I - Evaluation of the Responses of different Distance Relays to various Power System Transmission Line Models

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Abstract — **During the past few years, the protection relays as well as the digital power system simulators and the relay test equipment with its respective software have had very significant technological advances. The digital technology and the implementation of numerical algorithms through sophisticated software have permitted the development of much more complex, versatile and fast response relays. Similarly, the simulation software has included more exact and sophisticated power system models. Finally, the digital technology has permitted the development of relay test equipment, which permits now a number of tests which a few years ago were not only difficult but time consuming to carry out. This paper has as objective to show how the use of various power system models (the transmission line in this specific case), used to obtain COMTRADE cases to test power system protective relays could, depending on the selected model, lead to very different test results and therefore give rise to very different relay response interpretations. An implication of this is the care that should be taken in the selection of the power system models used to generate COMTRADE files to test power system digital relays.**

Index Terms-- **Relays, Distance Relays, Digital Models, Power System Simulators, Relay Test Equipment, Transients, COMTRADE.**

INTRODUCTION

The subject of what, when and how to test power system protection relays is a subject frequently considered by power system protection personnel. There are a number of points of view such as: the group that selects the relay for the intended application; the group that verifies that the relay selected meets the appropriate criteria; the relay manufacturer; the purchasing group that verifies the acquired relay; the relay settings group; the installation group; the commissioning group; the periodic maintenance group and the group which analyses the relay operations. As it is to be expected, each one of these groups "sees" the relay from different points of view and therefore deals with it appropriately to their specific objective.

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OBJECTIVES

The objectives of this paper are:

1) To show and evaluate the operating performance of four different relays, from different manufactures, when they are tested using transient simulations with different transmission line models.

2) To demonstrate what has been indicated in some references i.e., [7], [8], that relays behave in a deterministic way when they are tested using steady state test i.e., using as inputs phasor signals with power frequency of 60/50 Hz, whereas when the relays are tested using transient simulations, with a close representation of real power operating conditions, the relays behave in a random fashion. This is related to the transients that occur in real power systems. [8]

3) To show that to test impedance type protective relays under real power system operating conditions, it is better to carry out transient simulations with frequency dependent transmission lines which allow a better representation of the real power system conditions to which the impedance relays are submitted while in service. Simulations using concentrated parameters transmission line models, do not adequately represent the conditions of the power system.

GROUPS WHICH TEST PROTECTIVE RELAYS:

Then, the groups that verify that the selected relay is the appropriate for the specific application, is interested to test the relay under various conditions where the relay is going to be used. It is interested that the relay meets the international as well as any applicable national standard and any other requirement for the specific application (be it applied to generation, transmission or distribution). The tests carried by this group are very strict and cover a wide number of tests using various test methods (described later on), with a variety of settings and under various power system-operating conditions. For this group, the relay may be used in different parts of the power system. Therefore, it may test it under known power system conditions applicable to various potential locations.

For the protection engineer which needs a relay for an specific application, once the relay has been selected (approved by the group that has given it the basic approval, i.e., listed in the "approved supplier" list) he/she would like to submit the relay to tests which will demonstrate not only that it is applicable for its intended use but that it will respond reliably and securely. Therefore, he/she will test it under various operating-modes applicable to its intended use.

The manufacturer is interested mainly in offering the users an appropriate, reliable device (operates when it is required), secure (it will not operate when it is not required) and a reasonable price, which covers the development, manufacturing, marketing, sale and a reasonable profit.

From the testing point of view, the manufacturer by and large considers that once it tests it, there is no very much need for the user to test it "as thorough" as it did. As long as the relay functions appropriately (the output contacts "operate" when they should) and according to the selected settings, that should be enough. Modern relays monitor a number of internal components and parameters as well as its firmware and algorithms continuously in order to detect faults, reducing thus the need to periodically test the relay.

The purchasing group is mainly interested in verifying that the purchased relay meets the purchasing specifications. That is to say, that it should be in good condition in general, that the output contacts, communication with the relay, basic functions are all in good working conditions. This group is not very much interested in verifying its intended application.

The group in charge of calculating and installing the applicable relay settings "sees" the relay as a device that must meet the conditions reflected in the calculated settings. For this, it needs to verify that the calculated settings are the appropriate ones for the intended specific application under the appropriate power system conditions.

The relay test equipment manufacturer "sees" the relay as a "black box" and as such it must provide the relay tester not only the necessary hardware for the different users which may test the relay under various test modes and test but the appropriate software that allows the user not only to test different relay components but different relay algorithms. Thus, this group must provide each one of the testing groups the testing capabilities to test the relay from their specific needs.

The relay-commissioning group (startup) is interested in that the relay installed in its panel will function as such under normal operating conditions. Therefore, it will be interested in basically verifying that its settings have been installed correctly, as per the calculated settings and that it will operate correctly under normal operating conditions and abnormal (fault) conditions as well depending on the specific relay function.

The periodic maintenance group will "see" the relay as a device to which the relay settings should be periodically verified and that in general it should work under the testing conditions used by the commissioning group. In a number of companies this group may test the relay installed in the substation panel. These tests are usually steady state tests.

Finally the group or technical personnel that, once the relay has operated incorrectly, studies what happened, how did it happen and what should be corrected to try to avoid the incorrect operation from happening again. This groups "sees" the relay as a device to which a number of tests are to be made not only to verify its basic operation (basic relay functions) but additional tests to try to determine why the relay operated incorrectly, under what system conditions operated incorrectly and how to avoid this incorrect operation from happening again. It is possible that after the analysis the relay be exchanged for another model or even to use a completely different relay.

