Fall 2002

Pattern recognition for electric power system protection

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PATTERN RECOGNITION FOR ELECTRIC POWER SYSTEM PROTECTION

by

Yong Sheng, Master of Science in Electrical Engineering

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

November 2002

UMI Number: 3066657

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Date

We hereby recommend that the dissertation prepared under our supervision by YONG SHENG

entitled Pattern Recognition for Electric Power System Protection

be accepted in partial fulfillment of the requirements for the Degree of Ph. D. in Computational Analysis and Modeling

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Director of Graduate Studies

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Approved:
Dean of the Graduate School

GS Form 13
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ABSTRACT

The objective of this research is to demonstrate pattern recognition tools such as decision trees (DTs) and neural networks that will improve and automate the design of relay protection functions in electric power systems. Protection functions that will benefit from the research include relay algorithms for high voltage transformer protection (TP) and for high impedance fault (HIF) detection. A methodology, which uses DTs and wavelet analysis to distinguish transformer internal faults from other conditions that are easily mistaken for internal faults, has been developed. Also, a DT based solution is proposed to discriminate HIFs from normal operations that may confuse relays. Both methods have been verified with simulation data generated by the Electromagnetic Transients Program. Compared with traditional methods, both show better performance. After being trained with a large number of carefully selected features, the desired DTs can obtain an accuracy of greater than 95%. Further, no special equipment is necessary; the DT-based controller only needs the standard relay input signals sampled at 1920 Hz. So far, no one has applied the same methodologies to solve these problems. Even though some future work with experimental data is needed to make the methods more convincing for utilities, the research has already shown that pattern recognition is a promising direction in developing power system protection algorithms.

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ACKNOWLEDGEMENTS

I wish to thank my advisor, Dr. Steven Rovnyak, for his supervision. Without his advice and suggestions during the whole procedure of the research, I could not have gone through the research smoothly. I also wish to thank him for his support and encouragement which enabled me to overcome difficulties in research, study, and life.

I wish to thank my wife, Xiaoling Ye, for her continuous support, encouragement and sacrifice. Without them, I could not concentrate in the research.

And I also wish to thank the Louisiana Board of Regents for the financial support for the research through the Board of Regents Support Fund under contract LEQSF (1999-02)-RD-A-25.

CHAPTER 1

INTRODUCTION

Large transformers are generally protected by percentage current differential relays with restraining algorithms based on second and sometimes fifth harmonics [1]. Pattern recognition techniques are promising for integrating inputs from many sensors and other variables derived from the input stream called features [2]. Averages and harmonics calculated over the most recent cycle are examples of features. In this dissertation we propose additional features that could be used by a pattern recognition tool for transformer protection. We explain how decision trees (DTs) are constructed from simulation data and then evaluated.

For a Δ-Y transformer the CTs can be connected Y-Δ to compensate for the phase difference in the currents that are being compared. The differential current calculation also uses the transformer ratio. A turn to turn fault that shorts part of a winding effectively changes the transformer ratio and causes an increase in the calculated differential current. Turn to earth faults increase the differential current as well. However magnetizing inrush current and CT saturation also increase the differential current. Measures to prevent tripping during inrush and CT saturation limit the dependability of a relay [3].

A high Impedance Fault (HIF) is the headache of most utilities for its difficulty of being detected promptly and accurately. For the public safety and the potential huge expenses incurred if sued for any loss or damages resulting from an energized downed conductor [4][5], utilities often install expensive and sophisticated commercial or self-developed HIF detection devices. Two most commonly installed commercial products are Digital Feeder Monitor (DFM) from General Electric and High Impedance Fault Analysis System (HIFAS) from Nordon Technologies [5].

This dissertation presents a Decision Tree (DT) based solution with reasonable cost to utilities. Regarding the implementation, a microprocessor-based controller would perform the proposed DT and the harmonics calculations. The DT for the results reported here has 45 nodes, which was too large to show here but is straightforward to program. Execution of the trained DT logic is negligible compared to the harmonics calculations. DTs are to be trained off-line from simulation and/or experimental data. DT training is relatively fast so updating with new data is a possibility. If the DT false trips for some reason, the DT could potentially be updated with the samples on which it false detected an HIF. The desired output for these samples would be set to *no* HIF.

The DT uses only feeder current signals, as these are standard substation relaying inputs. Also similar to what most researchers did, some of the feeder current harmonics are used in training the DTs. The DTs trained show excellent performance in 100 test cases. This technique is verified with the aid of Electromagnetic Transients Program (EMTP). The proposed method could also be trained using experimental data and those investigations are recommended using some or all of the techniques described in this dissertation.

CHAPTER 2

WAVELET TRANSFORM

Compared with Fourier transform, a type of one-parameter linear transform, wavelet transform is a kind of two-parameter linear transform that provides a basis for $L^2(\mathbf{R})$. In many wavelet systems the elements of this basis are orthogonal to each other and normalized. Wavelet analysis providing a basis for $L^2(\mathbf{R})$ is similar to the set $\{\cos(n\omega_0 t), \sin(n\omega_0 t) : n \in \mathbf{Z}\}$ forming an orthogonal basis for periodic functions having frequency ω_0. Using a wavelet expansion, any function in $L^2(\mathbf{R})$ can be expressed as a sum of the basis elements

$$f(t) = \sum_{k=-\infty}^{\infty} c_k \varphi(t-k) + \sum_{k=-\infty}^{\infty} \sum_{j=0}^{\infty} d_{j,k} 2^{j/2} \psi(2^j t - k) \qquad (1)$$

Parameter j determines the scale or the frequency range of each wavelet basis function ψ. Parameter k determines the time translation. The defining characteristic of a wavelet or multi-resolution system is that $\varphi(t)$ satisfies a scaling equation such as

$$\varphi(t) = \sum_{k=-\infty}^{\infty} h[k] \sqrt{2}\, \varphi(2t-k) \qquad (2)$$

for some sequence $h[k]$ that is usually finite. The wavelet function $\psi(t)$ is derived from $\varphi(t)$. Each coefficient can be calculated as the inner product between $f(t)$ and the respective basis element. The L^2 inner products and alternative notation for the coefficients in (1) are

$$c[\mathrm{k}] \equiv c_k = \int_{-\infty}^{\infty} f(t)\, \varphi(t-k)\, dt \qquad (3)$$

$$d_j[\mathrm{k}] \equiv d_{j,k} = \int_{-\infty}^{\infty} f(t)\, 2^{j/2}\, \psi(2^j t - k)\, dt$$

The $c[k]$ are called approximation coefficients and the $d_j[k]$ are called detail coefficients. The approximation coefficients together are comparable to the DC value in a Fourier expansion. The Haar wavelet system is the earliest and simplest. Its basis elements are translated and scaled versions of the following functions.

$\varphi(t) = 1$ for $t \in (0,1)$ and $\varphi(t) = 0$ otherwise.

$\psi(t) = 1$ for $t \in (0,0.5)$, $\quad \psi(t) = -1$ for $t \in (0.5,1)$, (4)

and $\psi(t) = 0$ otherwise.

The wavelet function $\psi(t)$ is somewhat similar to one period of $\sin(2\pi t)$. At a particular scale j the translates $\psi(2^j t - k)$ line up right next to each other without overlapping for $k \in \mathbf{Z}$. The integral for calculating a Fourier coefficient covers multiple periods of the sine in the integrand for second and higher order harmonics. For example with a period $T = 1$ the second Fourier sine coefficient is calculated as in (5).

$$a_2 = \int_0^1 2 f(t) \sin(4\pi t)\, dt. \qquad (5)$$

$a_2 = \int 2 f(t) \sin(4\pi t)\, dt$.

In the wavelet expansion or decomposition

$d_1[0]$ is comparable to $\int_0^{0.5} 2 f(t) \sin(4\pi t)\, dt$,

$d_1[1]$ is comparable to $\int_{0.5}^{1} 2 f(t) \sin(4\pi t)\, dt$.

Actually for the Haar wavelet system

$$d_1[0] = 2^{1/2}\,[\int_{0}^{0.25} f(t)\,dt - \int_{0.25}^{0.5} f(t)\,dt]\,, \tag{6}$$

$$d_1[1] = 2^{1/2}\,[\int_{0.5}^{0.75} f(t)\,dt - \int_{0.75}^{1} f(t)\,dt]\,.$$

The present application will look at one electrical cycle of measurements sampled at 1920 Hz on a 60 Hz system (32 samples/cycle). The number of samples limits the number of independent wavelet coefficients similar to the DFT. For 32 samples there can be 5 levels (d_0-d_4) in the wavelet decomposition. If $\{y[k]$ where $k = 0$ to $31\}$ are samples of a function between 0 and 1, the Haar wavelet coefficients can be calculated as

$$c_0[0] = 2^{-5}\sum_{k=0}^{31} y[k]$$

$$d_0[0] = 2^{-5}\,[\sum_{k=0}^{15} y[k] - \sum_{k=16}^{31} y[k]]$$

$$d_1[0] = 2^{-9/2}\,[\sum_{k=0}^{7} y[k] - \sum_{k=8}^{15} y[k]]$$

$$d_1[1] = 2^{-9/2}\,[\sum_{k=16}^{23} y[k] - \sum_{k=24}^{31} y[k]]$$

$$d_2[0] = 2^{-4}\,[\sum_{k=0}^{3} y[k] - \sum_{k=4}^{7} y[k]] \tag{7}$$

$$d_2[1] = 2^{-4}\,[\sum_{k=8}^{11} y[k] - \sum_{k=12}^{15} y[k]]$$

$$d_2[2] = 2^{-4}\,[\sum_{k=16}^{19} y[k] - \sum_{k=20}^{23} y[k]]$$

.

.

$d_4[13] = 2^{-3}\,[y[26] - y[27]\,]$

$d_4[14] = 2^{-3}\,[y[28] - y[29]\,]$

$d_4[15] = 2^{-3}\,[y[30] - y[31]\,]$

Each wavelet coefficient of a discrete signal can be calculated as a weighted sum in other wavelet systems as well. The calculation can also be realized with discrete-time filter banks using FIR filters [6][7]. The Matlab wavelet toolbox numbers the levels in reverse of what has been presented in this dissertation as shown in Table 1.

Table 1. Numbering of Detail Coefficients

This Dissertation	**Matlab**
$d_4[0], \ldots, d_4[15]$	$D_1[0], \ldots, D_1[15]$
$d_3[0], \ldots, d_3[7]$	$D_2[0], \ldots, D_2[7]$
$d_2[0], \ldots, d_2[3]$	$D_3[0], \ldots, D_3[3]$
$d_1[0], d_1[1]$	$D_4[0], D_4[1]$
$c_0[0], d_0[0]$	$A_5[0], D_5[0]$

CHAPTER 3

EMTP SIMULATIONS

Electromagnetic Transient Program (EMTP) [8] is a commercial computer program which is used to simulate electromagnetic, electromechanical, and control system transients on multiphase electric power systems. Because of its popularity and wide acceptance, it has become the *de facto* standard in the electric power industry. Alternative Transients Program (ATP) is the royalty-free version of EMTP. During the research, ATP was first used as the simulation tool; later we switched to EMTP for its powerful output processing and graphing abilities.

The basic work of EMTP is solving the Ordinary Differential Equations (ODEs) and/or algebraic equations associated with an arbitrary but reasonable interconnection of different electrical (power system) and control system components. The numerical methods, such as implicit trapezoidal rule of integration, are used to discretize the differential-algebraic equations. Like most numerical solutions, the selection of time step sometimes is critical in order to avoid numerical oscillations. Further, the program also provides a procedure called Critical Damping Adjustment (CDA) to eliminate oscillations.

EMTP offers supporting routines providing additional capabilities for use in simulations. In our research, BCTRAN and HYSDAT are the two most commonly used auxiliary routines. The former outputs data in a format suitable for a three-phase transformer model with testing data as input. The latter generates data for the hysteretic inductor.

Transformer Internal Fault Simulations

Three-phase EMTP simulations of a 230/34.5kV Δ-Y transformer with grounded neutral connected to a generator by a 50 km transmission line were run. A load on the secondary was represented as impedance.

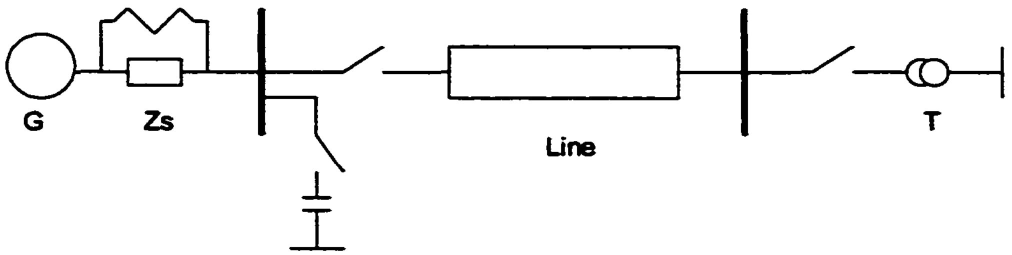


Figure 1. One-Phase System Diagram for Transformer Internal Fault Simulation

As shown in Figure 1, G is an ideal source of 230 kV; the equivalent source impedance Zs has $Z_1 = 0.135 + j0.845\%$ @ 100 MVA and $Z_0 = 0.105 + j0.640\%$ @ 100 MVA. The transmission line has line to line voltage of 230 kV. The conductors are single ACSR 954,000 cmil cables having parameters shown in Table 2. The spacing between conductors is: a to b = 7 meters and b to c = 7 meters. The conductors are 10 meters off the ground (average). The pole is a typical one as shown in Figure 2.

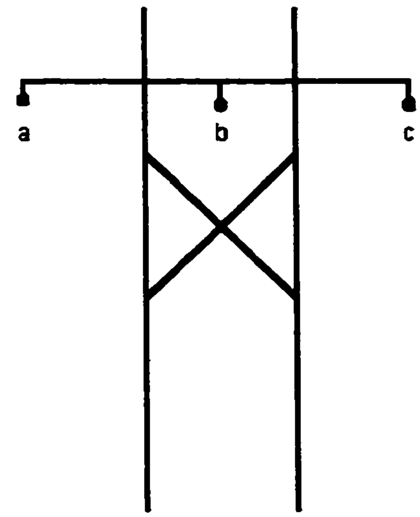


Figure 2. Transmission Line Pole

Table 2. Conductor Parameters

Code Word	Size (kcmil)	Diameter (ins)		Resistance (ohms/1000ft)	
		Steel Core	Complete Cable	DC (20 °C)	AC (75 °C)
Rail	954	0.2913 (0.7399 cm)	1.165 (2.9590 cm)	0.0180 (0.0591 Ω/km)	0.0225 (0.0738 Ω/km)
Cardinal	954	0.3987 (1.0127 cm)	1.196 (3.0378 cm)	0.0179 (0.0587 Ω/km)	0.0228 (0.0748 Ω/km)

The transformer is 230/34.5 kV, Δ/Y connected. Test data are shown in Table 3.

Table 3. Transformer Testing Data

Power rating	18/24/32 MVA
Excitation (no load) loss	23.0 kW
Short circuit (load) loss	70.2 kW
Positive sequence reactance	7.65% @ 18 MVA

In order to simulate the inrush current, a nonlinear element with hysteresis was used. A typical hysteresis loop is shown in Figure 3.

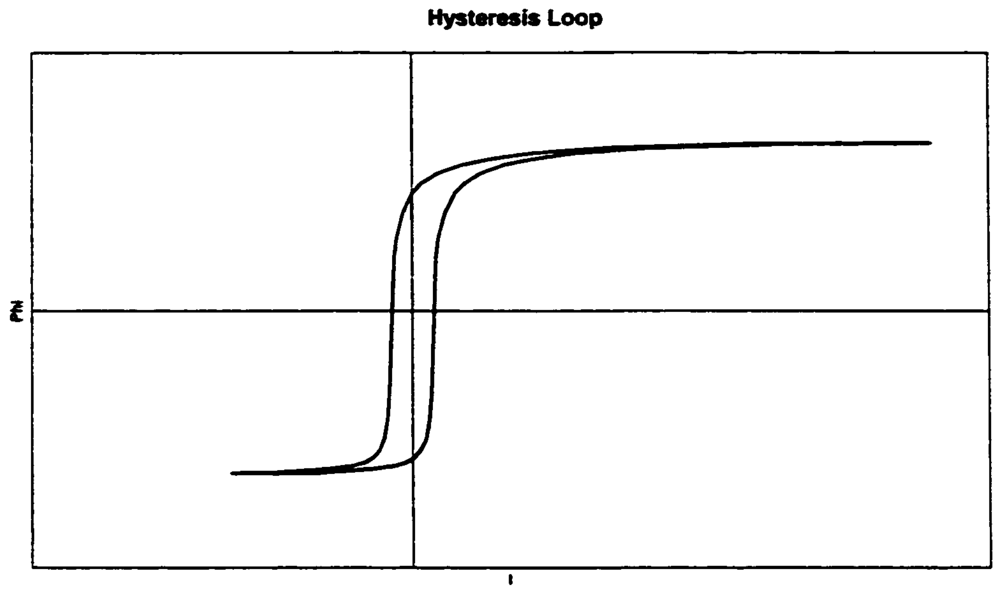


Figure 3. Hysteresis Loop

We simulated the phenomena shown in Table 4. Each simulation lasted eight cycles and saturable Current Transformer (CT) models [9] were always used. We adjusted the CT parameters so that saturation would occur during severe internal and external fault conditions and potentially confuse a current differential relay. In a practical application one would want to model the actual CTs accurately and possibly include some variation in the CT parameters similar to what is described in the section on running simulations for training data. Two well accepted models of transformer internal faults proposed by Bastard *et al* [10] were applied in the research. Appendix A contains examples of EMTP simulations.

