermediate fault locations, you will need to generate more line-sections. But please remember that when using distributed parameter models, you cannot make the length of the sections arbitrarily short.

C.2 Input File for the Two-Winding Transformer at Source S2

```
C Three-phase two-winding transformer.
C Test-data is in Transformer_Data.doc in this directory.
C High-side: 229893V, Grounded Y
C Low-side : 22800V, Delta
C MVA: 725.
C Excitation test data and short-circuit test data are
C available for the positive sequence only. Assume that
C tests are done with closed-delta, and zero-sequence
C quantities are same as positive sequence.
BEGIN NEW DATA CASE
ACCESS MODULE BCTRAN
$ERASE
C Excitation Data
C         1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C <  FREQ  >< IEXPOS ><  SPOS  >< LEXPOS >< IEXZERO><  SZERO  >< LEXZERO>NPITIWIP
 2     60.0     0.706     725.0    466.603     0.706     725.0    466.603 0 2 2 1
C         1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C K<  VRAT ><    R   > <BUS1><BUS2><BUS3><BUS4><BUS5><BUS6>
  1   132.729    0.1469 TR2HA       TR2HB       TR2HC
  2    22.8      0.0044 TR2LA TR2LB TR2LB TR2LC TR2LC TR2LA
C         1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
C J<  Pij  >< ZPOSij ><  SPOS  >< ZZEROij>< SZERO  >IDIL
 1 2 1333.689      9.21     725.0      9.21     725.0 0 0
BLANK
C         1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
$PUNCH
BLANK
BEGIN NEW DATA CASE
BLANK
```