Then, from the previous it could be noticed that in actuality it does not exist **a single test or test mode to completely test a protective relay. What it is common is that the relay is exhaustively tested throughout its useful life.**

The purpose then is to evaluate the testing needs of the commissioning (startup), maintenance and relay operation analysis groups. It is considered these three groups have common objectives and testing procedures to try to reach their objectives: 1) To use the latest hardware and software tools to not only simulate as best as possible the power system "seeing" by the relay but the fault conditions that could reasonably occur in that part of the power system, 2) To test the relay in its substation panel, that is to say, in the normal place where the relay is installed, 3) To test the relay under normal and abnormal operating conditions (be they with faults or without faults) with a relay test set which may allow to carry out these simulations, as close as possible to the "real" one encountered in the power system, without having to use artifices which may falsify the tests (such as introducing higher fault resistances in order to reduce the test current needed by the test set to inject them to the relay) in order to carry out the required tests.

DIGITAL PROTECTIVE RELAYS - GENERIC CHARACTERISTICS

In general, a digital protective relay is made up of the following main components [3]:

a) Protection of the analog and digital signals against transient substation (MOVs) (all cabling should have been selected to withstand this environment)

b) Substation environment transient filters (low pass filters)

c) Signal conditioning circuit (ADC)

d) Multiplexers and / or A/D Converters, Sampling clocks, Sampling buffer, Sample and Hold circuit.

e) RAM memory

f) ROM / EPROM Memory

g) Long time memory / permanent

h) Digital outputs

i) Serial / parallel ports

j) Ethernet Communication port (LAN)

NOTE: The design, type and / or use of each one of these components may vary among the various manufacturers depending on the technology used by each one of them.

These components are shown diagrammatically in Fig. 1, below (from Ref. 3, pg. 6)

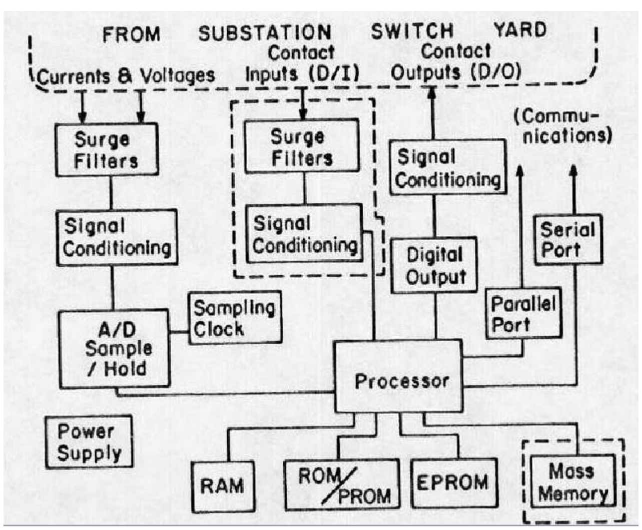


Fig. 1 – Main Components of a generic Digital Relay [3]

The different type and test modes will have then the objective of exhaustively testing that each one of these components has been designed and manufactured for the relay to function and operates as it should.

Each one of the previously mentioned groups or persons interested in the relay behavior / verification may use different relay test types and relay test modes to verify their respective objective briefly previously described.

For example: The acquisition group may be interested in verifying that the power supply, communications and output contacts operate appropriately. To test these components, they may use Steady State tests (at fundamental frequency, i.e. 50 Hz or 60 Hz). This test mode is simple, fast and versatile. This test mode will not test the signal conditioning input signals, the Sample and Hold circuit, the CPU nor the different relay memories. The frequency used (50 Hz or 60 Hz) and the test mode: slow variation of one parameter only (current or voltage) until the parameter reaches the setting point at which time the output contact may operate will not permit to “challenge” the relay behavior. According to [2] “If the signal would be a pure sinusoid, virtually each suggested algorithm would work perfectly”. It is therefore an “idealized” test mode. Not very realistic to try to “challenge” the digital relay algorithms.

The commissioning group (startup) could be more interested in testing the Signal Conditioning circuit, the Sampling and Hold circuits, the Memory, A/D and processor (where the different relay functions algorithms, which define the different relay types, reside), as well as the output circuits. For these tests, the Transient Mode of testing, at various frequencies, depending of the component being tested, type of fault, fault location, fault duration and opening / reclosing times, may be more in use. This test mode demands more from the relay and therefore “challenge” more some of the relay components. By “challenging” more relay components it is considered to be a more complete test than the Steady State test.

RELAY TEST TYPES

In general, there are two major relay-testing types:

1) ***Integrity Tests.*** Its purpose is to establish that the relay has been designed, manufactured, delivered, installed and maintained as per its technical specifications.

These tests are considered to be routine and carried out more than once to the relay during its useful life.

These tests use basic test procedures, which may be performed before the Application Tests. Basically, they are used to verify that the relay meets the purchasing specifications. Steady State or Dynamic tests may be used.

1) ***Application Tests***. Have the purpose to verify if the relay performance is satisfactory for the intended application.

These tests are recommended for those situations where the published specifications do not include enough details to assure an adequate application.

Used to verify a specific relay behavior for a specific application. Dynamic State and / or Transient State tests may be used.

RELAY TESTING MODES

With the purpose of testing protective relays, three test modes may be considered:

1) Steady State,

2) Dynamic State, and

3) Transient

Each mode has very specific characteristics as follows:

The Steady State mode it is characterized by the use of current and voltage phasors, a fundamental frequency (50 Hz or 60 Hz) and by the relatively **slow variation of the magnitude of one of its two parameters**, be it the current or the voltage but not both at the same time. Fig. 2 shows the characteristics waveform for this test mode

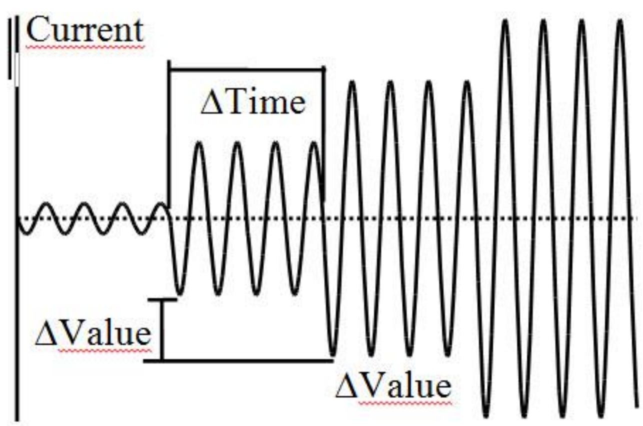


Fig. 2 – Typical Current and Voltage waveforms used in the Steady State testing mode

The Dynamic State is characterized by the use of current and phasors, at a fundamental frequency (50 Hz or 60 Hz) and by the **simultaneous variation of its magnitude and phase angle**, i.e., the current and the voltage **at the same time**.