Table 4. Simulations

Condition	Attributes Varied
all conditions	load impedance and phase angle for switch-on
inrush	remnant flux
external fault	one or three-phase
turn to turn fault	two locations
turn to earth fault	one location

Simulations for Training Data

Using a pattern recognition methodology it is easy to include new counterexamples in the training data. The first DT performed much worse on the first test set compared with the results presented here. For the results on TP we added the original 486 training simulations and the original 100 test simulations together into a new training set. Then we created a new test set with different random variations. Thus the training set contained 100 faults with random variations in addition to the 486 deterministic faults described in the next paragraph for a total of 586 simulations.

The two locations of a turn to turn fault are probably fairly close together. For the deterministic data, we simulate turn to turn faults shorting 2%, 4%, and 6% of the winding. Each length of turn to turn fault is simulated to occur centered at 20%, 50%, and 80% along the length of the entire winding. Our model for a transformer is only valid for faults within approximately 10-90% of the winding. Turn to earth faults are simulated to occur at 20%, 50%, and 80% of the winding. We simulate one three-phase and two single-phase solid short circuit to ground external faults. One single-phase fault involves the phase being protected and the other single-phase fault involves either of the remaining phases. For inrush simulation with different values of remnant flux we disconnected the transformer for 2 cycle, 23/12 cycle, ..., 13/12 cycle prior to the eight cycles of inrush simulation. Load Z with a lagging power factor of 0.8 was selected to draw 30%, 70%, and 110% of the transformer rated MVA. The phase angle for switch-on was varied as 0°, 30°, ... , 150°. The number of deterministic simulations in the training set can be counted as 6 angles * 3 loads * [12 inrush + 3 external + 9 turn to turn + 3 turn to earth] = 486 deterministic simulations.

Simulations for Test Data

There are 100 simulations in the test set. We simulate 25 turn to turn faults shorting a random percent of the winding and centered in a random location. The random percent is to be selected in the interval [0, 0.05], which means from 0% to 5%, and the random center is in the interval [0.2, 0.8]. Twenty-five turn to earth faults are simulated at random locations in [0.2, 0.8]. We simulate 25 single-phase low-impedance circuit to ground external faults. The external fault impedance is a random value in [0, 1] Ohms. Fifteen of the single-phase external faults occur on the line being monitored and 10 are on another line. For inrush we simulate 25 random remnant flux values by disconnecting the transformer for a random interval between one and two cycles. In each simulation the load Z has a lagging power factor of 0.8 and a per unit magnitude in [.3, 1.1] of the transformer rated MVA. The phase angle for switch-on is a random value in [0, 180] degrees.

High Impedance Fault Simulations

The one-line diagram of a 60 Hz distribution system is given in Figure 4. Four overhead feeders are connected to a 138/12.5 kV substation transformer, which is served by a 50 km transmission line from a bus considered to be infinite. Assume HIF faults occur near the end of a 5 km feeder that serves an industrial user having a load transformer and 1800 kVar of shunt capacitors. The loads have a lagging power factor equal to 0.80.

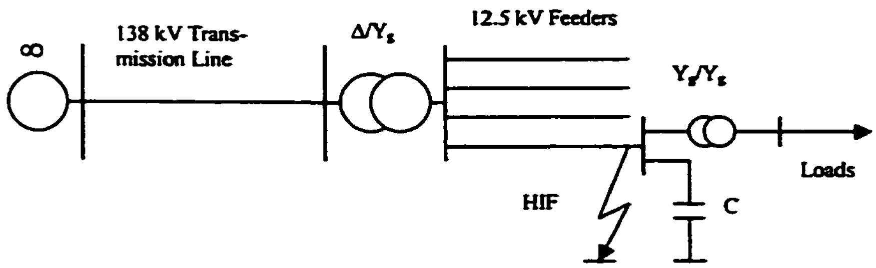


Figure 4. One-Line Diagram of a Distribution System for Simulation

The modeling of most distribution system components is quite straightforward, including infinite source, transmission line, feeders, shunt capacitors, circuit breakers, and loads. For the transformers, BCTRAN has been used to build their models. However, the most difficult model is the HIF fault because most HIF phenomena involve arcing, which has not been accurately modeled so far. Some previous researchers have reached certain agreement that HIF is nonlinear and asymmetric, and modeling should include random and dynamic qualities of arcing. Emanuel *et al* presented two DC sources connected in anti-parallel with two diodes to simulate zero periods of arcing and asymmetry [11]. Yu and Khan used combinations of nonlinear resistors [12]. Wai and Xia introduced a sophisticated TACS switch controlling the open/close loop of HIF to reach nonlinearity and asymmetry [6]. In this dissertation, a more dynamic and random HIF model is applied. It combines most advantages of previous models proposed while it remains simple and universal.

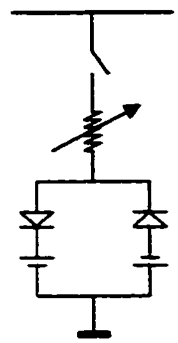


Figure 5. HIF Model

The HIF model, as shown in Figure 5, consists of a nonlinear resistor, two diodes, and two DC sources that change amplitudes randomly every half cycle. Thus some dynamics and randomness are represented. Changing the mean and standard deviation of the DC source voltage amplitudes could be used to more closely approximate different ground surfaces such as asphalt, sand, or grass. A typical HIF current and its frequency spectrum are shown in Figures 6 and 7. Compared with real life HIF current waveforms that are appropriately conditioned and low-pass filtered, such as the one shown in Figure 8 of [13] by Russell and Chinchali, the current waveform in Fig. 6 shows a nearly perfect match.

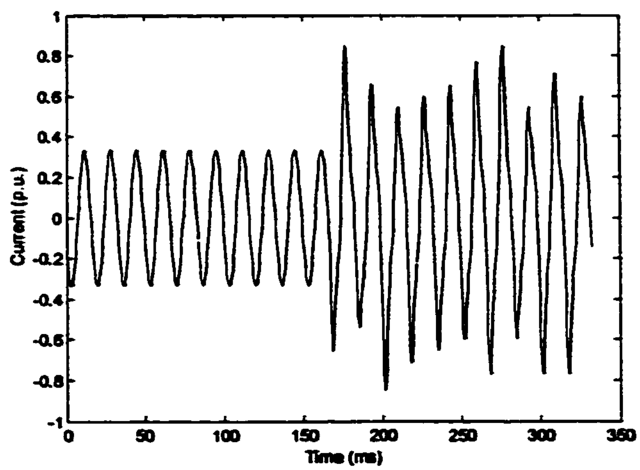


Figure 6. Typical HIF Current Waveform

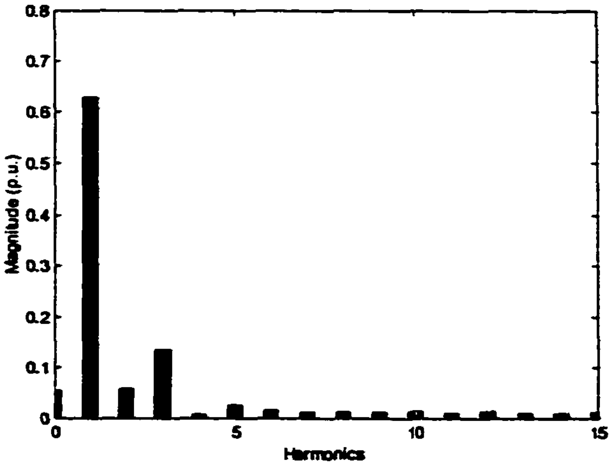


Figure 7. Spectrum of HIF Current Corresponding to Figure 6

EMTP Simulations

The following events have been studied to distinguish HIF faults from normal operations: 3-phase or single phase load switching, shunt capacitor switching, no-load transformer switching, and HIF with or without downed conductor. For all load switching events, the power factor is kept unchanged, namely equal to 0.80. We also assume that no more than one event occurs simultaneously. EMTP input files, corresponding to different events, are generated by a C++ program according to the following rules.

Training data:

- Phase of infinite source varies from 0 to 150 degrees in increments of 30 degrees for all events, namely, 0, 30, 60, ..., 150 degrees.
- Six 3-phase load changes: 30% ↔ 70%, 70% ↔ 110%, 30% ↔ 110%.
- Eight single phase load changes: 30% ↔ 40%, 60% ↔ 70%, 70% ↔ 80%, 100% ↔ 110% on each phase for a total of 8 x 3 = 24 load changes.
- No-load transformer is energized and then cut off at different times in a cycle to obtain different remnant flux in the iron core of the load

transformer. The cut off occurs at 1/12, 2/12, ..., and 12/12 cycle.

- The following events were repeated for loads at 30%, 70%, and 110% of their base-case amounts.
- Shunt capacitors are switched on or off.
- Five random configurations are selected as described below and repeated for downed and not downed conductors for a total of 10 HIF events. In each configuration, the central value, V_C, is randomly selected from the set {1000, 2000, ..., 5000} V. The two DC sources are then set to a_1 V_C and a_2 V_C where a_1 and a_2 are selected randomly from {-25%, -20%, ..., 25%}.

The grand total of training cases is hence equal to 6x(6+8x3+12+3x(2+5x2))=468 cases.

Test data:

- Phase of infinite source equals a random value in the interval [0, 180] degrees. This notation means $0° < \phi < 180°$.
- 25 events of load switching. The loads are randomly either 3 phase or single phase. For single-phase switches, the initial load, L_1, is randomly selected from the interval [30%, 110%], and the load after switching is randomly selected from [L_1-10%, L_1+10%]. Also the switching occurs randomly on or off the monitored phase. For three phase switches, both initial and final loads are randomly chosen from the interval [30%, 110%]. Switching between the two levels occurs at the starting moment of the 8-cycle window.
- 25 events of no-load transformer switching. The cut off time, after no-load

transformer is energized, is randomly picked in the interval [0, 1] cycle.

- Shunt capacitors have been randomly switched either on or off for 25 times with random loads in the interval [30%, 110%].
- 25 events of HIF faults. The central value for the HIF model, V_C, is randomly selected from [1000, 5000] V, and two DC sources are chosen in the same way as for training events. The conductor is randomly either downed or not downed and the loads are randomly chosen in [30%, 110%].

The number of test cases is 25x4=100.

One difficulty in EMTP simulations is to get random magnitudes of DC sources on every half cycle. In Figure 6, it can be easily inferred that any DC source should change its magnitude during the open period of the diode with which it is in series. If bad timing occurs, abrupt changes will be observed on current waveforms. A C++ program, which implements trial and correction methodology, is used to find the appropriate changing times.

The output of EMTP is 32 points per cycle, which simulates a 1920 Hz sampling rate. In order to take advantage of the powerful computation ability of Matlab, the optional MCAT package has been installed for EMTP. The ICAT field in the second miscellaneous data card is set to 3 so that EMTP exports data in Matlab form.

The data and programs developed for this dissertation are included in Appendices B and C.

CHAPTER 4

PATTERN RECOGNITION

Generally speaking, pattern recognition is a type of learn-by-example mathematical tools, which are extremely useful for the problems that cannot be solved with analytical methods. Other artificial intelligence (AI) techniques include neural networks, expert systems, and decision trees. The common idea behind all AI techniques is to mimic functions of human brains, which can associate and recognize input patterns.

DTs are capable of classifying input vectors into discrete categories such as $\{0,1\}$. It is based on the principle that many separation boundaries can be approximated by combinations of hyperplanes that are parallel to coordinate axes. The advantages of DTs include fast training compared with other popular pattern recognition tools, such as neural networks.

For HIF detection problems, several efforts have been made to implement pattern recognition methods. GE's DFM is based on an expert system with nine algorithms [5]. Kim and Russell also proposed expert systems [14], and Ebron *et al* introduced a neural network based method verified with simulation data [15].

Transformer Internal Fault

We trained DTs to recognize internal faults using the wavelet detail coefficients $d_3[k]$ and other features. Training data consists of input-output pairs derived from a large number of simulations. Three-phase simulations involving various instances of inrush, CT saturation, internal and external faults were performed using EMTP. The conversion of simulation data into input-output pairs for DT training is accomplished using methodology similar to training a DT to act like an R-Rdot relay [16]. The DT training software [17] allows the user to specify a parameter called relative misclassification cost. Misclassification cost is the consequence of misclassification in the objective function that is minimized during DT training. This parameter can be used to adjust the tendency of the relay to false trip versus fail to trip.

The following design was motivated by the desire to extract features that would remain approximately constant if the input stream were quasi-periodic. The vector to be processed by wavelet analysis is first normalized as in [18]. Calculating the L^2 inner product with scaled and translated copies of the wavelet function is actually similar to the transversal or matched filters in [18]. In the present application we sort the 8 $d_3[k]$ coefficients in order of size. Each detail coefficient $d_3[k]$ measures activity in 1/8 cycle time frame. A new input vector is calculated and processed by the DT every 1/8 cycle, which is every four samples. If the input signal were periodic, then the elements of the unsorted input vector ($d_3[0], \dots , d_3[7]$) would rotate as the one-cycle window progressed. Thus each successive cycle of detail coefficients from a quasi-periodic signal contains approximately the same values as the previous cycle but in a different order. Ideally one might like to rearrange the detail coefficients so the one-cycle window started in the same place every time. This could be a future area of research. In any case, we sorted the $d_3[k]$ coefficients from smallest to largest.

The following describes the input-output pair creation and the selection of the desired output for a classifier that distinguishes *fault* from *no fault*. It is also possible to train a classifier to distinguish whether CT saturation or inrush is present but we will use a global approach [3] in this dissertation. A case refers to an input-output pair, which contains an input vector along with the desired output, *i.e.* the output the classifier is supposed to assign this input vector. Let 1 indicate that the desired output for a case is *fault*. Let 0 indicate that the desired output for a case is *no fault*. Let ($d_3[0], \ldots, d_3[63]$) represent the vector of Matlab level 2 detail coefficients from an 8 cycle simulation and suppose that the simulation does not contain a fault. The desired output for all cases created from this simulation will be *no fault*. The variable $I_D[0\text{-}7]$ represents the RMS differential current averaged over the one-cycle interval corresponding to $d_3[0]$ - $d_3[7]$. The variable $I_R[0\text{-}7]$ represents the RMS restraining current, which is the sum rather than the difference of the two currents. The variable $I_P[0\text{-}7]$ is the percent differential current, which is the ratio of the differential current and the restraining current. We also calculate several second and fifth harmonics and include them in the DT input vector for comparison with the proposed wavelet coefficient features. The variable $I_{D2}[0\text{-}7]$ is the second harmonic component of the differential current, and $I_{D5}[0\text{-}7]$ is the fifth harmonic of I_D. The harmonic coefficient magnitude calculated as in (8) was always normalized by dividing it by the RMS value of the signal over the cycle being analyzed. Variables $I_{R2}[0\text{-}7]$, $I_{R5}[0\text{-}7]$ are harmonics from the restraining current, and $I_{S2}[0\text{-}7]$, $I_{S5}[0\text{-}7]$ are sums of second and fifth harmonic coefficient magnitudes of all primary and secondary currents. The calculation for the second harmonic from 32 samples is as follows:

$$a_2 = \sum_{k=0}^{31} \frac{2}{32} y[k] \sin(4\pi k/32)$$
$$b_2 = \sum_{k=0}^{31} \frac{2}{32} y[k] \cos(4\pi k/32) \qquad (8)$$
$$I_2 = \sqrt{a_2^{\,2} + b_2^{\,2}}$$

The 57 input-output pairs derived from an 8-cycle simulation with no fault are indicated in Table 5.