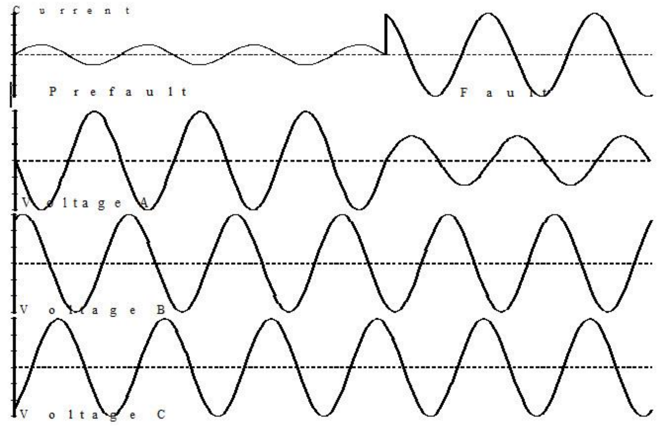


Fig. 3 – Current and voltage waveforms used in the Dynamic State testing mode

The Transient State testing mode is characterized by the use of **waveforms with certain harmonic frequency content** which depend on the transmission line (or power system components) characteristics or their respective models, as well as the type, location and fault duration.

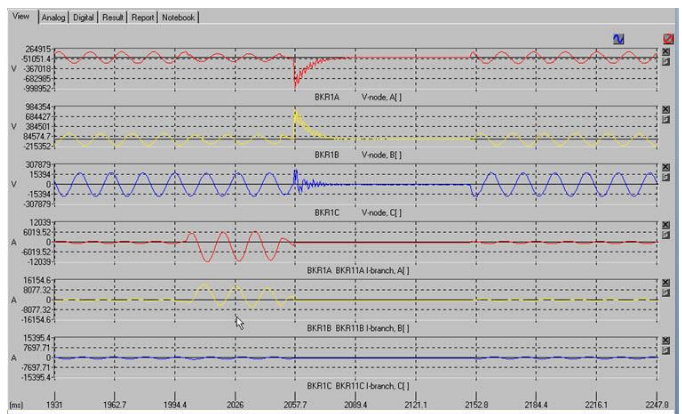


Fig. 4 – Current and voltage waveforms used in the Transient testing mode

SIMULATIONS TO TEST PROTECTIVE RELAYS

Initially, to test relays using Transient testing mode, real fault records obtained from DFR (Digital Fault Recorder), protective relaying recorders or digital simulation records obtained as COMTRADE type files were used.

Considering that a protective relay operates when there is a problem in the power system to which the relay should operate correctly and that the three groups of commissioning (startup), maintenance and disturbance analysis are interested in determining the relay operation under system conditions under which the relay should have operated correctly (fault conditions – for a protective relay), the current and voltage waveforms "seen" by the relay most likely will be distorted by the fault characteristics (arcs, various frequencies – which may have a frequency spectrum up to 5 kHz, different fault magnitude, different phasing, etc.). It is for these reasons that the Transient State testing mode tends to "challenge" more the relay different relay components. It is considered to be one of the most complete tests performed by these three groups.

Up until now the following has been described: Who test protective relaying, what do they test and how they test. Next the different type of faults used to test protective relays will be described.

There are various ways test fault records may be obtained:

a) Digital Fault Recorders (DFR – Digital Fault Recorders)

b) Relay fault recordings

c) Analog power system simulators (such as from the TNA – Transient Network Analyzer)

d) Digital Simulators (such as EMTP, ATP, PSCAD, EMTP-RV, etc.)

Presently, it is not rare to find DFRs with frequencies in the 5 kHz to 10 kHz and sometimes more. Formerly, these fault recorders had a maximum frequency in the 2 kHz range. However, in order to completely test a distance protective relay a great number of faults are required: different types, different fault locations, different power system loadings, etc., and the DFR recorded faults are relatively few and of very specific characteristics. Therefore, this type of fault medium to obtain test faults is rather limited.

In reference to the fault records obtained from protective relaying, they suffer from similar deficiencies as those of the DFRs. In addition, just until recently, the sampling frequency used in these relay records was rather low, in the order of 16 samples per cycle, i.e., 16 samples/ cycle x 60 cycles = 960 Hz and applying the Nyquist criteria, the frequency will be in actuality 960/2 = 480 Hz. That is to say, a very low frequency to be able to reproduce a real transmission line fault, which may reach frequencies in the 3.5 kHz to 5 kHz.

Pertaining the oscillograms obtained from TNAs, even though not as deficient as the records obtained from relays with a very low sampling rate, these suffer from a similar deficiency: the reproduction of a phenomenon at lower frequencies than those occurring in the real power system.

So then we are left to obtain the test faults to test distance protective relays from digital power system simulators.

FAULTS TO TEST DIGITAL DISTANCE PROTECTIVE RELAYS

The model shown in Fig. 5 below could be used to test the digital distance relays of a transmission line. It will be used to describe the different power system models used in a digital simulation.

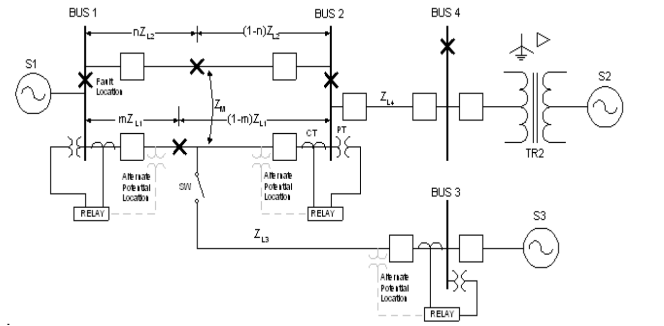


Fig. 5 – Typical Power System model to obtain faults to test transmission line protective relays

NOTE: The power system model used to evaluate the various digital distance relays in this paper is described later on.

1 – **TRANSMISSION LINE MODELS:**

As described in [6], "The Resistance, inductance and capacitances of transmission lines are distributed along the line length. Therefore, in general, they should not be considered as concentrated elements. In addition, some of the transmission line parameters are a function of the frequency. For Steady State studies such as Load Flow and Short Circuit, the only parameters required are the positive and zero sequence parameters calculated from tables and simple formulas from reference books at the fundamental frequency. For electromagnetic transient studies, the parameters calculated with simple formulas are not adequate and the line parameters must be calculated using auxiliary subroutines available in different electromagnetic transient programs."

Thus, it has been understood and demonstrated that for transient simulations the transmission line model should not use concentrated parameters. However, even today steady state transmission line models continue to be used to obtain test cases simulations with which it is intended to test the behavior of protective relaying, which should operate when there is a transmission line fault, that is to say when the fault frequencies are in the 3.5 kHz to 5.0 kHz range, i.e., when the fault phenomena is an electromagnetic transient phenomena.

In general, for different studies two main transmission line models are used:

a) Constant Parameters Model

b) Frequency Dependent Models

In reference to the **constant parameters**, the programs offer the following three models:

1) **Concentrated** parameters for the positive, and zero sequence.

2) PI Representation

3) **Distributed** parameters (Bergeron Model), for transposed and un-transposed lines.

As far as the **frequency dependent** parameters, the programs offer the following models:

1) Frequency dependent model for transposed and un-transposed lines **using modal transformation constant matrices**

2) Frequency dependent model for transposed and un-transposed lines **using modal transformation frequency dependent**

3) Frequency dependent model for transposed and un-transposed lines **without using the modal transformation.**

2 – GENERATOR MODELS:

By and large two types are used:

a) An ideal Sinusoidal source behind the sub transient reactance or system Thevenin impedances (Z1, Z0).

b) Detailed synchronous machine model

3 – POWER TRANSFORMER MODEL:

Even though its modeling for Load Flow or Short Circuit studies is rather simple (the short circuit impedance obtained from the transformer nameplate), for models as a function of the frequency, it is more complicated. In general, there are three models commonly used:

a) Ideal Transformer Model.
b) Saturable Reactance Model
c) Model based on coupled windings using program subroutines (Matrix models with three leg cores and five leg cores, shell and core type).

4 – CURRENT TRANSFORMER MODELS:

Two models are used. The most complete is shown in Fig. 6. The simplified one is shown in Fig. 7, below. In some occasions, these current transformers are model as ideal transformers, using only its transformation ratio, i.e., 800:5A or 1200:5A, etc.

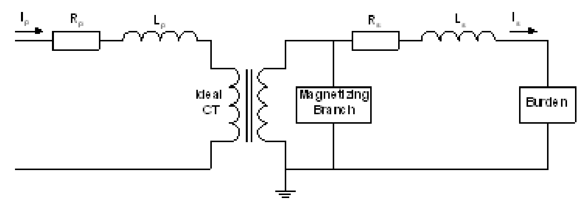


Fig. 6 – Typical coupled model of a CT [6]

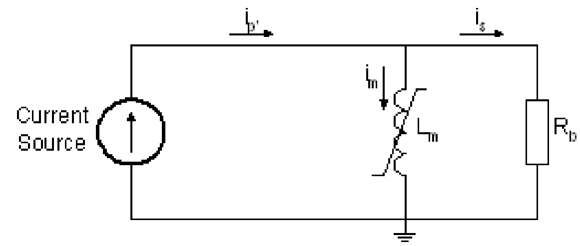


Fig. 7 – Typical simplified model of a CT [6]

5 – VOLTAGE TRANSFORMER MODELS:

Two types are considered depending if a Ferro resonance study is going to be performed or not. Fig. 8 shows the generic model used for Ferro resonance studies. Fig. 9 shows a model for a magnetic type PT.

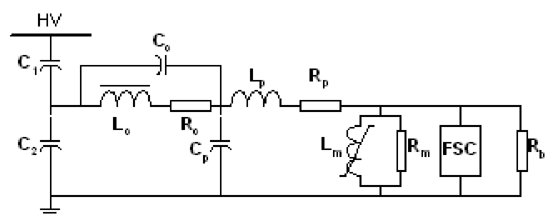


Fig. 8 – VT Model of a transformer for Ferro resonance studies (FSC) [6]

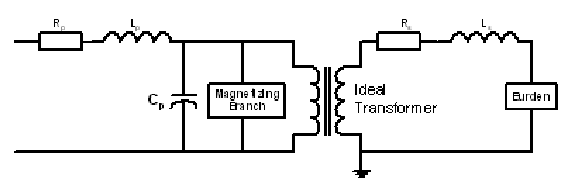


Fig. 9 – Simplified Model of a magnetic PT [6]

Similar to CTs, in some occasions these PT are simulated using ideal models using the PT ratio only, i.e., 3000 / 120 V o 2000 / 115 V, etc.

6 – CIRCUIT BREAKER MODELS:

In these models, the CB is considered as a switch interrupting the current at zero crossing. Neither the dynamic arc nor the arc losses are modeled. Some programs treat the switch opening as a random function (with Gaussian distribution or Uniform Density).

The CB controls can be modeled for single pole or three-phase reclosing operations as well as for the modeling of pre-insertion (at closing) or post-insertion resistors.