Table 5. Input-Output Pairs From an 8-cycle Simulation with No Fault

Unsorted Input Vector Variables	**Desired Output**
$d_3[0]$, ... , $d_3[7]$, $I_D[0\text{-}7]$, $I_R[0\text{-}7]$, $I_P[0\text{-}7]$, $I_{D2}[0\text{-}7]$, $I_{D5}[0\text{-}7]$, $I_{R2}[0\text{-}7]$, $I_{R5}[0\text{-}7]$, $I_{S2}[0\text{-}7]$, $I_{S5}[0\text{-}7]$	0
$d_3[1]$, ... , $d_3[8]$, $I_D[1\text{-}8]$, $I_R[1\text{-}8]$, $I_P[1\text{-}8]$, $I_{D2}[1\text{-}8]$, $I_{D5}[1\text{-}8]$, $I_{R2}[1\text{-}8]$, $I_{R5}[1\text{-}8]$, $I_{S2}[1\text{-}8]$, $I_{S5}[1\text{-}8]$	0
:	:
:	:
$d_3[56]$, ... , $d_3[63]$, $I_D[56\text{-}63]$, $I_R[56\text{-}63]$, $I_P[56\text{-}63]$, $I_{D2}[56\text{-}63]$, $I_{D5}[56\text{-}63]$, ... , $I_{S2}[56\text{-}63]$, $I_{S5}[56\text{-}63]$	0

We similarly collect cases from simulations of fault conditions. The desired output for these cases is *fault*, if and only if a fault was present during the cycle of data that the measurements represent. In our simulation the fault was present for the entire simulation as shown in Table 6. Probably a four-cycle simulation length would be sufficient.

Table 6. Input-Output Pairs from an 8-cycle Simulation with a Fault

Unsorted Input Vector Variables	**Desired Output**
$d_3[0]$, ... , $d_3[7]$, $I_D[0\text{-}7]$, $I_R[0\text{-}7]$, $I_P[0\text{-}7]$, $I_{D2}[0\text{-}7]$, $I_{D5}[0\text{-}7]$, $I_{R2}[0\text{-}7]$, $I_{R5}[0\text{-}7]$, $I_{S2}[0\text{-}7]$, $I_{S5}[0\text{-}7]$	1
$d_3[1]$, ... , $d_3[8]$, $I_D[1\text{-}8]$, $I_R[1\text{-}8]$, $I_P[1\text{-}8]$, $I_{D2}[1\text{-}8]$, $I_{D5}[1\text{-}8]$, $I_{R2}[1\text{-}8]$, $I_{R5}[1\text{-}8]$, $I_{S2}[1\text{-}8]$, $I_{S5}[1\text{-}8]$	1
:	:
:	:
$d_3[56]$, ... , $d_3[63]$, $I_D[56\text{-}63]$, $I_R[56\text{-}63]$, $I_P[56\text{-}63]$, $I_{D2}[56\text{-}63]$, $I_{D5}[56\text{-}63]$, ... , $I_{S2}[56\text{-}63]$, $I_{S5}[56\text{-}63]$	1

Options for DT Training and Relay Testing

In addition to building DTs using all the variables in Tables 3 and 4, we constructed DTs using only subsets of these variables. The "standard" features in Tables V and VI refer to I_D, I_R, I_P. The harmonics are I_{D2}, I_{D5}, I_{R2}, I_{R5}, I_{S2}, I_{S5}, and the wavelets are $d_3[n]$, ... , $d_3[n+7]$. DTs were trained using CART [17] software, which allows the user to specify several variables including one called misclassification cost. We specified during the DT training that the cost of a false trip on an individual input-output pair is 10 times the cost of a failure to trip. The resulting performance is about right because the DT has 10 or 9 opportunities to trip during each simulation, as explained in the section below. We set a complexity parameter that limited the trees to about 10-20 nodes. A DT having too many nodes is likely to over-fit the training data and will probably not work well on new test data. We reduced the number of false trips by requiring the DT to output *trip* on two consecutive input vectors. Table 7 shows the DT performance if the proposed relay is programmed to operate on the first *trip* output from the DT. Table 8 shows the DT performance if the relay is programmed to operate only after two consecutive *trips*. The DT decision on each input vector is independent of its decision on other input vectors. The DT is memoryless but the relay has a memory if it is programmed to operate only after multiple consecutive trips. The discussion in the following section refers to the *relay* output, which could be programmed to require one or several consecutive *trip* outputs from the DT classifier.

High Impedance Fault

Each simulation lasts ten cycles, of which eight cycles are picked up for further processing. Only current signals are processed and made available to DTs. Most commonly used features of HIF faults, which have been reinforced with either field or simulation data, including RMS value, amplitudes of 2^{nd}, 3^{rd}, and 5^{th} harmonics relative to the RMS value, and phase of 3^{rd} harmonics, are grouped into the input vectors of DTs. All the values are calculated on one cycle window, which consists of 32 sampling points. In order to make values comparable for different cases, amplitudes of harmonics have been normalized by dividing by the RMS value of the signal over the window being analyzed. The window slides 1/8 cycle (4 sampling points) between calculations. An eight-cycle interval contains 57 of these windows. Features calculated from one window together with the desired output are defined as a *case* and the 8-cycle interval is called an *event* so there are 57 cases per event and they all have the same desired output. The desired output is the output the classifier is supposed to produce for that input vector. A Matlab program does all the processing, including reading data from EMTP output files, doing Fast Fourier Transform (FFT), and writing input-output pairs into a data file in the format required by CART DT software [17].

The desired outputs *yes* or *no* are represented as 1 or 0. For the training set, 288 events or 16416 cases have outputs of 0; 180 events or 10260 cases have outputs of 1. For the test set, 25 events implying 1425 cases are associated with 1, and 75 events containing 4275 cases are paired with 0.

CHAPTER 5

RESULTS

Transformer Internal Fault

For a simulation without an internal fault the *relay* must output *no trip* for every set of measurements extracted from that simulation in order to have operated correctly. Otherwise the relay is said to have *false tripped* on that simulation. For a simulation with an internal fault we require the relay to output trip at least once during the first 10 input vectors it sees. Otherwise the relay is judged to have *failed to trip* on that simulation. The first ten cases correspond to the first 1.25 cycles of the simulation. Using these criteria and a relative misclassification cost of 10 during DT training the performances on the test data are shown in Tables 7 and 8. The numbers in Tables 7 and 8 are misclassified cases out of one hundred (100) simulations. Table 8 shows a 3% improvement from using the wavelet coefficients in addition to the harmonics.

Table 7. Performance of Relay Requiring One Trip from DT

Features Used	**False Trip**	**Failure to Trip**
Standard	5	27
Standard + Harmonic	2	4
Standard + Wavelet	2	3
Standard + Harmonic + Wavelet	5	1

Table 8. Performance of Relay Requiring Two Consecutive Trips from DT

Features Used	False Trip	Failure to Trip
Standard	5	30
Standard + Harmonic	1	6
Standard + Wavelet	2	3
Standard + Harmonic + Wavelet	3	1

High Impedance Fault

Four hundred and sixty-eight events containing 26676 cases have been used to train the DTs. The DT training software, CART, allows the user to specify a parameter called relative misclassification cost, which can be used to adjust the tendency of the misclassification of 1 to 0 versus 0 to 1. This parameter specifies the consequence of misclassification. The misclassification cost for 0 to 1 is set to be 10 times bigger than that for 1 to 0 to make it much difficult for a 0 to be classified as a 1.

One hundred events consisting of 5700 cases are used in testing the DTs previously trained. The raw DT output for these 5700 cases requires further processing to decide whether the proposed DT based controller produced the correct output for every case in the event. The criterion used here is similar to studies of R-Rdot relays [15] in which two consecutive 1's from the DT are required to output *yes* from the DT based relay. This also gives the reason for setting relative misclassification cost. For an event with a fault, it ideally should consist of 57 cases of 1's. If the DT makes some mistakes and misclassifies some 1's as 0's, it can be seen that this event is much more error tolerant even though scores of cases may have been misclassified. On the other hand, for an event with no fault, it is much more vulnerable to mistakes the DT may make. Two misclassifications of 0 as 1 result in a wrong judgment if they are consecutive.

The results based on the test set of 100 events are perfect. The DTs distinguish all

25 events of HIF from 75 events of normal operations in two cycles. In other words, the DT in fact produces two consecutive 1 outputs during the first two cycles for every HIF in the test set. No false operations occur during the entire 8 cycles of each normal event.

CHAPTER 6

CONCLUSION

This dissertation proposes a methodology to construct DTs from simulation data. Using a pattern recognition methodology it is feasible to include new counterexamples in the training data until errors on new data are low. For example, the DT for transformer protection (TP) was trained on 100 random simulations in addition to the 486 deterministic simulations that were originally conceived. These 100 simulations were from the first test set. This DT performed quite well on a new test set having different random numbers.

We propose a sorted vector of wavelet coefficients as additional features for the pattern recognition tool input vector. Wavelet features performed favorably in TP compared with a variety of second and fifth harmonic coefficients. Requiring two or more consecutive trips from the DT in order to operate the relay can sometimes reduce the number of false trips without increasing the number of failures to trip.

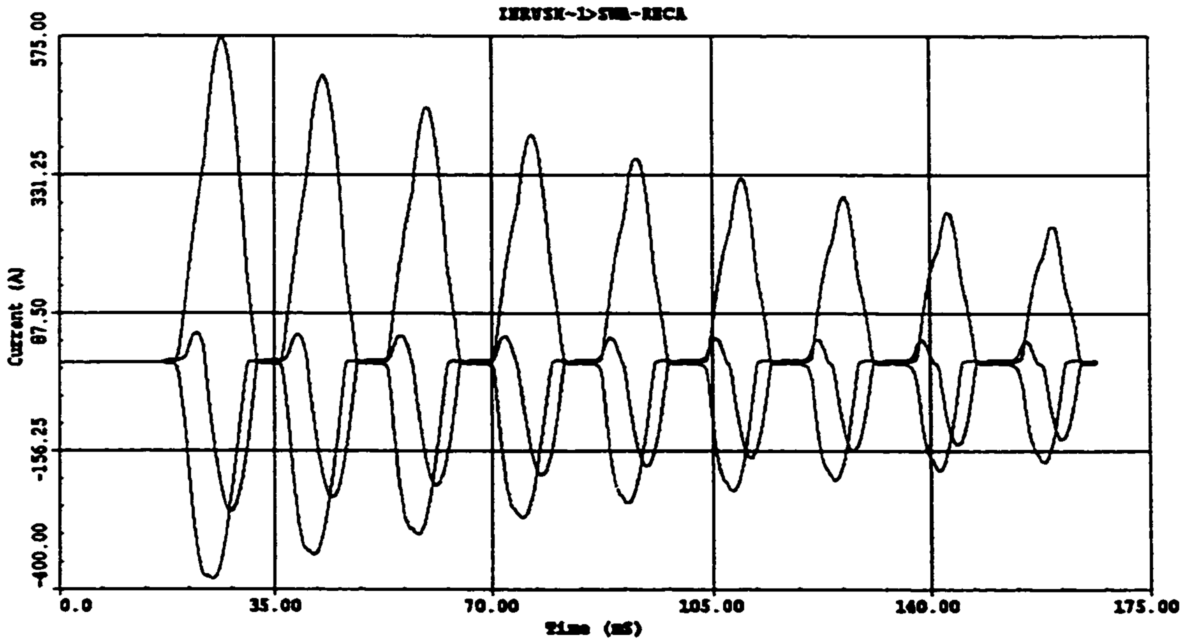
A decision tree based method is also proposed to detect HIF faults using the well-known features: phase current (in RMS), magnitudes of 2^{nd}, 3^{rd}, and 5^{th} harmonics, and phase of 3^{rd} harmonics. Excellent results are obtained on simulation data using EMTP. The DT training and testing could also be performed on experimental data and doing so appears to be a promising future direction. Another requirement for HIF detectors is low cost. The only measurements required for the method proposed here are the current signals for each phase sampled at the rate of 1920Hz.

A new HIF model is also presented in this dissertation. The HIF model consists of a nonlinear resistor, two diodes, and two DC sources that change amplitudes randomly every half cycle. Thus some dynamics and randomness are represented in the randomly changing DC values. Perhaps wavelet coefficients could be used to improve the performance of DTs for HIF detection on experimental data in case the need arises.