SIMULATION PROCEDURE

Once the models described above have been created, they are interconnected between them to form the system, which will be tested as shown in Fig. 5 above. Subsequently, the following parameters are considered:

1 – FAULT CHARACTERISTICS:

The relays should be tested for all faults, which the relay may experience in its normal operating life. Thus, the following faults should be considered:

a) The following 10 fault types: A to ground, B to ground, C to ground, A-B, A-C, B-C, A-B to ground, A-C to ground, B-C to ground and A-B-C-G.

b) Fault location: There exist a number of points of views depending on the system protection personnel. Type I: At 0%, 25%, 50%, 75% from each line terminal and 50% forward y behind the protected line. Type II: A 10%, 50% 80% from each line terminal and at 25% forward and behind the protected line.

c) Fault Resistance: This parameter has to do with the MHO and QUADRILATERAL element's sensitivity for faults to ground. It is therefore important to measure the relay's sensitivity at its limits. In this case, the sensitivity could be understood to be the maximum fault resistance to which the relay does not detect the fault. This parameter has to do with the fault location with one terminal of the line open also. [6].

d) Evolving Faults: In this type of faults, a line to ground fault may be converted in time into a phase-to-phase or three-phase fault. They should be applied inside and outside the protected line.

e) Fault Inception Angle (fault initiation): This is the voltage angle at the fault initiation instant. By and large, the phase A is taken as reference. Currents will move their angles ahead or behind depending on voltages phase angles before the fault based on the load conditions just before the fault [6].

f) System Loading Conditions: This parameter may affect the MHO and QUADRILATERAL element's sensitivity, especially when the faults are resistive. [6].

g) System parameter's variations: Different system loading conditions: System slightly loaded (night operation) and system heavily loaded (operation during the system peak loading condition).

h) Protection schemes assisted by communication channels: In these cases, the simulation of these schemes should be implemented, such as (POTT (Permissive Overreaching Transfer Trip), PUTT (Permissive Underreaching Transfer Trip), Transient Blocking (power reversal) and Weak In feed.

2 – CASE IDENTIFICATION CONVENTION

All the simulation runs will have as an output the generation of COMTRADE type files, as seen from both ends of the protected transmission line under test.

At each end of the protected transmission line under test, the cases should identify each case having into account to clearly and consistently identify each one with:

- System Conditions
- Fault Type
- Fault inception angle
- Fault Resistance
- Fault Location
- Fault duration

MODELS USED IN THE SIMULATIONS ANALYZED IN THIS PAPER

For better visualization, Figures 10, 11, 12, 13 and 14 showing the 5 different power system models used in this paper have been placed at the end of the paper.

The **LT90-0** (90 mile) transmission line characteristics are:

- Coupled Pi
- Nominal Frequency: 60 Hz
- **Length: 1.0E [m]**
- Nominal Voltage: 230 kV
- MVA for all the phases: 100 MVA
- Positive seq. Resistance: 0.662167893E-02 [pu/m]
- Positive Seq. Inductance: 0.104849098 [pu/m]
- Positive Seq. Capacitance: 0.328891885 [pu/m]
- Zero Seq. Resistance: 0.876497807E-01 [pu/m
- Zero Seq. Inductance: .345315534[pu/m]
- Zero Seq. Capacitance: 0.225803641 [pu/m]

The **LT90-1** transmission line characteristics are:

- Coupled Pi
- Nominal Frequency: 60 Hz

- **Length: 0.8E [m]**
- Nominal Voltage: 230 kV
- MVA for all the phases: 100 MVA
- Positive seq. Resistance: 0.662167893E-02 [pu/m]
- Positive Seq. Inductance: 0.104849098 [pu/m]
- Positive Seq. Capacitance: 0.328891885 [pu/m]
- Zero Seq. Resistance: 0.876497807E-01 [pu/m
- Zero Seq. Inductance: .345315534[pu/m]
- Zero Seq. Capacitance: 0.225803641 [pu/m]

The **LT90-2** transmission line characteristics are:

- Coupled Pi
- Nominal Frequency: 60 Hz
- **Length: 0.2E [m]**
- Nominal Voltage: 230 kV
- MVA for all the phases: 100 MVA
- Positive seq. Resistance: 0.662167893E-02 [pu/m]
- Positive Seq. Inductance: 0.104849098 [pu/m]
- Positive Seq. Capacitance: 0.328891885 [pu/m]
- Zero Seq. Resistance: 0.876497807E-01 [pu/m
- Zero Seq. Inductance: .345315534[pu/m]
- Zero Seq. Capacitance: 0.225803641 [pu/m]

The **LT90-3** transmission line characteristics are:

- Coupled Pi
- Nominal Frequency: 60 Hz
- **Length: 1.0E [m]**
- Nominal Voltage: 230 kV
- MVA for all the phases: 100 MVA
- Positive seq. Resistance: 0.662167893E-02 [pu/m]
- Positive Seq. Inductance: 0.104849098 [pu/m]
- Positive Seq. Capacitance: 0.328891885 [pu/m]
- Zero Seq. Resistance: 0.876497807E-01 [pu/m
- Zero Seq. Inductance: .345315534[pu/m]
- Zero Seq. Capacitance: 0.225803641 [pu/m]

The System Equivalent parameters are:

- MVA Base (three phase) = 850 MVA
- Voltage Base = 230 kV
- Nominal Frequency = 60 Hz
- Positive Seq. Resistance = 0.06 [ohm]
- Positive Seq. Reactance = 15.0758 [ohm]
- Zero Seq. Resistance = 0.13 [ohm]
- Zero Seq. Reactance = 8.93845 [ohm]

The Generator #1 parameters are:

- MVA Base (three phase) = 200 MVA
- Voltage Base = 13.8 kV
- Nominal Frequency = 60 Hz
- Positive Seq, Resistance = 0.001 [ohm]
- Positive Seq, Reactance = .114264 [ohm]
- Zero Seq. Resistance = 0.001 [ohm
- Zero Seq. Reactance = .114264 [ohm]

The Generator #2 parameters are:

- MVA Base (three phase) = 200 MVA
- Voltage Base = 13.8 kV
- Nominal Frequency = 60 Hz
- Positive Seq. Resistance = 0.001 [ohm]
- Positive Seq. Reactance = .114264 [ohm]
- Zero Seq. Resistance = 0.001 [ohm
- Zero Seq. Reactance = .114264 [ohm]

The Transformer T1 parameters are:

- MVA Base (three phase) = 200 MVA
- Voltage / Connection type: 13.8 kV, DELTA / 230 kV, WYE
- Nominal Frequency = 60 Hz
- Positive Seq. Reactance = 0.1 [p.u.]