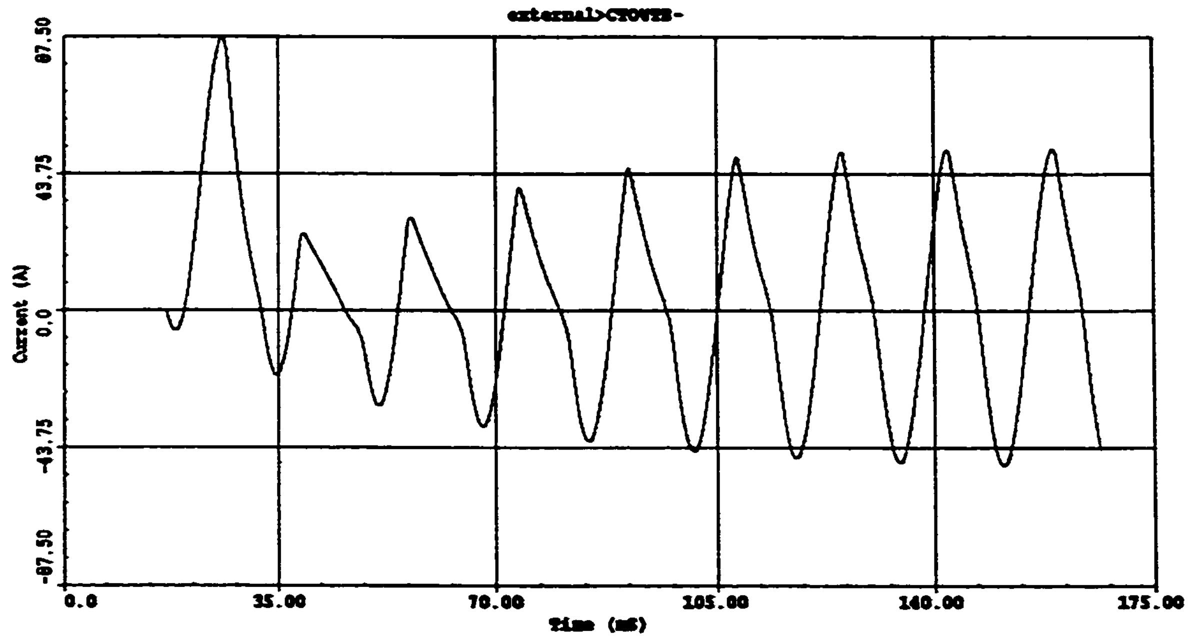
APPENDIX A

EMTP OUTPUT

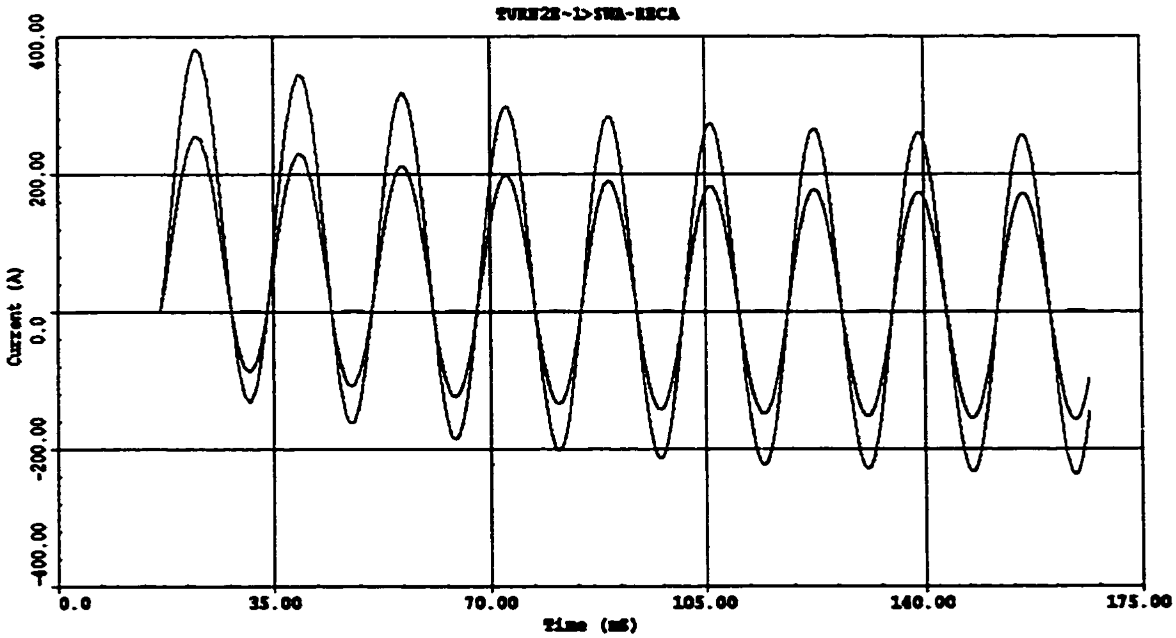
Transformer Inrush Current



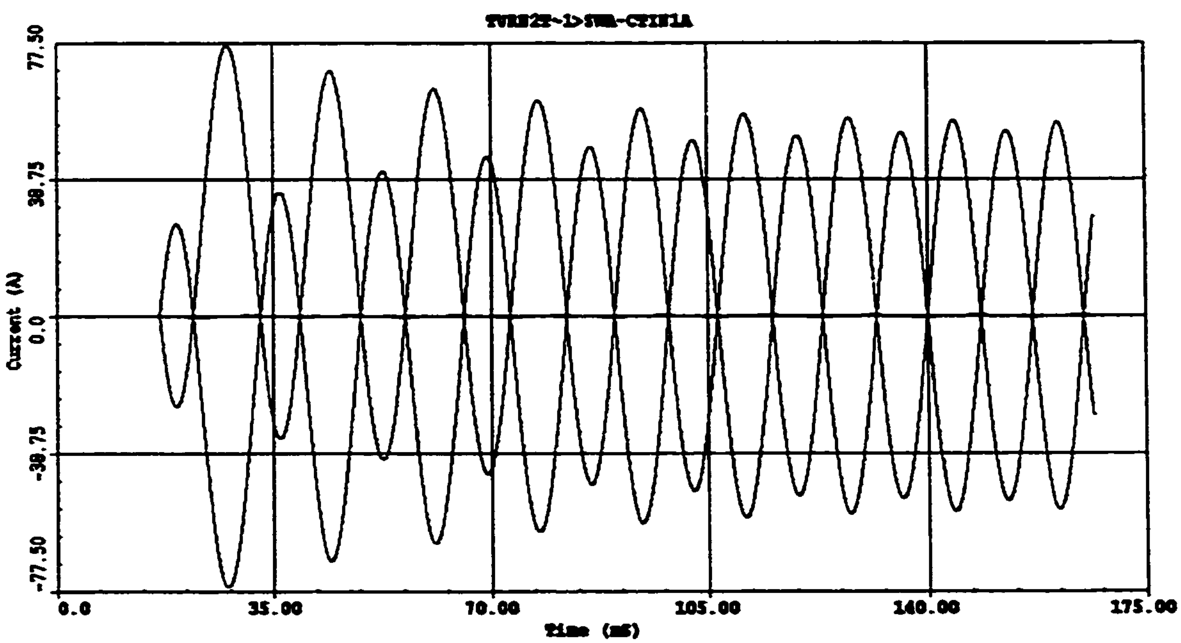
CT Saturation Current



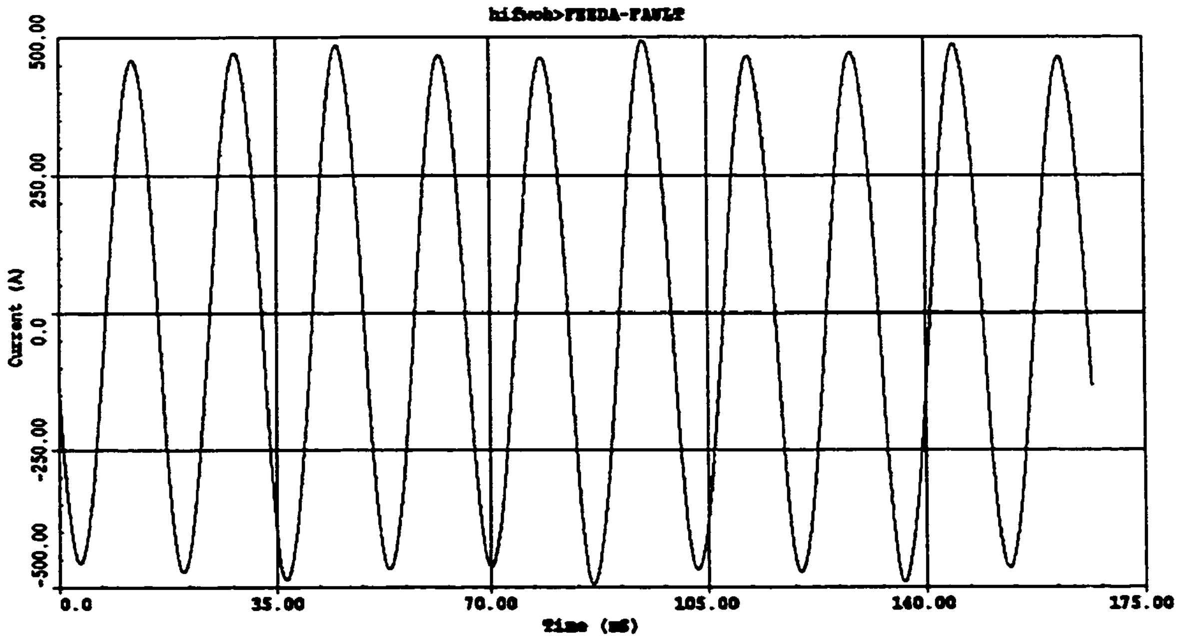
Turn to Earth Fault Current



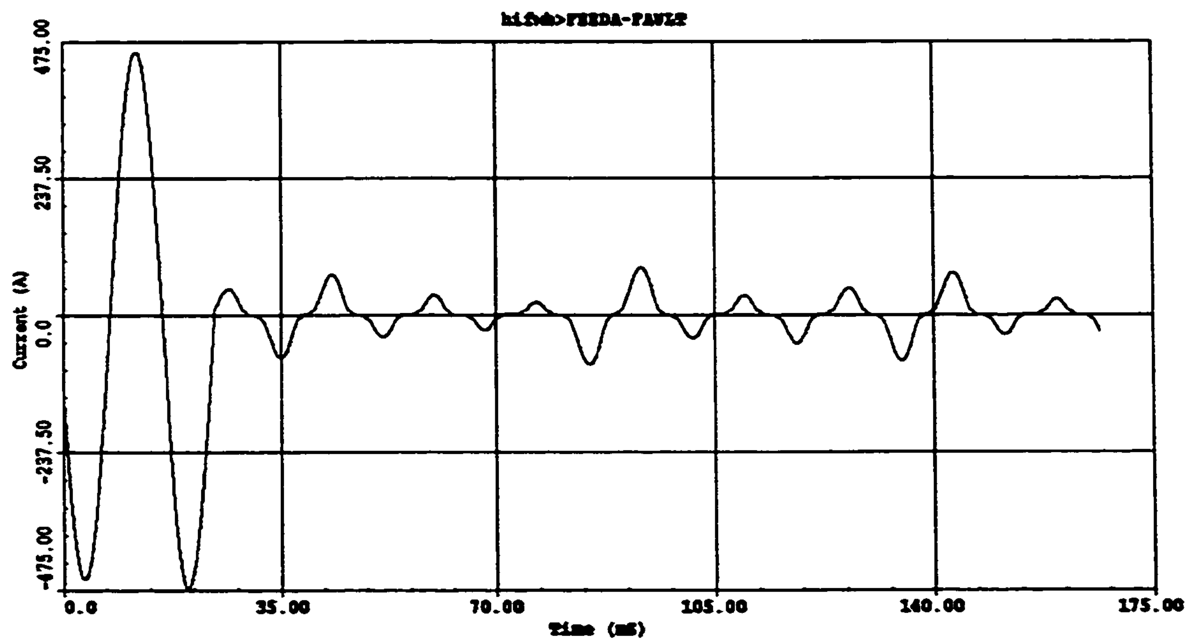
Turn to Turn Fault Current



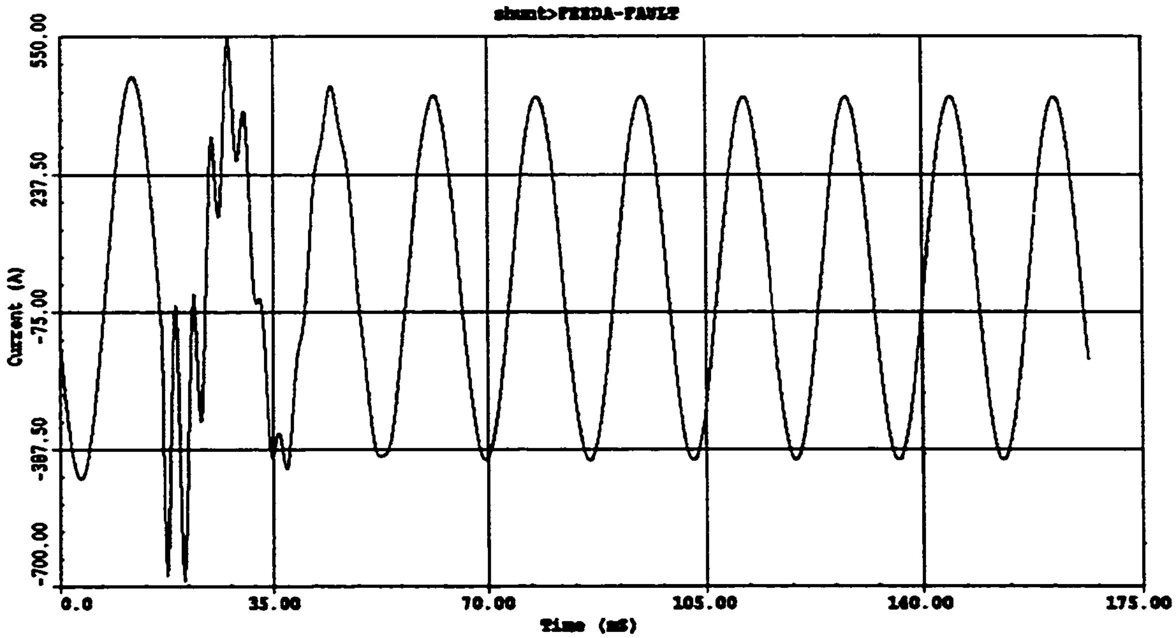
HIF without Broken Conductor



HIF with Broken Conductor



Capacitor Switch on Current



APPENDIX B

EMTP INPUT FILES

Transformer Inrush Current

```
BEGIN NEW DATA CASE
C Miscellaneous Data Card ....
C  dT  >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Huge resistance instead of open circuit makes model of CT to work
  LOADA                   1.E12                                                1
  LOADB       LOADA                                                            1
  LOADC       LOADA                                                            1
C Nonlinear element represents hysteresis
96TERA  TERN              8888.     0.
 -0.96825002E+02 -0.65618825E+02
 -0.64550000E+02 -0.65223529E+02
 -0.29047501E+02 -0.63839998E+02
 -0.12910000E+02 -0.62456471E+02
 -0.48412498E+01 -0.61270588E+02
  0.16137499E+01 -0.58898822E+02
  0.56481249E+01 -0.56131764E+02
  0.93597496E+01 -0.51388235E+02
  0.11296250E+02 -0.43482353E+02
  0.12910000E+02 -0.31623529E+02
  0.16137500E+02  0.21148235E+02
  0.17751250E+02  0.29251765E+02
  0.22592500E+02  0.39529412E+02
  0.29047501E+02  0.47435294E+02
  0.35179749E+02  0.51388235E+02
  0.45991874E+02  0.55341176E+02
  0.62936247E+02  0.58898822E+02
  0.86335628E+02  0.61665884E+02
  0.11296250E+03  0.63642354E+02
  0.16137500E+03  0.65618825E+02
  0.25820000E+03  0.67200000E+02
  0.35502500E+03  0.67595296E+02
  0.99990000E+04
96TERB  TERN  TERA  TERN
96TERC  TERN  TERA  TERN
C Primary Side CT's internal impendance and burdens
C CT's internal impendance
  SEC21ACTOUTA                .07  .126
C CT Burden .5 Ohm
        CTOUTA                .32   .24                                        1
  SEC21BCTOUTBSEC21ACTOUTA
        CTOUTB      CTOUTA                                                     1
  SEC21CCTOUTCSEC21ACTOUTA
        CTOUTC      CTOUTA                                                     1
C Secondary Side CT's internal impendance and burdens
  SEC22ACTOUPA                .07  .126
        CTOUPA                .32   .24                                        1
  SEC22BCTOUPBSEC22ACTOUPA
        CTOUPB      CTOUPA                                                     1
  SEC22CCTOUPCSEC22ACTOUPA
        CTOUPC      CTOUPA                                                     1
C Generator Impedance
C < n 1>< n 2>            < R  ><    L     >
51SOURCASENDA             .55545     3.38560
52SOURCBSENDB             .71415     4.47005
53SOURCCSENDC
C Transmission Line Parameters
$VINTAGE,1
```

```
 1SENDA SWA                         5.89478E+00      4.21243E+01      1.50001E+02
 2SENDB SWB                         2.88722E+00      1.81725E+01     -2.18592E+01
                                    5.89478E+00      4.21243E+01      1.52734E+02
 3SENDC SWC                         2.88624E+00      1.55596E+01     -8.24160E+00
                                    2.88722E+00      1.81725E+01     -2.18592E+01
                                    5.89478E+00      4.21243E+01      1.50001E+02
$VINTAGE,0
C Transformer Parameters
$VINTAGE, 1
 1TERA  TERN                0.5174990000E+05
 2TERB  TERN                0.0000000000E+00
                            0.5174990000E+05
 3TERC  TERN                0.0000000000E+00
                            0.0000000000E+00
                            0.5174990000E+05
 1RECC  RECA                0.1719250000E+020.1795491095E+08
 2TERA  TERN                0.0000000000E+000.1554882230E+07
                            0.1289436945E+000.1346567221E+06
 3RECA  RECB                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.1719250000E+020.1795491095E+08
 4TERB  TERN                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.1554882230E+07
                            0.1289436945E+000.1346567221E+06
 5RECB  RECC                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.1719250000E+020.1795491095E+08
 6TERC  TERN                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.1554882230E+07
                            0.1289436945E+000.1346567221E+06
$VINTAGE, 0
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  SWA   CTIN1A      -1.    .00833       1.
  SWB   CTIN1B      -1.    .00833       1.
  SWC   CTIN1C      -1.    .00833       1.
  SWA   CTIN1A    .01666       1.                                        1
  SWB   CTIN1B    .01666       1.                                        1
  SWC   CTIN1C    .01666       1.                                        1
  TERN                                            MEASURING
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14SOURCA 0   132790.      60.                                     -1.       1.
14SOURCB 0   132790.      60.     -120.                           -1.       1.
14SOURCC 0   132790.      60.      120.                           -1.       1.
C Primary side CT's three ideal transformers
C Phase A
14TERA          10.       60.       0.0       0.0                  5.      10.
18LOADA          .1CTOUPCSEC22A
C Phase B
14TERB          10.       60.       0.0       0.0                  5.      10.
18LOADB          .1CTOUPASEC22B
C Phase C
14TERC          10.       60.       0.0       0.0                  5.      10.
18LOADC          .1CTOUPBSEC22C
C Secondary side CT's three ideal transformers
C Phase A
14CTIN1A        10.       60.       0.0       0.0                  5.      10.
18RECA           .1       SEC21A
C Phase B
14CTIN1B        10.       60.       0.0       0.0                  5.      10.
18RECB           .1       SEC21B
C Phase C
14CTIN1C        10.       60.       0.0       0.0                  5.      10.
18RECC           .1       SEC21C
```

```
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Turn to Earth Fault

```
BEGIN NEW DATA CASE
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Huge resistance instead of open circuit makes model of CT to work
  LOADA                   1.E12                                                1
  LOADB       LOADA                                                            1
  LOADC       LOADA                                                            1
C Primary Side CT's internal impendance and burdens
C CT's internal impendance
  SEC21ACTOUTA              .07  .126
C CT Burden .5 Ohm
        CTOUTA              .32   .24                                          1
  SEC21BCTOUTBSEC21ACTOUTA
        CTOUTB      CTOUTA                                                     1
  SEC21CCTOUTCSEC21ACTOUTA
        CTOUTC      CTOUTA                                                     1
C Secondary Side CT's internal impendance and burdens
  SEC22ACTOUPA              .07  .126
        CTOUPA              .32   .24                                          1
  SEC22BCTOUPBSEC22ACTOUPA
        CTOUPB      CTOUPA                                                     1
  SEC22CCTOUPCSEC22ACTOUPA
        CTOUPC      CTOUPA                                                     1
C Generator Impedance
C < n 1>< n 2>             < R  ><    L     >
51SOURCASENDA             .55545    3.38560
52SOURCBSENDB             .71415    4.47005
53SOURCCSENDC
C Transmission Line Parameters
$VINTAGE,1
 1SENDA SWA                 5.89478E+00     4.21243E+01     1.50001E+02
 2SENDB SWB                 2.88722E+00     1.81725E+01    -2.18592E+01
                            5.89478E+00     4.21243E+01     1.52734E+02
 3SENDC SWC                 2.88624E+00     1.55596E+01    -8.24160E+00
                            2.88722E+00     1.81725E+01    -2.18592E+01
                            5.89478E+00     4.21243E+01     1.50001E+02
$VINTAGE,0
C Transformer Parameters
$VINTAGE, 1
 1TERA  TERN              0.5175140000E+05
 2TERB  TERN              0.0000000000E+00
                          0.5175140000E+05
 3TERC  TERN              0.0000000000E+00
                          0.0000000000E+00
                          0.5175140000E+05
 1RECC  RECA              0.1719250000E+020.2010584556E+07
 2TERA  TERN              0.0000000000E+000.1740633574E+06
                          0.1289436945E+000.1507432569E+05
 3RECA  T2E               0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
```

```
                          6.87700000000000321786.231213613
 4T2E    RECB             0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+00482389.652277877
                          10.31550000000000724019.020230631
 5TERB   TERN             0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+0069625.3429600000
                          0.0000000000E+00104438.014440000
                          0.1289436945E+000.1507432569E+05
 6RECB   RECC             0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.1719250000E+020.2010584556E+07
 7TERC   TERN             0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.1740633574E+06
                          0.1289436945E+000.1507432569E+05
$VINTAGE, 0
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP >< type  >
  SWA   CTIN1A    .01666       1.                                          1
  SWB   CTIN1B    .01666       1.                                          1
  SWC   CTIN1C    .01666       1.                                          1
  T2E                                                MEASURING
  TERN                                               MEASURING
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1    ><    T1   >< TSTART >< TSTOP  >
14SOURCA 0   132790.       60.                                       -1.        1.
14SOURCB 0   132790.       60.     -120.                             -1.        1.
14SOURCC 0   132790.       60.      120.                             -1.        1.
C Primary side CT's three ideal transformers
C Phase A
14TERA           10.       60.       0.0       0.0                    5.       10.
18LOADA           .1CTOUPCSEC22A
C Phase B
14TERB           10.       60.       0.0       0.0                    5.       10.
18LOADB           .1CTOUPASEC22B
C Phase C
14TERC           10.       60.       0.0       0.0                    5.       10.
18LOADC           .1CTOUPBSEC22C
C Secondary side CT's three ideal transformers
C Phase A
14CTIN1A         10.       60.       0.0       0.0                    5.       10.
18RECA            .1       SEC21A
C Phase B
14CTIN1B         10.       60.       0.0       0.0                    5.       10.
18RECB            .1       SEC21B
C Phase C
14CTIN1C         10.       60.       0.0       0.0                    5.       10.
18RECC            .1       SEC21C
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Turn to Turn Fault

```
BEGIN NEW DATA CASE
```

```
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Huge resistance instead of open circuit makes model of CT to work
  LOADA                       1.E12                                            1
  LOADB       LOADA                                                            1
  LOADC       LOADA                                                            1
C Primary Side CT's internal impendance and burdens
C CT's internal impendance
  SEC21ACTOUTA                  .07   .126
C CT Burden .5 Ohm
        CTOUTA                  .32    .24                                     1
  SEC21BCTOUTBSEC21ACTOUTA
        CTOUTB      CTOUTA                                                     1
  SEC21CCTOUTCSEC21ACTOUTA
        CTOUTC      CTOUTA                                                     1
C Secondary Side CT's internal impendance and burdens
  SEC22ACTOUPA                  .07   .126
        CTOUPA                  .32    .24                                     1
  SEC22BCTOUPBSEC22ACTOUPA
        CTOUPB      CTOUPA                                                     1
  SEC22CCTOUPCSEC22ACTOUPA
        CTOUPC      CTOUPA                                                     1
C Generator Impedance
C < n 1>< n 2>              < R  ><     L     >
51SOURCASENDA               .55545     3.38560
52SOURCBSENDB               .71415     4.47005
53SOURCCSENDC
C Transmission Line Parameters
$VINTAGE,1
 1SENDA SWA                     5.89478E+00     4.21243E+01     1.50001E+02
 2SENDB SWB                     2.88722E+00     1.81725E+01    -2.18592E+01
                                5.89478E+00     4.21243E+01     1.52734E+02
 3SENDC SWC                     2.88624E+00     1.55596E+01    -8.24160E+00
                                2.88722E+00     1.81725E+01    -2.18592E+01
                                5.89478E+00     4.21243E+01     1.50001E+02
$VINTAGE,0
C Transformer Parameters
$VINTAGE, 1
 1TERA  TERN                0.5175140000E+05
 2TERB  TERN                0.0000000000E+00
                            0.5175140000E+05
 3TERC  TERN                0.0000000000E+00
                            0.0000000000E+00
                            0.5175140000E+05
 1RECC  RECA                0.1719250000E+020.2010584556E+07
 2TERA  TERN                0.0000000000E+000.1740633574E+06
                            0.1289436945E+000.1507432569E+05
 3RECA  T2T1                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            6.8770000000000321836.012038285
 4T2T1  T2T2                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+0050219.7282500130
                            1.0745312500000007857.3245126534
 5T2T2  RECB                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+00432182.362346005
                            0.0000000000E+0067479.6586505879
                            9.2409687499999581127.720955848
 6TERB  TERN                0.0000000000E+000.0000000000E+00
                            0.0000000000E+000.0000000000E+00
                            0.0000000000E+0069625.3429600000
                            0.0000000000E+0010878.9598375000
                            0.0000000000E+0093559.0546025000
```

```
                         0.1289436945E+000.1507432569E+05
 7RECB   RECC            0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.1719250000E+020.2010584556E+07
 8TERC   TERN            0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.1740633574E+06
                         0.1289436945E+000.1507432569E+05
$VINTAGE, 0
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  SWA   CTIN1A    .01666       1.                                      1
  SWB   CTIN1B    .01666       1.                                      1
  SWC   CTIN1C    .01666       1.                                      1
  T2T1  T2T2                                         MEASURING
  TERN                                               MEASURING
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14SOURCB 0   132790.      60.                                      -1.        1.
14SOURCC 0   132790.      60.     -120.                            -1.        1.
14SOURCA 0   132790.      60.      120.                            -1.        1.
C Primary side CT's three ideal transformers
C Phase A
14TERA           10.      60.       0.0       0.0                   5.       10.
18LOADA           .1CTOUPCSEC22A
C Phase B
14TERB           10.      60.       0.0       0.0                   5.       10.
18LOADB           .1CTOUPASEC22B
C Phase C
14TERC           10.      60.       0.0       0.0                   5.       10.
18LOADC           .1CTOUPBSEC22C
C Secondary side CT's three ideal transformers
C Phase A
14CTIN1A         10.      60.       0.0       0.0                   5.       10.
18RECA            .1      SEC21A
C Phase B
14CTIN1B         10.      60.       0.0       0.0                   5.       10.
18RECB            .1      SEC21B
C Phase C
14CTIN1C         10.      60.       0.0       0.0                   5.       10.
18RECC            .1      SEC21C
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

HIF with Broken Conductor

```
BEGIN NEW DATA CASE
CDA
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
```

```
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Transmission Line Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SWINGASUBA              .473442.9590
  SWINGBSUBB  SWINGASUBA
  SWINGCSUBC  SWINGASUBA
  SWINGA                              106.07
  SWINGB                              106.07
  SWINGC                              106.07
  SUBA                                106.07
  SUBB                                106.07
  SUBC                                106.07
C Substation Transformer Parameters
$VINTAGE, 1
 1FEEDA                   0.5725300000E+04
 2FEEDB                   -0.283921000E+04
                          0.5725300000E+04
 3FEEDC                   -0.283921000E+04
                          -0.283921000E+04
                          0.5725300000E+04
 1SUBC  SUBA              0.4489642433E+010.9062070852E+06
 2FEEDA                   0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
 3SUBA  SUBB              0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.4489642433E+010.9062070852E+06
 4FEEDB                   0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
 5SUBB  SUBC              0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.4489642433E+010.9062070852E+06
 6FEEDC                   0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
$VINTAGE, 0
C Feeder Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
C Feeder #1
  FEEDA FAULT               .658 1.935                                      1
  FEEDB USER1BFEEDA FAULT
  FEEDC USER1CFEEDA FAULT
  FEEDA                               20.848
  FEEDB                               20.848
  FEEDC                               20.848
  FAULT                               20.848
  USER1B                              20.848
  USER1C                              20.848
C Feeder #2
  FEEDA USER2A              .658 1.935
  FEEDB USER2BFEEDA USER2A
  FEEDC USER2CFEEDA USER2A
  FEEDA                               20.848
  FEEDB                               20.848
  FEEDC                               20.848
  USER2A                              20.848
  USER2B                              20.848
  USER2C                              20.848
C Feeder #3
  FEEDA USER3A              .658 1.935
  FEEDB USER3BFEEDA USER3A
  FEEDC USER3CFEEDA USER3A
  FEEDA                               20.848
```

```
  FEEDB                                 20.848
  FEEDC                                 20.848
  USER3A                                20.848
  USER3B                                20.848
  USER3C                                20.848
C Feeder #4
  FEEDA USER4A                .658 1.935
  FEEDB USER4BFEEDA USER4A
  FEEDC USER4CFEEDA USER4A
  FEEDA                                 20.848
  FEEDB                                 20.848
  FEEDC                                 20.848
  USER4A                                20.848
  USER4B                                20.848
  USER4C                                20.848
C Shunt Capacitors
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SHUNTA                        .3      5760.0
  SHUNTB                        .3      5760.0
  SHUNTC                        .3      5760.0
C Load Transformer Parameters
$VINTAGE, 1
 1      LOAD1A             0.4614840000E+04
 2      LOAD1B             0.0000000000E+00
                           0.4614840000E+04
 3      LOAD1C             0.0000000000E+00
                           0.0000000000E+00
                           0.4614840000E+04
 1LTRANA                   0.7295832596E-010.2644881090E+05
 2LOAD1A                   0.0000000000E+000.8801840054E+04
                           C.8080560687E-020.2929252372E+04
 3LTRANB                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.7295832596E-010.2644881090E+05
 4LOAD1B                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.8801840054E+04
                           0.8080560687E-020.2929252372E+04
 5LTRANC                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.7295832596E-010.2644881090E+05
 6LOAD1C                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.8801840054E+04
                           0.8080560687E-020.2929252372E+04
$VINTAGE, 0
96HYSTRA                     8888.     0.
 -0.15075000E+02 -0.12889412E+02
 -0.10050000E+02 -0.12811765E+02
 -0.45225001E+01 -0.12540000E+02
 -0.20099999E+01 -0.12268235E+02
 -0.75374997E+00 -0.12035294E+02
  0.25124999E+00 -0.11569411E+02
  0.87937499E+00 -0.11025882E+02
  0.14572499E+01 -0.10094118E+02
  0.17587500E+01 -0.85411765E+01
  0.20099999E+01 -0.62117647E+01
  0.25125000E+01  0.41541176E+01
  0.27637499E+01  0.57458824E+01
  0.35175000E+01  0.77647059E+01
  0.45225001E+01  0.93176471E+01
  0.54772498E+01  0.10094118E+02
  0.71606248E+01  0.10870588E+02
  0.97987495E+01  0.11569411E+02
  0.13441875E+02  0.12112941E+02
  0.17587499E+02  0.12501177E+02
  0.25125000E+02  0.12889412E+02
```

```
  0.40200000E+02  0.13200000E+02
  0.55275000E+02  0.13277647E+02
  0.99990000E+04
96HYSTRB      HYSTRA
96HYSTRC      HYSTRA
C Load #1 & #2
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  Z1A                     3.37  2.53
  Z1B         Z1A
  Z1C         Z1A
  Z2A                     3.37  2.53
  Z2B         Z2A
  Z2C         Z2A
C HIF impedance
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
99HIF   DIODE              .01
            4.           1250.
            8.           3500.
           20.           5000.
           40.           6750.
           80.           9000.
         9999
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
C Type-11 switch (diode)
11DIODE DC1
11DC2   DIODE
C Switches to load transformer (5)
C  USER1ALTRANA       -1.    .00833        1.
C  USER1BLTRANB       -1.    .00833        1.
C  USER1CLTRANC       -1.    .00833        1.
  USER1ALTRANA   -.01666       2.
  USER1BLTRANB   -.01666       2.
  USER1CLTRANC   -.01666       2.
C Switch to shunt capacitors (6)
  USER1ASHUNTA   1.01666       2.        1.
  USER1BSHUNTB   1.01666       2.        1.
  USER1CSHUNTC   1.01666       2.        1.
C Switch to HIF (7)
  FAULT HIF       .01666       2.        1.                          1
C Switch to Load #1 (10)
  LOAD1AZ1A      -.01666       2.        1.
  LOAD1BZ1B      -.01666       2.        1.
  LOAD1CZ1C      -.01666       2.        1.
C Switch to Load #2 (10)
  LOAD1AZ2A      -.01666       2.        1.
  LOAD1BZ2B      -.01666       2.        1.
  LOAD1CZ2C      -.01666       2.        1.
C Switch Simulating broken line on phase A (14)
  FAULT USER1A   -.01666    .01666       1.
C Switch to hysterestic reactor (15)
  LOAD1AHYSTRA   1.01666       2.        1.
  LOAD1BHYSTRB   1.01666       2.        1.
  LOAD1CHYSTRC   1.01666       2.        1.
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
C 2 DC sources
11DC1        2500.                                                   16.667e-3
11DC1        3100.                                          16.667e-3 33.333e-3
11DC1        1700.                                          33.333e-3 50.000e-3
11DC1        3900.                                          50.000e-3 66.667e-3
11DC1        5000.                                          66.667e-3 83.333e-3
11DC1        1000.                                          83.333e-3100.000e-3
11DC1        4000.                                          100.000e-3116.667e-3
11DC1        3000.                                          116.667e-3133.333e-3
11DC1        1500.                                          133.333e-3150.000e-3
11DC1        4500.                                          150.000e-3166.667e-3
11DC2       -2000.                                                    8.333e-3
11DC2       -2800.                                           8.333e-3 25.000e-3
11DC2       -1400.                                          25.000e-3 41.667e-3
11DC2       -3500.                                          41.667e-3 58.333e-3
```

```
11DC2          -4500.                                                    58.333e-3 75.000e-3
11DC2           -750.                                                    75.000e-3 91.667e-3
11DC2          -3300.                                                    91.667e-3108.333e-3
11DC2          -2800.                                                   108.333e-3125.000e-3
11DC2          -1100.                                                   125.000e-3141.667e-3
11DC2          -3900.                                                   141.667e-3158.333e-3
11DC2          -2600.                                                   158.333e-3175.000e-3
C Swing bus
14SWINGA  112676.528       60.                                               -1.        1.
14SWINGB  112676.528       60.     -120.                                     -1.        1.
14SWINGC  112676.528       60.      120.                                     -1.        1.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