The Transformer T2 parameters are:

- MVA Base (three phase) = 200 MVA
- Voltage / Connection: 13.8 kV, DELTA / 230 kV, WYE
- Nominal Frequency = 60 Hz
- Positive Seq. Reactance = 0.1 [p.u.]

For the transmission line models shown in Fig. 11, the parameters of the transmission lines LT90-0 and LT90-3 were used. For the five transmission lines models the data for the LT90-2 were used.

The generators and transformer models shown in Fig. 10 were used.

For the transmission line models shown in Fig. 12, the parameters of the transmission lines LT90-0 and LT90-3 of the model shown in Fig. 11 were used. For the five transmission lines models the data for the LT90-2 were used.

The generators and transformer models shown in Fig. 10 were used.

For the Bergeron Model, the following data was used:

The Transmission line LT90-0 characteristics are:

- Bergeron
- Nominal Frequency: 60 Hz
- **Segment Length: 144.81**

The Transmission line LT90-1 characteristics are:

- Bergeron
- Nominal Frequency: 60 Hz
- **Segment Length: 115.848**

The Transmission line LT90-2 characteristics are:

- Bergeron
- Nominal Frequency: 60 Hz
- **Segment Length: 28.962**

The Transmission line LT90-3 characteristics are:

- Bergeron
- Nominal Frequency: 60 Hz
- **Segment Length: 144.81**

For the generators and transformers, the same data as shown for the Coupled Pi model was used.

For the Frequency Model, the following TL parameters were used:

- Initial frequency to adjust the frequency = 0.5 Hz
- Final frequency to adjust the frequency = 1.0E6 Hz
- Total number of frequency increments = 100
- Maximum order to adjust Y Surge = 20
- Maximum order to adjust the propagation function = 20
- Maximum error for the adjustment of Y Surge = 2%
- Maximum error for the Propagation Function adjustment = 2%

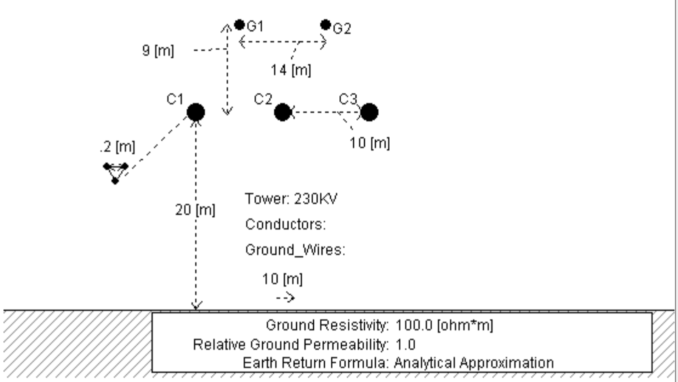


Fig. 15 – Tower Configuration for the Frequency Dependent Model (phase)

RELAYS USED IN THE SIMULATIONS ANALYZED IN THIS PAPER

Four impedance relays (relay 1, relay 2, relay 3 and relay 4) of 3 manufacturers (A, B and C) were used.

Mfg A: Relay 1 and Relay 2

Mfg B: Relay 3

Mfg C: Relay 4

The relay settings for the mfg A: Relay 1, Relay 2 and mfg B: Relay 3, and mfg C: Relay 4, were:

Z1 = 3.36 Ω at 86.38°

Z0 = 11.30 Ω at 75.75°

Phase MHO element setting:

Z1 = 2.66 Ω at 86.38°

Z1 of the Quadrilateral element:

R1 = 1.6738 Ω

X1 = 2.66 Ω

For the relays of manufacturer A: Relay 1, Relay 2 and manufacturer B: Relay 3, the K0 constant was:

K0 = 2.4152 Ω at -14.962°

The settings are graphically shown in Fig. 16, Fig. 17 and Fig. 18, below.