HIF without Broken Conductor

```
BEGIN NEW DATA CASE
CDA
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Transmission Line Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SWINGASUBA            .473442.9590
  SWINGBSUBB  SWINGASUBA
  SWINGCSUBC  SWINGASUBA
  SWINGA                            106.07
  SWINGB                            106.07
  SWINGC                            106.07
  SUBA                              106.07
  SUBB                              106.07
  SUBC                              106.07
C Substation Transformer Parameters
$VINTAGE, 1
 1FEEDA                 0.5725300000E+04
 2FEEDB                 -0.283921000E+04
                        0.5725300000E+04
 3FEEDC                 -0.283921000E+04
                        -0.283921000E+04
                        0.5725300000E+04
 1SUBC  SUBA            0.4489642433E+010.9062070852E+06
 2FEEDA                 0.0000000000E+000.4736901177E+05
                        0.1227869774E-010.2477220137E+04
 3SUBA  SUBB            0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.4489642433E+010.9062070852E+06
 4FEEDB                 0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.1233982153E+04
                        0.0000000000E+000.4736901177E+05
                        0.1227869774E-010.2477220137E+04
 5SUBB  SUBC            0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.4489642433E+010.9062070852E+06
 6FEEDC                 0.0000000000E+00-.2359601161E+05
```

```
                                0.0000000000E+00-.1233982153E+04
                                0.0000000000E+00-.2359601161E+05
                                0.0000000000E+00-.1233982153E+04
                                0.0000000000E+000.4736901177E+05
                                0.1227869774E-010.2477220137E+04
$VINTAGE, 0
C Feeder Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
C Feeder #1
  FEEDA FAULT             .658 1.935                                        1
  FEEDB USER1BFEEDA FAULT
  FEEDC USER1CFEEDA FAULT
  FEEDA                            20.848
  FEEDB                            20.848
  FEEDC                            20.848
  FAULT                            20.848
  USER1B                           20.848
  USER1C                           20.848
C Feeder #2
  FEEDA USER2A            .658 1.935
  FEEDB USER2BFEEDA USER2A
  FEEDC USER2CFEEDA USER2A
  FEEDA                            20.848
  FEEDB                            20.848
  FEEDC                            20.848
  USER2A                           20.848
  USER2B                           20.848
  USER2C                           20.848
C Feeder #3
  FEEDA USER3A            .658 1.935
  FEEDB USER3BFEEDA USER3A
  FEEDC USER3CFEEDA USER3A
  FEEDA                            20.848
  FEEDB                            20.848
  FEEDC                            20.848
  USER3A                           20.848
  USER3B                           20.848
  USER3C                           20.848
C Feeder #4
  FEEDA USER4A            .658 1.935
  FEEDB USER4BFEEDA USER4A
  FEEDC USER4CFEEDA USER4A
  FEEDA                            20.848
  FEEDB                            20.848
  FEEDC                            20.848
  USER4A                           20.848
  USER4B                           20.848
  USER4C                           20.848
C Shunt Capacitors
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SHUNTA                    .3      5760.0
  SHUNTB                    .3      5760.0
  SHUNTC                    .3      5760.0
C Load Transformer Parameters
$VINTAGE, 1
 1      LOAD1A          0.4614840000E+04
 2      LOAD1B          0.0000000000E+00
                        0.4614840000E+04
 3      LOAD1C          0.0000000000E+00
                        0.0000000000E+00
                        0.4614840000E+04
 1LTRANA                0.7295832596E-010.2644881090E+05
 2LOAD1A                0.0000000000E+000.8801840054E+04
                        0.8080560687E-020.2929252372E+04
 3LTRANB                0.0000000000E+000.0000000000E+00
                        0.0000000000E+000.0000000000E+00
                        0.7295832596E-010.2644881090E+05
 4LOAD1B                0.0000000000E+000.0000000000E+00
                        0.0000000000E+000.0000000000E+00
                        0.0000000000E+000.8801840054E+04
                        0.8080560687E-020.2929252372E+04
```

```
 5LTRANC                  0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.7295832596E-010.2644881090E+05
 6LOAD1C                  0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.8801840054E+04
                          0.8080560687E-020.2929252372E+04
$VINTAGE, 0
96HYSTRA                    8888.     0.
 -0.15075000E+02 -0.12889412E+02
 -0.10050000E+02 -0.12811765E+02
 -0.45225001E+01 -0.12540000E+02
 -0.20099999E+01 -0.12268235E+02
 -0.75374997E+00 -0.12035294E+02
  0.25124999E+00 -0.11569411E+02
  0.87937499E+00 -0.11025882E+02
  0.14572499E+01 -0.10094118E+02
  0.17587500E+01 -0.85411765E+01
  0.20099999E+01 -0.62117647E+01
  0.25125000E+01  0.41541176E+01
  0.27637499E+01  0.57458824E+01
  0.35175000E+01  0.77647059E+01
  0.45225001E+01  0.93176471E+01
  0.54772498E+01  0.10094118E+02
  0.71606248E+01  0.10870588E+02
  0.97987495E+01  0.11569411E+02
  0.13441875E+02  0.12112941E+02
  0.17587499E+02  0.12501177E+02
  0.25125000E+02  0.12889412E+02
  0.40200000E+02  0.13200000E+02
  0.55275000E+02  0.13277647E+02
  0.99990000E+04
96HYSTRB      HYSTRA
96HYSTRC      HYSTRA
C Load #1 & #2
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  Z1A                       3.37  2.53
  Z1B         Z1A
  Z1C         Z1A
  Z2A                       3.37  2.53
  Z2B         Z2A
  Z2C         Z2A
C HIF impedance
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
99HIF   DIODE                 .01
              4.          1250.
              8.          3500.
             20.          5000.
             40.          6750.
             80.          9000.
           9999
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
C Type-11 switch (diode)
11DIODE DC1
11DC2   DIODE
C Switches to load transformer (5)
C  USER1ALTRANA       -1.    .00833       1.
C  USER1BLTRANB       -1.    .00833       1.
C  USER1CLTRANC       -1.    .00833       1.
  USER1ALTRANA   -.01666        2.
  USER1BLTRANB   -.01666        2.
  USER1CLTRANC   -.01666        2.
C Switch to shunt capacitors (6)
  USER1ASHUNTA   1.01666        2.        1.
  USER1BSHUNTB   1.01666        2.        1.
  USER1CSHUNTC   1.01666        2.        1.
```

```
C Switch to HIF (7)
  FAULT HIF       .01666        2.         1.
C Switch to Load #1 (10)
  LOAD1AZ1A      -.01666        2.         1.
  LOAD1BZ1B      -.01666        2.         1.
  LOAD1CZ1C      -.01666        2.         1.
C Switch to Load #2 (10)
  LOAD1AZ2A      -.01666        2.         1.
  LOAD1BZ2B      -.01666        2.         1.
  LOAD1CZ2C      -.01666        2.         1.
C Switch Simulating broken line on phase A (14)
  FAULT USER1A   -.01666        2.         1.
C Switch to hysterestic reactor (15)
  LOAD1AHYSTRA   1.01666        2.         1.
  LOAD1BHYSTRB   1.01666        2.         1.
  LOAD1CHYSTRC   1.01666        2.         1.
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1    ><    T1    >< TSTART >< TSTOP  >
C 2 DC sources
11DC1         2500.                                                       16.667e-3
11DC1         3100.                                              16.667e-3 33.333e-3
11DC1         1700.                                              33.333e-3 50.000e-3
11DC1         3900.                                              50.000e-3 66.667e-3
11DC1         5000.                                              66.667e-3 83.333e-3
11DC1         1000.                                              83.333e-3100.000e-3
11DC1         4000.                                             100.000e-3116.667e-3
11DC1         3000.                                             116.667e-3133.333e-3
11DC1         1500.                                             133.333e-3150.000e-3
11DC1         4500.                                             150.000e-3166.667e-3
11DC2        -2000.                                                        8.333e-3
11DC2        -2800.                                               8.333e-3 25.000e-3
11DC2        -1400.                                              25.000e-3 41.667e-3
11DC2        -3500.                                              41.667e-3 58.333e-3
11DC2        -4500.                                              58.333e-3 75.000e-3
11DC2         -750.                                              75.000e-3 91.667e-3
11DC2        -3300.                                              91.667e-3108.333e-3
11DC2        -2800.                                             108.333e-3125.000e-3
11DC2        -1100.                                             125.000e-3141.667e-3
11DC2        -3900.                                             141.667e-3158.333e-3
11DC2        -2600.                                             158.333e-3175.000e-3
C Swing bus
14SWINGA  112676.528       60.                                         -1.        1.
14SWINGB  112676.528       60.      -120.                              -1.        1.
14SWINGC  112676.528       60.       120.                              -1.        1.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Switching Loads

```
BEGIN NEW DATA CASE
CDA
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.      60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Transmission Line Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
```

```
  SWINGASUBA            .473442.9590
  SWINGBSUBB  SWINGASUBA
  SWINGCSUBC  SWINGASUBA
  SWINGA                            106.07
  SWINGB                            106.07
  SWINGC                            106.07
  SUBA                              106.07
  SUBB                              106.07
  SUBC                              106.07
C Substation Transformer Parameters
$VINTAGE, 1
 1FEEDA                 0.5725300000E+04
 2FEEDB                 -0.283921000E+04
                        0.5725300000E+04
 3FEEDC                 -0.283921000E+04
                        -0.283921000E+04
                        0.5725300000E+04
 1SUBC  SUBA            0.4489642433E+010.9062070852E+06
 2FEEDA                 0.0000000000E+000.4736901177E+05
                        0.1227869774E-010.2477220137E+04
 3SUBA  SUBB            0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.4489642433E+010.9062070852E+06
 4FEEDB                 0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.1233982153E+04
                        0.0000000000E+000.4736901177E+05
                        0.1227869774E-010.2477220137E+04
 5SUBB  SUBC            0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.4512104671E+06
                        0.0000000000E+00-.2359601161E+05
                        0.4489642433E+010.9062070852E+06
 6FEEDC                 0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.1233982153E+04
                        0.0000000000E+00-.2359601161E+05
                        0.0000000000E+00-.1233982153E+04
                        0.0000000000E+000.4736901177E+05
                        0.1227869774E-010.2477220137E+04
$VINTAGE, 0
C Feeder Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
C Feeder #1
  FEEDA FAULT             .658 1.935                                        1
  FEEDB USER1BFEEDA FAULT
  FEEDC USER1CFEEDA FAULT
  FEEDA                             20.848
  FEEDB                             20.848
  FEEDC                             20.848
  FAULT                             20.848
  USER1B                            20.848
  USER1C                            20.848
C Feeder #2
  FEEDA USER2A            .658 1.935
  FEEDB USER2BFEEDA USER2A
  FEEDC USER2CFEEDA USER2A
  FEEDA                             20.848
  FEEDB                             20.848
  FEEDC                             20.848
  USER2A                            20.848
  USER2B                            20.848
  USER2C                            20.848
C Feeder #3
  FEEDA USER3A            .658 1.935
  FEEDB USER3BFEEDA USER3A
  FEEDC USER3CFEEDA USER3A
  FEEDA                             20.848
  FEEDB                             20.848
  FEEDC                             20.848
  USER3A                            20.848
  USER3B                            20.848
  USER3C                            20.848
```

```
C Feeder #4
  FEEDA USER4A                .658 1.935
  FEEDB USER4BFEEDA USER4A
  FEEDC USER4CFEEDA USER4A
  FEEDA                                 20.848
  FEEDB                                 20.848
  FEEDC                                 20.848
  USER4A                                20.848
  USER4B                                20.848
  USER4C                                20.848
C Shunt Capacitors
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SHUNTA                       .3      5760.0
  SHUNTB                       .3      5760.0
  SHUNTC                       .3      5760.0
C Load Transformer Parameters
$VINTAGE, 1
 1      LOAD1A           0.4614840000E+04
 2      LOAD1B           0.0000000000E+00
                         0.4614840000E+04
 3      LOAD1C           0.0000000000E+00
                         0.0000000000E+00
                         0.4614840000E+04
 1LTRANA                 0.7295832596E-010.2644881090E+05
 2LOAD1A                 0.0000000000E+000.8801840054E+04
                         0.8080560687E-020.2929252372E+04
 3LTRANB                 0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.7295832596E-010.2644881090E+05
 4LOAD1B                 0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.8801840054E+04
                         0.8080560687E-020.2929252372E+04
 5LTRANC                 0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.7295832596E-010.2644881090E+05
 6LOAD1C                 0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.0000000000C0E+00
                         0.0000000000E+000.0000000000E+00
                         0.0000000000E+000.8801840054E+04
                         0.8080560687E-020.2929252372E+04
$VINTAGE, 0
96HYSTRA                   8888.    0.
 -0.15075000E+02 -0.12889412E+02
 -0.10050000E+02 -0.12811765E+02
 -0.45225001E+01 -0.12540000E+02
 -0.20099999E+01 -0.12268235E+02
 -0.75374997E+00 -0.12035294E+02
  0.25124999E+00 -0.11569411E+02
  0.87937499E+00 -0.11025882E+02
  0.14572499E+01 -0.10094118E+02
  0.17587500E+01 -0.85411765E+01
  0.20099999E+01 -0.62117647E+01
  0.25125000E+01  0.41541176E+01
  0.27637499E+01  0.57458824E+01
  0.35175000E+01  0.77647059E+01
  0.45225001E+01  0.93176471E+01
  0.54772498E+01  0.10094118E+02
  0.71606248E+01  0.10870588E+02
  0.97987495E+01  0.11569411E+02
  0.13441875E+02  0.12112941E+02
  0.17587499E+02  0.12501177E+02
  0.25125000E+02  0.12889412E+02
  0.40200000E+02  0.13200000E+02
  0.55275000E+02  0.13277647E+02
  0.99990000E+04
96HYSTRB        HYSTRA
96HYSTRC        HYSTRA
```

```
C Load #1 & #2
C < nl >< n2 ><refl><ref2>< R  >< wL >< wC >
  Z1A                       3.37  2.53
  Z1B         Z1A
  Z1C         Z1A
  Z2A                       3.37  2.53
  Z2B         Z2A
  Z2C         Z2A
C HIF impedance
C < nl >< n2 ><refl><ref2>< R  >< wL >< wC >
99HIF   DIODE              .01
             4.           1250.
             8.           3500.
            20.           5000.
            40.           6750.
            80.           9000.
          9999
/SWITCH
C < n l>< n 2>< Tclose ><Top/Tde ><    Ie    ><Vf/CLOP ><  type   >
C Type-11 switch (diode)
11DIODE DC1
11DC2   DIODE
C Switches to load transformer (5)
C  USER1ALTRANA       -1.    .00833        1.
C  USER1BLTRANB       -1.    .00833        1.
C  USER1CLTRANC       -1.    .00833        1.
  USER1ALTRANA   -.01666        2.
  USER1BLTRANB   -.01666        2.
  USER1CLTRANC   -.01666        2.
C Switch to shunt capacitors (6)
  USER1ASHUNTA   1.01666        2.         1.
  USER1BSHUNTB   1.01666        2.         1.
  USER1CSHUNTC   1.01666        2.         1.
C Switch to HIF (7)
  FAULT HIF      1.01666        2.         1.
C Switch to Load #1 (10)
  LOAD1AZ1A      -.01666        2.         1.
  LOAD1BZ1B      -.01666        2.         1.
  LOAD1CZ1C      -.01666        2.         1.
C Switch to Load #2 (10)
  LOAD1AZ2A       .01666        2.         1.
  LOAD1BZ2B       .01666        2.         1.
  LOAD1CZ2C       .01666        2.         1.
C Switch Simulating broken line on phase A (14)
  FAULT USER1A   -.01666        2.         1.
C Switch to hysterestic reactor (15)
  LOAD1AHYSTRA   1.01666        2.         1.
  LOAD1BHYSTRB   1.01666        2.         1.
  LOAD1CHYSTRC   1.01666        2.         1.
/SOURCE
C < n l><>< Ampl.  >< Freq.  ><Phase/T0><   A1    ><    T1    >< TSTART >< TSTOP  >
C 2 DC sources
11DC1         2500.                                                        16.667e-3
11DC1         3100.                                              16.667e-3 33.333e-3
11DC1         1700.                                              33.333e-3 50.000e-3
11DC1         3900.                                              50.000e-3 66.667e-3
11DC1         5000.                                              66.667e-3 83.333e-3
11DC1         1000.                                              83.333e-3100.000e-3
11DC1         4000.                                             100.000e-3116.667e-3
11DC1         3000.                                             116.667e-3133.333e-3
11DC1         1500.                                             133.333e-3150.000e-3
11DC1         4500.                                             150.000e-3166.667e-3
11DC2        -2000.                                                         8.333e-3
11DC2        -2800.                                               8.333e-3 25.000e-3
11DC2        -1400.                                              25.000e-3 41.667e-3
11DC2        -3500.                                              41.667e-3 58.333e-3
11DC2        -4500.                                              58.333e-3 75.000e-3
11DC2         -750.                                              75.000e-3 91.667e-3
11DC2        -3300.                                              91.667e-3108.333e-3
11DC2        -2800.                                             108.333e-3125.000e-3
11DC2        -1100.                                             125.000e-3141.667e-3
```

```
11DC2         -3900.                                                      141.667e-3158.333e-3
11DC1         -2600.                                                      158.333e-3175.000e-3
C Swing bus
14SWINGA  112676.528      60.                                                   -1.        1.
14SWINGB  112676.528      60.     -120.                                         -1.        1.
14SWINGC  112676.528      60.      120.                                         -1.        1.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Switching Shunt Capacitors

```
BEGIN NEW DATA CASE
CDA
C Miscellaneous Data Card ....
C  dT   >< Tmax >< Xopt >< Copt >
5.208e-6.1666667    60.     60.
     100       5       0       0       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Transmission Line Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SWINGASUBA                .473442.9590
  SWINGBSUBB  SWINGASUBA
  SWINGCSUBC  SWINGASUBA
  SWINGA                            106.07
  SWINGB                            106.07
  SWINGC                            106.07
  SUBA                              106.07
  SUBB                              106.07
  SUBC                              106.07
C Substation Transformer Parameters
$VINTAGE, 1
 1FEEDA                   0.5725300000E+04
 2FEEDB                   -0.283921000E+04
                          0.5725300000E+04
 3FEEDC                   -0.283921000E+04
                          -0.283921000E+04
                          0.5725300000E+04
 1SUBC  SUBA              0.4489642433E+010.9062070852E+06
 2FEEDA                   0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
 3SUBA  SUBB              0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.4489642433E+010.9062070852E+06
 4FEEDB                   0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
 5SUBB  SUBC              0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.4512104671E+06
                          0.0000000000E+00-.2359601161E+05
                          0.4489642433E+010.9062070852E+06
 6FEEDC                   0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+00-.2359601161E+05
                          0.0000000000E+00-.1233982153E+04
                          0.0000000000E+000.4736901177E+05
                          0.1227869774E-010.2477220137E+04
```

```
$VINTAGE, 0
C Feeder Parameters
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
C Feeder #1
  FEEDA FAULT                .658 1.935                                            1
  FEEDB USER1BFEEDA FAULT
  FEEDC USER1CFEEDA FAULT
  FEEDA                                20.848
  FEEDB                                20.848
  FEEDC                                20.848
  FAULT                                20.848
  USER1B                               20.848
  USER1C                               20.848
C Feeder #2
  FEEDA USER2A               .658 1.935
  FEEDB USER2BFEEDA USER2A
  FEEDC USER2CFEEDA USER2A
  FEEDA                                20.848
  FEEDB                                20.848
  FEEDC                                20.848
  USER2A                               20.848
  USER2B                               20.848
  USER2C                               20.848
C Feeder #3
  FEEDA USER3A               .658 1.935
  FEEDB USER3BFEEDA USER3A
  FEEDC USER3CFEEDA USER3A
  FEEDA                                20.848
  FEEDB                                20.848
  FEEDC                                20.848
  USER3A                               20.848
  USER3B                               20.848
  USER3C                               20.848
C Feeder #4
  FEEDA USER4A               .658 1.935
  FEEDB USER4BFEEDA USER4A
  FEEDC USER4CFEEDA USER4A
  FEEDA                                20.848
  FEEDB                                20.848
  FEEDC                                20.848
  USER4A                               20.848
  USER4B                               20.848
  USER4C                               20.848
C Shunt Capacitors
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  SHUNTA                       .3      11520.
  SHUNTB                       .3      11520.
  SHUNTC                       .3      11520.
C Load Transformer Parameters
$VINTAGE, 1
 1      LOAD1A             0.4614840000E+04
 2      LOAD1B             0.0000000000E+00
                           0.4614840000E+04
 3      LOAD1C             0.0000000000E+00
                           0.0000000000E+00
                           0.4614840000E+04
 1LTRANA                   0.7295832596E-010.2644881090E+05
 2LOAD1A                   0.0000000000E+000.8801840054E+04
                           0.8080560687E-020.2929252372E+04
 3LTRANB                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.7295832596E-010.2644881090E+05
 4LOAD1B                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.8801840054E+04
                           0.8080560687E-020.2929252372E+04
 5LTRANC                   0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.0000000000E+000.0000000000E+00
                           0.7295832596E-010.2644881090E+05
```

```
 6LOADIC                  0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.0000000000E+00
                          0.0000000000E+000.8801840054E+04
                          0.8080560687E-020.2929252372E+04
$VINTAGE, 0
96HYSTRA                   8888.    0.
 -0.15075000E+02 -0.12889412E+02
 -0.10050000E+02 -0.12811765E+02
 -0.45225001E+01 -0.12540000E+02
 -0.20099999E+01 -0.12268235E+02
 -0.75374997E+00 -0.12035294E+02
  0.25124999E+00 -0.11569411E+02
  0.87937499E+00 -0.11025882E+02
  0.14572499E+01 -0.10094118E+02
  0.17587500E+01 -0.85411765E+01
  0.20099999E+01 -0.62117647E+01
  0.25125000E+01  0.41541176E+01
  0.27637499E+01  0.57458824E+01
  0.35175000E+01  0.77647059E+01
  0.45225001E+01  0.93176471E+01
  0.54772498E+01  0.10094118E+02
  0.71606248E+01  0.10870588E+02
  0.97987495E+01  0.11569411E+02
  0.13441875E+02  0.12112941E+02
  0.17587499E+02  0.12501177E+02
  0.25125000E+02  0.12889412E+02
  0.40200000E+02  0.13200000E+02
  0.55275000E+02  0.13277647E+02
  0.99990000E+04
96HYSTRB      HYSTRA
96HYSTRC      HYSTRA
C Load #1 & #2
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
  Z1A                       3.37  2.53
  Z1B         Z1A
  Z1C         Z1A
  Z2A                       3.37  2.53
  Z2B         Z2A
  Z2C         Z2A
C HIF impedance
C < n1 >< n2 ><ref1><ref2>< R  >< wL >< wC >
99HIF   DIODE                .01
              4.           1250.
              8.           3500.
             20.           5000.
             40.           6750.
             80.           9000.
           9999
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
C Type-11 switch (diode)
11DIODE DC1
11DC2   DIODE
C Switches to load transformer (5)
C  USER1ALTRANA       -1.    .00833       1.
C  USER1BLTRANB       -1.    .00833       1.
C  USER1CLTRANC       -1.    .00833       1.
  USER1ALTRANA   -.01666       2.
  USER1BLTRANB   -.01666       2.
  USER1CLTRANC   -.01666       2.
C Switch to shunt capacitors (6)
  USER1ASHUNTA    .01666       2.       1.
  USER1BSHUNTB    .01666       2.       1.
  USER1CSHUNTC    .01666       2.       1.
C Switch to HIF (7)
  FAULT HIF      1.01666       2.       1.
C Switch to Load #1 (10)
  LOAD1AZ1A      -.01666       2.       1.
  LOAD1BZ1B      -.01666       2.       1.
```

```
  LOAD1CZ1C      -.01666        2.        1.
C Switch to Load #2 (10)
  LOAD1AZ2A      -.01666        2.        1.
  LOAD1BZ2B      -.01666        2.        1.
  LOAD1CZ2C      -.01666        2.        1.
C Switch Simulating broken line on phase A (14)
  FAULT USER1A   -.01666        2.        1.
C Switch to hysterestic reactor (15)
  LOAD1AHYSTRA   1.01666        2.        1.
  LOAD1BHYSTRB   1.01666        2.        1.
  LOAD1CHYSTRC   1.01666        2.        1.
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
C 2 DC sources
11DC1         2500.                                                  16.667e-3
11DC1         3100.                                        16.667e-3 33.333e-3
11DC1         1700.                                        33.333e-3 50.000e-3
11DC1         3900.                                        50.000e-3 66.667e-3
11DC1         5000.                                        66.667e-3 83.333e-3
11DC1         1000.                                        83.333e-3100.000e-3
11DC1         4000.                                       100.000e-3116.667e-3
11DC1         3000.                                       116.667e-3133.333e-3
11DC1         1500.                                       133.333e-3150.000e-3
11DC1         4500.                                       150.000e-3166.667e-3
11DC2        -2000.                                                   8.333e-3
11DC2        -2800.                                         8.333e-3 25.000e-3
11DC2        -1400.                                        25.000e-3 41.667e-3
11DC2        -3500.                                        41.667e-3 58.333e-3
11DC2        -4500.                                        58.333e-3 75.000e-3
11DC2         -750.                                        75.000e-3 91.667e-3
11DC2        -3300.                                        91.667e-3108.333e-3
11DC2        -2800.                                       108.333e-3125.000e-3
11DC2        -1100.                                       125.000e-3141.667e-3
11DC2        -3900.                                       141.667e-3158.333e-3
11DC1        -2600.                                       158.333e-3175.000e-3
C Swing bus
14SWINGA  112676.528       60.                                   -1.        1.
14SWINGB  112676.528       60.      -120.                        -1.        1.
14SWINGC  112676.528       60.       120.                        -1.        1.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

APPENDIX C

COMPUTER PROGRAMS

Generating Turn-to-Earth Model

```
#include <iostream.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>
#include <fstream.h>

void main ( ) {
	double na3,nb3,sigma_ab,k;
	cout<<"Please input the fault location (in percentage of the coil): ";
	cin>>na3;
	nb3=1-na3;
	k=na3/nb3;
	cout<<"Please input the leakage factor: ";
	cin>>sigma_ab;

	ifstream in("..\\tran230.pun");
	char str_in[24][83],str_out[30][83];
	const char comm[]="T2E   ";
	char temp[]="              ";

	// Read all contents from the input file
	int i=0;
	while(in.getline(str_in[i++],83,'\n'));
	in.close();

	// Build the prototype of the output file
	// First copy coils 1-3 totally
	for(i=0;i<7;i++)
		strcpy(str_out[i],str_in[i]);
	// Repeatedly copy the first line of coil 3
	strcpy(str_out[7],str_in[4]);
	// Add three new lines
	for(i=8;i<11;i++)
		strcpy(str_out[i],str_in[5]);
	// Copy first line of coil 4
	strcpy(str_out[11],str_in[7]);
	// Add a new line
	strcpy(str_out[12],str_in[5]);
	// Copy the remaining lines of coil 4 and the first line of coil 5
	for(i=8;i<12;i++)
		strcpy(str_out[i+5],str_in[i]);
	// Add a new line
	strcpy(str_out[17],str_in[5]);
	// Copy the remaining lines of coil 5 and the first line of coil 6
	for(i=12;i<17;i++)
		strcpy(str_out[i+6],str_in[i]);
	// Add a new line
	strcpy(str_out[23],str_in[5]);
	// Copy the remaining lines of coil 6
	for(i=17;i<23;i++)
		strcpy(str_out[i+7],str_in[i]);

	// Add the fault point's node name to coil 3 & 4
	for(i=8;i<14;i++) {
		str_out[4][i]=comm[i-8];
		str_out[7][i-6]=comm[i-8];
	}

	// Change the coil number to be correct
	str_out[7][1]='4';
	str_out[11][1]='5';
	str_out[16][1]='6';
	str_out[22][1]='7';
```

```
// Process the fault coil

// Read R
for(i=26;i<42;i++)
        temp[i-26]=str_in[6][i];
double r3=atof(temp);
// Calculate Ra and Rb
double ra=r3*na3;
double rb=r3*nb3;
// Write Ra and Rb
_gcvt(ra,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=26;i<42;i++)
        str_out[6][i]=temp[i-26];
_gcvt(rb,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=26;i<42;i++)
        str_out[10][i]=temp[i-26];

// Read wL3
for(i=42;i<58;i++) temp[i-42]=str_in[6][i];
double wl3=atof(temp);
// Calculate wLa, wLb, and wMab
double wla=wl3/(1/(k*k)+2*sqrt(1-sigma_ab)/k+1);
double wlb=wl3/(k*k+2*k*sqrt(1-sigma_ab)+1);
double wmab=wl3*sqrt(1-sigma_ab)/(k+1/k+2*sqrt(1-sigma_ab));
// Write wLa, wLb, and wMab
_gcvt(wla,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[6][i]=temp[i-42];
_gcvt(wlb,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[10][i]=temp[i-42];
_gcvt(wmab,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[9][i]=temp[i-42];

// Read wM34
for(i=42;i<58;i++) temp[i-42]=str_in[9][i];
double wm34=atof(temp);
// Calculate wMa4 and wMb4
double wma4=na3*wm34;
double wmb4=nb3*wm34;
// Write wMa4 and wMb4
_gcvt(wma4,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
```

```
                        temp[i]='0';
        temp[i]='\0';
        for(i=42;i<58;i++)
                str_out[13][i]=temp[i-42];
        _gcvt(wmb4,16,temp);
        // Remove the side effect of convertion function
        for(i=0;i<16;i++)
                if (temp[i]=='\0')
                        temp[i]='0';
        temp[i]='\0';
        for(i=42;i<58;i++)
                str_out[14][i]=temp[i-42];

        // Open prototype file
        ifstream prot("..\\prototype.t2e");
        // Open output file
        ofstream out("..\\turn2earth.dat");
        char buffer[83];
        while(prot.getline(buffer,83,'\n')) {
                if (!strcmp(buffer,"$VINTAGE, 0")) {
                        // Write to the output file
                        for(i=1;i<30;i++)
                                out<<str_out[i]<<endl;
                }
                else
                        out<<buffer<<endl;
        }
        prot.close();
        out.close();

}
```

Generating Turn-to-Turn Model

```
#include <iostream.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>
#include <fstream.h>
#include "engine.h"

void main ( ) {
        double na3,nb3,nc3,sigma_a,sigma_b,sigma_c;

        // Input parameters
        cout<<"Please input the first fault location (in percentage of the coil): ";
        cin>>na3;
        cout<<"Please input the second fault location (in percentage of the coil): ";
        cin>>nb3;
        nc3=1-na3-nb3;
        cout<<"Please input the leakage factor between coil a and coil (b+c): ";
        cin>>sigma_a;
        cout<<"Please input the leakage factor between coil b and coil (a+c): ";
        cin>>sigma_b;
        cout<<"Please input the leakage factor between coil c and coil (a+b): ";
        cin>>sigma_c;

        // Input original transformer model
        ifstream in("..\\tran230.pun");
        char str_in[24][83],str_out[38][83];
        const char comm1[]="T2T1    ",comm2[]="T2T2    ";
        char temp[]="                ";

        // Read all contents from the input file
        int i=0;
        while(in.getline(str_in[i++],83,'\n'));
        in.close();
```

```
// Build the prototype of the output file
// First copy coils 1-3 totally corresponding to coils 1-2, and a
for(i=0;i<7;i++)
        strcpy(str_out[i],str_in[i]);

// Build coil b
// Repeatedly copy the first line of coil 3
strcpy(str_out[7],str_in[4]);
// Add three new lines
for(i=8;i<11;i++)
        strcpy(str_out[i],str_in[5]);

// Build coil c
// Repeatedly copy the first line of coil 3
strcpy(str_out[11],str_in[4]);
// Add four new lines
for(i=12;i<16;i++)
        strcpy(str_out[i],str_in[5]);

// Copy first line of coil 4
strcpy(str_out[16],str_in[7]);
// Add two new lines
for(i=17;i<19;i++)
        strcpy(str_out[i],str_in[5]);
// Copy the remaining lines of coil 4 and the first line of coil 5
for(i=19;i<23;i++)
        strcpy(str_out[i],str_in[i-11]);
// Add two new lines
for(i=23;i<25;i++)
        strcpy(str_out[i],str_in[5]);
// Copy the remaining lines of coil 5 and the first line of coil 6
for(i=25;i<30;i++)
        strcpy(str_out[i],str_in[i-13]);
// Add two new lines
for(i=30;i<32;i++)
        strcpy(str_out[i],str_in[5]);
// Copy the remaining lines of coil 6
for(i=32;i<38;i++)
        strcpy(str_out[i],str_in[i-15]);

// Add the fault point's node name to coil a & b
for(i=8;i<14;i++) {
        str_out[4][i]=comm1[i-8];
        str_out[7][i-6]=comm1[i-8];
        str_out[7][i]=comm2[i-8];
        str_out[11][i-6]=comm2[i-8];
}

// Change the coil number to be correct
str_out[7][1]='4';
str_out[11][1]='5';
str_out[16][1]='6';
str_out[22][1]='7';
str_out[29][1]='8';

// Process the fault coil

// Read R
for(i=26;i<42;i++)
        temp[i-26]=str_in[6][i];
double r3=atof(temp);
// Calculate Ra, Rb, and Rc
double ra=r3*na3;
double rb=r3*nb3;
double rc=r3*nc3;
// Write Ra, Rb, and Rc
_gcvt(ra,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
```

```
                    temp[i]='0';
        temp[i]='\0';
        for(i=26;i<42;i++)
                str_out[6][i]=temp[i-26];
        _gcvt(rb,16,temp);
        // Remove the side effect of convertion function
        for(i=0;i<16;i++)
                if (temp[i]=='\0')
                        temp[i]='0';
        temp[i]='\0';
        for(i=26;i<42;i++)
                str_out[10][i]=temp[i-26];
        _gcvt(rc,16,temp);
        // Remove the side effect of convertion function
        for(i=0;i<16;i++)
                if (temp[i]=='\0')
                        temp[i]='0';
        temp[i]='\0';
        for(i=26;i<42;i++)
                str_out[15][i]=temp[i-26];