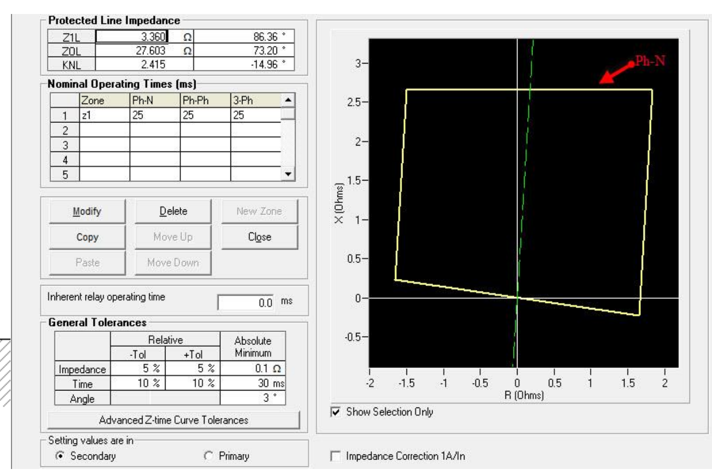


Fig. 16 – Relay setting – Line to neutral

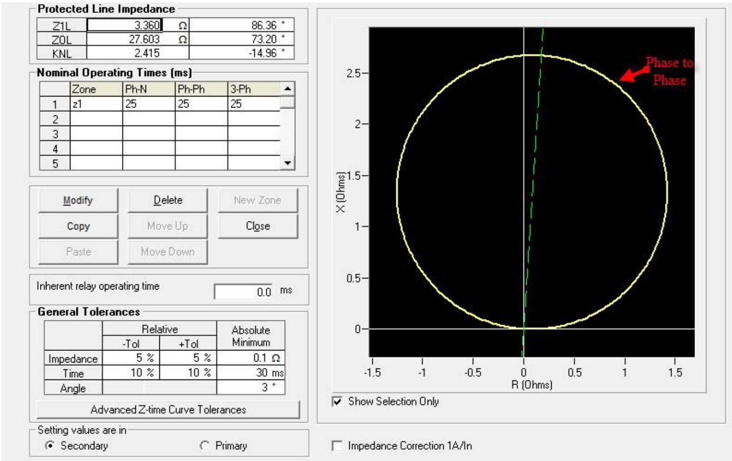


Fig. 17 – Relay Setting – Phase-to-Phase

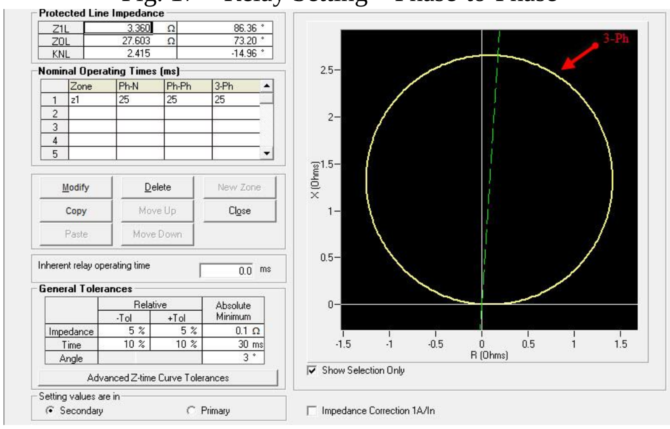


Fig. 18 – Relay Settings – Three Phase

TEST PROCEDURE

In order to obtain the relay operation data the following procedure was followed:

1) The 5 power system digital models to be used were created
2) The fault runs were obtained (4 fault types and 2 ground resistance magnitudes)
3) The COMTRADE files were obtained for both ends of the protected transmission line under test
4) The relay, test equipment and computers were connected in a network through a HUB
5) The relays under test were set with the previously indicated settings
6) The output contacts operation was verified with Steady State tests
7) The tests for each power system model type and for each relay were run (from one end of the transmission line only).
8) The relay LEDS, flags and screen records were recorded.
9) In the computer, the relay operating time and the fault location was recorded for each fault and each.
10) This was done 20 times for each condition. A results' table was created to record all the operations.
11) Subsequently, the 8 tables with test results were statistically analyzed.
12) The analysis consisted in verifying: a) The % of trips for each relay, b) Line Model used and c) fault type (As an example, see Table 1, below).
13) The same was done for the Fault Location (As an example see Table 1, below).
14) Finally, the relay operating time was statistically processed: a) For each relay, b) for each line model, taking all the faults into account (As an example see Fig. 29, below).

SIMULATION RESULTS ANALYZED IN THIS PAPER

Manufacturer A: Relay 1

TABLE 1

Percentage of Correct Operations and Fault Locations

Fault resistance = 0 Ohms

	Model		A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	90%	65%	95%
2	Freq. Model	Fault Loc.	100%	55%	25%	60%
3	Bergeron Model	Trip	100%	100%	100%	100%
4	Bergeron Model	Fault Loc.	100%	100%	35%	100%
5	Distr. Pi	Trip	100%	100%	15%	100%
6	Distr. Pi	Fault Loc.	100%	0%	0%	70%
7	Coupled Pi	Trip	100%	0%	0%	20%
8	Coupled Pi	Fault Loc.	100%	0%	0%	0%
9	Symm. Comp.	Trip	100%	0%	35%	100%
10	Symm. Comp.	Fault Loc.	100%	0%	0%	5%

Observations of the results shown in Table 1:

1) From the simulation results using the **frequency dependent model (phase)**, the mfg A relay 1 operated correctly in 100% to **detect** the A-G faults, in 90% of the cases **detected** correctly fault B-C-G and in 95% fault A-B-C-G. In 65 % **detected** the A-C phase-to-phase fault.

2) As far as the fault location is concerned, using the **frequency dependent (phase)**, the mfg A relay 1, corrected **located** on 100% the A-G faults. In 55% of the cases located correctly the B-C-G fault and in 60% the A-B-C-G fault. Only in 25% of the cases correctly located the A-C phase-to-phase fault.

3) From the simulation results using the **Bergeron model**, the mfg A relay 1 correctly operated in 100% of the cases to detect all the faults, i.e., A-G, B-C-G, A-C, A-B-C-G.

4) As far as the fault location is concerned, using the **Bergeron Model**, the mfg A, relay 1, corrected **located** on 100% all the faults, i.e., A-G, B-C-G, and A-B-C-G. It located the A- C, phase-to-phase fault, in 35% of the cases.

5) From the simulation results using the **Distributed PI model**, the mfg A relay 1 correctly operated in 100% of the cases to **detect** all the faults, i.e., A-G, B-C-G, A-C, A-B-C-G. It detected the A-C fault in 15% of the cases.

6) As far as the fault location is concerned, using the **Distributed Pi Model**, the mfg A relay 1, corrected **located** on 100% all the faults, i.e., A-G. Fault A-B-C-G located in 70% of the cases. It **did not locate** at all the B-C-G and A-C, phase to phase faults.

7) From the simulation results using the **Coupled PI model**, the mfg A relay 1 correctly operated in 100% of the cases to **detect** the A-G fault. The A-B-C-G was detected in 20% of the cases. Faults C-G and A-C were not detected

8) As far as the fault location is concerned, using the **Coupled Pi Model**, the mfg A relay 1, corrected **located** in 100% the A-G fault. Faults C-G, A-C and A-B-C-G were not **located**.