        // Read wL3
        for(i=42;i<58;i++) temp[i-42]=str_in[6][i];
        double wl3=atof(temp);
        // Declare input and output arrays for Matlab routine
        double x[6],*x1;
        // Build input array for Matlab routine
        x[0]=wl3;
        x[1]=na3;
        x[2]=nb3;
        x[3]=sigma_a;
        x[4]=sigma_b;
        x[5]=sigma_c;

        // Declare input and output arrays' pointers in mxArray format
        mxArray *px=NULL,*px1=NULL;
    // Allocate px matrix
    px=mxCreateDoubleMatrix(6,1,mxREAL);

        // Copy input array (C type) to input array (mxArray type)
        mxSetPr(px,x);

        // Declare matlab engine pointer
        Engine *ep;

        // Start the MATLAB engine
        if (!(ep = engOpen(NULL)))
                exit(-1);

        // Place the variable x into the MATLAB workspace
        mxSetName(px,"x");
        engPutArray(ep, px);

        // Evaluate the function 'solve6'
        engEvalString(ep,"x1=solve6(x);");

        // Get the results from mxArray format output
        px1= engGetArray(ep,"x1");

        // Close matlab engine
        engClose(ep);

        // Copy output array (mxArray type) to output array (C type)
        x1=mxGetPr(px1);

        // Free memory space
        mxDestroyArray(px);
        mxDestroyArray(px1);

        // Get wLa, wLb, wLc, wMab, wMac, and wMbc
        double wla=x1[0];
```

```
double wlb=x1[1];
double wlc=x1[2];
double wmab=x1[3];
double wmac=x1[4];
double wmbc=x1[5];
// Delete pointer x1
delete x1;

// Write wLa, wLb, wLc, wMab, wMac, and wMbc
_gcvt(wla,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[6][i]=temp[i-42];
_gcvt(wlb,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[10][i]=temp[i-42];
_gcvt(wlc,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[15][i]=temp[i-42];
_gcvt(wmab,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[9][i]=temp[i-42];
_gcvt(wmac,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[13][i]=temp[i-42];
_gcvt(wmbc,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
temp[i]='\0';
for(i=42;i<58;i++)
        str_out[14][i]=temp[i-42];

// Read wM34
for(i=42;i<58;i++) temp[i-42]=str_in[9][i];
double wm34=atof(temp);
// Calculate wMa4, wMb4, and wMc4
double wma4=na3*wm34;
double wmb4=nb3*wm34;
double wmc4=nc3*wm34;
// Write wMa4, wMb4, and wMc4
_gcvt(wma4,16,temp);
// Remove the side effect of convertion function
for(i=0;i<16;i++)
        if (temp[i]=='\0')
                temp[i]='0';
```

```
        temp[i]='\0';
        for(i=42;i<58;i++)
                str_out[18][i]=temp[i-42];
        _gcvt(wmb4,16,temp);
        // Remove the side effect of convertion function
        for(i=0;i<16;i++)
                if (temp[i]=='\0')
                        temp[i]='0';
        temp[i]='\0';
        for(i=42;i<58;i++)
                str_out[19][i]=temp[i-42];
        _gcvt(wmc4,16,temp);
        // Remove the side effect of convertion function
        for(i=0;i<16;i++)
                if (temp[i]=='\0')
                        temp[i]='0';
        temp[i]='\0';
        for(i=42;i<58;i++)
                str_out[20][i]=temp[i-42];

        // Open prototype file
        ifstream prot("..\\prototype.t2t");
        // Open output file
        ofstream out("..\\turn2turn.dat");
        char buffer[83];

        // Output turn-to-turn fault transformer model
        while(prot.getline(buffer,83,'\n')) {
                if (!strcmp(buffer,"$VINTAGE, 0")) {
                        // Write to the output file
                        for(i=1;i<38;i++)
                                out<<str_out[i]<<endl;
                }
                else
                        out<<buffer<<endl;
        }
        prot.close();
        out.close();
}
```

Generating Data for DTs

```
function wavelet(dummy)
% Calculate the wavelet on the interval of 8 cycles
clear all;
typeid=input('Please choose 1) Generate training set, 2) Generate test set: ');
switch typeid
case 1
    % Open output file
    fout = fopen('c:/hif/training.dat','a');
    % Handling HIF 180 cases
    for i=1:180
        % Create filename
        if i<10
            filehead='hif00';
        elseif i<100
            filehead='hif0';
        else
            filehead='hif';
        end
        filename=[filehead int2str(i) 'X.mdt'];
        % Open file for input
        fid=fopen(filename,'r');
        % Read data from file
        [x,y]=loadmdt(fid,3);
        fclose(fid);
        % Process data and write to file (2nd-9th cycles)
```

```
            haar(fout,x(33:288),y(33:288,:),1);
        end
        % Handling inrush 72 cases
        for i=1:72
            % Create filename
            if i<10
                filehead='inrush00';
            else
                filehead='inrush0';
            end
            filename=[filehead int2str(i) 'X.mdt'];
            % Open file for input
            fid=fopen(filename,'r');
            % Read data from file
            [x,y]=loadmdt(fid,3);
            fclose(fid);
            % Process data and write to file (3rd-10th cycles)
            haar(fout,x(65:320),y(65:320,:),0);
        end
        % Handling loads 180 cases
        for i=1:180
            % Create filename
            if i<10
                filehead='loads00';
            elseif i<100
                filehead='loads0';
            else
                filehead='loads';
            end
            filename=[filehead int2str(i) 'X.mdt'];
            % Open file for input
            fid=fopen(filename,'r');
            % Read data from file
            [x,y]=loadmdt(fid,3);
            fclose(fid);
            % Process data and write to file (2nd-9th cycles)
            haar(fout,x(33:288),y(33:288,:),0);
        end
        % Handling shunt 36 cases
        for i=1:36
            % Create filename
            if i<10
                filehead='shunt00';
            else
                filehead='shunt0';
            end
            filename=[filehead int2str(i) 'X.mdt'];
            % Open file for input
            fid=fopen(filename,'r');
            % Read data from file
            [x,y]=loadmdt(fid,3);
            fclose(fid);
            % Process data and write to file (3rd-10th cycles)
            haar(fout,x(33:288),y(33:288,:),0);
        end
        fclose(fout);
        disp('Training set has been generated.');
    case 2
        % Open output file
        fout = fopen('c:/hif/test.dat','a');
        % Handling HIF 25 cases
        for i=1:25
            % Create filename
            if i<10
                filehead='hif00';
            else
                filehead='hif0';
            end
            filename=[filehead int2str(i) 'X.mdt'];
            % Open file for input
            fid=fopen(filename,'r');
```

```
        % Read data from file
        [x,y]=loadmdt(fid,3);
        fclose(fid);
        % Process data and write to file (2nd-9th cycles)
        haar(fout,x(33:288),y(33:288,:),1);
    end
    % Handling inrush 25 cases
    for i=1:25
        % Create filename
        if i<10
            filehead='inrush00';
        else
            filehead='inrush0';
        end
        filename=[filehead int2str(i) 'X.mdt'];
        % Open file for input
        fid=fopen(filename,'r');
        % Read data from file
        [x,y]=loadmdt(fid,3);
        fclose(fid);
        % Process data and write to file (3rd-10th cycles)
        haar(fout,x(65:320),y(65:320,:),0);
    end
    % Handling loads 25 cases
    for i=1:25
        % Create filename
        if i<10
            filehead='loads00';
        else
            filehead='loads0';
        end
        filename=[filehead int2str(i) 'X.mdt'];
        % Open file for input
        fid=fopen(filename,'r');
        % Read data from file
        [x,y]=loadmdt(fid,3);
        fclose(fid);
        % Process data and write to file (2nd-9th cycles)
        haar(fout,x(33:288),y(33:288,:),0);
    end
    % Handling shunt 25 cases
    for i=1:25
        % Create filename
        if i<10
            filehead='shunt00';
        else
            filehead='shunt0';
        end
        filename=[filehead int2str(i) 'X.mdt'];
        % Open file for input
        fid=fopen(filename,'r');
        % Read data from file
        [x,y]=loadmdt(fid,3);
        fclose(fid);
        % Process data and write to file (3rd-10th cycles)
        haar(fout,x(33:288),y(33:288,:),0);
    end
    fclose(fout);
    disp('Test set has been generated.');
otherwise
    disp('Wrong choice! Quit program.');
end

function [x,y]=loadmdt(fidm,ncols)
% fidm: file id number
% ncols: the total number of columns in this file
% Get the number of rows
fseek(fidm,0,'eof');
nlines=ftell(fidm);
n=ncols-1; % Number of variables except time t
ncols=ncols+2;   % due to byte offset seen by Matlab
```

```
nlines=nlines/(ncols*4); %number of rows in this file
% Temporary variables
a=zeros(1,ncols);
x=zeros(nlines,1);
y=zeros(nlines,n);
column=[];
i=3;
while i<ncols
    column=[column i];
    i=i+1;
end
fseek(fidm,0,'bof'); % goto to first record of file
i=1;
while i<=nlines
    a=fread(fidm,[1,ncols],'float');
    x(i)=a(1,2); % starts on 2nd column
    y(i,1:n)=a(1,column);
    i=i+1;
end

function haar(fid,t,X,dtout)
% Perform a level 3 decomposition of the current
[C,L]=wavedec(X(:,2),3,'db1');
% Extract the level 3 approximation coefficients
cA3=appcoef(C,L,'db1',3);
% Extract the levels 3, 2, and 1 detail coefficients
cD3=detcoef(C,L,3);
cD2=detcoef(C,L,2);
cD1=detcoef(C,L,1);
% Reconstruct the level 3 approximation
A3=wrcoef('a',C,L,'db1',3);
% Reconstruct the details at levels 1, 2, and 3
D1=wrcoef('d',C,L,'db1',1);
D2=wrcoef('d',C,L,'db1',2);
D3=wrcoef('d',C,L,'db1',3);
% Build output vector
for k=1:57
   dtin=cD2(k:k+7);
   m=1+(k-1)*4;
   % Current
   I=X(m:m+31,2);
   % Voltage
   U=X(m:m+31,1);
   % RMS of differential current of phase A in 1 cycle
   Irms=sqrt(sum(I.*I)/32);
   % Normalize wavelet coefficiences
   dtin=sort(dtin/Irms);
   % Do discrete Fourier transforms for current
   [Iamp,Iang]=dft(I);
   % Normalize the 2nd, 3rd and 5th harmonics of differential current
   Ip235=Iamp([3 4 6])/Irms;
   % Do discrete Fourier transforms for voltage
   [Uamp,Uang]=dft(U);
   % Get the angle difference between the 3rd harmonics and the fundamental
voltage
   Ad=Iang(4)-Uang(2);
   if Ad<=-180
       Ad=Ad+360;
   elseif Ad>180
       Ad=Ad-360;
   end
   dtv=[dtout dtin' Irms Ip235' Iang(4) Ad];
   fprintf(fid,'%g %6.3f %6.3f %6.3f %6.3f %6.3f %6.3f %6.3f %6.3f %7.3f %6.3f
%6.3f %6.3f %8.3f %8.3f\n',dtv);
end
% figure;
% subplot(2,2,1);
% plot(t,X,t,A3);
% title('Approximation A3');
% subplot(2,2,2);
% plot(t,X,t,D1);
```

```
% title('Detail D1');
% plot(t,X,t,A3,t,D1,t,D2,t,D3)
% subplot(2,2,3);
% plot(t,X,t,D2);
% title('Detail D2');
% subplot(2,2,4);
% plot(t,X,t,D3);
% title('Detail D3');
% pause;

% FFT routine to get 2nd and 3rd harmonics
function [MX,MP]=dft(x)
Fs=1920;                    % sampling frequency
Fn=Fs/2;                    % Nyquist frequency
t=0:1/Fs:31/Fs;             % time vector sampled at Fs Hz,
                            % length of 8 cycles
X = x;                      % sampling points.
% Next highest power of 2 greater than or equal to
% length(x):
NFFT=2.^(ceil(log(length(X))/log(2)));
% Take fft, padding with zeros, length(FFTX)==NFFT
FFTX=fft(X,NFFT);
NumUniquePts = ceil((NFFT+1)/2);
% fft is symmetric, throw away second half
FFTX=FFTX(1:NumUniquePts);
MX=abs(FFTX);                    % Take magnitudes of X
MP=angle(FFTX)*180/pi;           % Take angles of X
% Multiply by 2 to take into account the fact that we
% threw out second half of FFTX above
MX=MX*2;
MX(1)=MX(1)/2;   % Account for endpoint uniqueness
MX(length(MX))=MX(length(MX))/2;  % We know NFFT is even
% Scale the FFT so that it is not a function of the
% length of x.
MX=MX/length(X);                   %
% f=(0:NumUniquePts-1)*2*Fn/NFFT;
% plot(f,MX);
% f=f(1:11)/60;
% MX=MX(1:11,:);
% figure;
% bar(f,MX);
```

Converting Cases to Events

```
#include <iostream.h>
#include <fstream.h>

void main(){
        char ch;
        int col[4];
        int trip=0, no_trip=0, false_trip=0, failure_to_trip=0;
        int num;
        int n=2;
        int previous[4];

        // Initialize previous array
        for(int i=0;i<4;i++)
                previous[i]=0;

        // Open input file
        ifstream in;
        cout<<"Please select 1) All; 2) Wavelet only; 3) Harmonics and angles; 4) Currents
only; 5) Current magnitude only: ";
        int fid;
        cin>>fid;
        switch(fid) {
        case 1:
```

```
                in.open("c:\\hif\\resultall.dat");
                break;
        case 2:
                in.open("c:\\hif\\resultwd2.dat");
                break;
        case 3:
                in.open("c:\\hif\\resultothers.dat");
                break;
        case 4:
                in.open("c:\\hif\\resultionly.dat");
                break;
        case 5:
                in.open("c:\\hif\\resultimag.dat");
                break;
        default:
                return;
        }
        while (!in.eof()) {
                // Read first 4 columns from the input file
                in>>col[0]>>col[1]>>col[2]>>col[3];
                // Quit loop if eof is reached
                if (in.eof()) break;

                // Analyze the results

                // 1 occurs
                if(col[2]==1) {
                        // Define a trip: 2 continuous 1's in 1 case
                        if(previous[2]==1&&col[0]/57==previous[0]/57&&col[0]==previous[0]+1)
{
                                // It's a correct trip and occurs in 2 cycles
                                if(col[3]==1&&previous[3]==1&&col[0]%57<=8) {
                                        ++trip;
                                        num=57-col[0]%57;
                                }
                                // It's an incorrect trip
                                else if(col[3]==0&&previous[3]==0) {
                                        ++false_trip;
                                        num=57-col[0]%57;
                                }
                                else if(col[0]%57==56) {
                                        // It's the last window
                                        ++no_trip;
                                        num=0;
                                }
                                else
                                        num=0;
                        }
                        else if(col[0]%57==56) {
                                // It's the last window
                                ++no_trip;
                                num=0;
                                }
                        else
                                num=0;
                }
                // 0 occurs
                else {
                        // It's not a correct no trip
                        if(col[3]==0) {
                                // It reaches 2 cycles
                                if(col[0]%57==8||col[0]%57==9) {
                                        // Failure to trip
                                        ++failure_to_trip;
                                        // Calculate number of remaining lines
                                        num=57-col[0]%57;
                                }
                                // Do nothing
                                else
                                        // Go to next line, so number of remaining lines
equals 0
```

```
                        num=0;
                }
                // It's a correct no trip
                else {
                        // It's the last window
                        if(col[0]%57==56)
                                ++no_trip;
                        // Go to next line, so number of remaining lines equals 0
                        num=0;
                }
        }

        // Skip to the next available line
        for(i=0;i<=num;i++) {
                do {
                        in.get(ch);
                        // Quit loop if it reaches end of file
                        if (in.eof()) break;
                }
                while (ch!='\n');
        }

        // Set current record to previous one
        for(i=0;i<4;i++)
                previous[i]=col[i];
    }

    // Close input file
    in.close();

    // Print the results
    cout<<"Correct trip(s):    "<<trip<<endl;
    cout<<"Correct no trip(s): "<<no_trip<<endl;
    cout<<"False trip:         "<<false_trip<<endl;
    cout<<"Failure to trip:    "<<failure_to_trip<<endl;

    // Open output file
    ofstream out("c:\\prdt\\results.dat");
    out<<"Correct trip(s):    "<<trip<<endl;
    out<<"Correct no trip(s): "<<no_trip<<endl;
    out<<"False trip:         "<<false_trip<<endl;
    out<<"Failure to trip:    "<<failure_to_trip<<endl;
    out.close();
}
```

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