9) From the simulation results using the **Symmetrical Components model**, the mfg A relay 1 correctly operated in 100% of the A-G, and A-B-C-G cases but only 35% for B-C-G and 0% for A-C.

10) From the simulation results for symmetrical components model, the mfg A relay 1 corrected located in 100% the A-G fault. Faults B-C-G and A-C were not located. Only 5% of all A-B-C-G cases were located.

11) From the type of faults point of view, fault A-G was detected and located correctly by the mfg A relay with all the TL models used in this paper.

12) The C-G fault was detected correctly using the Frequency Dependent Model, the Bergeron Model and the Distributed Pi models.

13) Fault C-G was not located using the Distributed Pi, Coupled Pi and Symmetrical components Models.

14) This mfg's relay had difficulties detecting and locating the A-C fault.

15) This mfg's relay had difficulties detecting and locating the A-B-C-G using the Coupled Pi and Symmetrical Components models.

TABLE 2

Manufacturer A: Relay 1

Percentage of Correct Operations and Fault Locations
Fault resistance = 5 Ohms

	Model		A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	100%	95%	95%
2	Freq. Model	Fault Loc.	100%	30%	40%	60%
3	Bergeron Model	Trip	100%	95%	100%	100%
4	Bergeron Model	Fault Loc.	100%	50%	65%	85%
5	Distr. Pi	Trip	100%	50%	100%	100%
6	Distr. Pi	Fault Loc.	100%	0%	45%	85%
7	Coupled Pi	Trip	100%	0%	100%	100%
8	Coupled Pi	Fault Loc.	100%	0%	0%	65%
9	Symm. Comp.	Trip	100%	0%	100%	100%
10	Symm. Comp.	Fault Loc.	100%	0%	100%	100%

The effect of the 5 Ohm fault resistance on the mfg A, relay 1, behavior was basically:

1) It did not have any effect on the A-G fault detection and location, using any of the models used in this paper.

2) The B-C-G fault detection and location worsen somewhat.

3) The A-C fault detection and location improved.

4) The A-B-C-G fault detection and location improved.

NOTE: For the statistical analysis, please refer to the Appendix II – Statistical Evaluation of the Simulation Results.

TABLE 3

Manufacturer A: Relay 2

Percentage of Correct Operations and Fault Locations
Fault resistance = 0 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	75%	30%	85%
2	Freq. Model	Fault Loc.	100%	60%	0%	65%
3	Bergeron Model	Trip	100%	100%	80%	100%
4	Bergeron Model	Fault Loc.	100%	85%	25%	80%
5	Distr. Pi	Trip	100%	100%	70%	100%
6	Distr. Pi	Fault Loc.	100%	95%	10%	75%
7	Coupled Pi	Trip	100%	0%	0%	20%
8	Coupled Pi	Fault Loc.	100%	0%	0%	0%
9	Symm. Comp.	Trip	100%	0%	0%	35%
10	Symm. Comp.	Fault Loc.	100%	0%	0%	0%

TABLE 4

Manufacturer A: Relay 2

Percentage of Correct Operations and Fault Locations
Fault resistance = 5 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	30%	90%	65%
2	Freq. Model	Fault Loc.	100%	15%	45%	25%
3	Bergeron Model	Trip	100%	80%	100%	80%
4	Bergeron Model	Fault Loc.	100%	50%	75%	35%
5	Distr. Pi	Trip	100%	65%	100%	85%
6	Distr. Pi	Fault Loc.	100%	30%	60%	5%
7	Coupled Pi	Trip	100%	0%	60%	55%
8	Coupled Pi	Fault Loc.	100%	0%	0%	0%
9	Symm. Comp.	Trip	100%	0%	100%	100%
10	Symm. Comp.	Fault Loc.	100%	0%	100%	5%

TABLE 5

Manufacturer B: Relay 3

Percentage of Correct Operations and Fault Locations
Fault resistance = 0 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	85%	80%	100%	100%
2	Freq. Model	Fault Loc.	85%	80%	1000%	90%
3	Bergeron Model	Trip	95%	0%	100%	85%
4	Bergeron Model	Fault Loc.	85%	0%	100%	85%
5	Distr. Pi	Trip	100%	30%	100%	50%
6	Distr. Pi	Fault Loc.	85%	25%	100%	40%
7	Coupled Pi	Trip	85%	10%	100%	65%
8	Coupled Pi	Fault Loc.	80%	10%	95%	55%
9	Symm. Comp.	Trip	95%	0%	100%	95%
10	Symm. Comp.	Fault Loc.	90%	0%	100%	95%

TABLE 6

Manufacturer B: Relay 3

Percentage of Correct Operations and Fault Locations
Fault resistance = 5 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	100%	100%	100%
2	Freq. Model	Fault Loc.	85%	45%	100%	100%
3	Bergeron Model	Trip	95%	75%	100%	75%
4	Bergeron Model	Fault Loc.	75%	30%	100%	75%
5	Distr. Pi	Trip	55%	0%	100%	95%
6	Distr. Pi	Fault Loc.	45%	0%	100%	80%
7	Coupled Pi	Trip	80%	60%	100%	100%
8	Coupled Pi	Fault Loc.	80%	15%	100%	50%
9	Symm. Comp.	Trip	100%	95%	95%	85%
10	Symm. Comp.	Fault Loc.	90%	70%	95%	65%

TABLE 7

Manufacturer C: Relay 4

Percentage of Correct Operations and Fault Locations
Fault resistance = 0 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	0%	0%	0%
2	Freq. Model	Fault Loc.	100%	0%	0%	0%
3	Bergeron Model	Trip	100%	0%	0%	45%
4	Bergeron Model	Fault Loc.	100%	0%	0%	45%
5	Distr. Pi	Trip	100%	100%	0%	80%
6	Distr. Pi	Fault Loc.	100%	100%	0%	80%
7	Coupled Pi	Trip	100%	0%	0%	20%
8	Coupled Pi	Fault Loc.	100%	0%	0%	20%
9	Symm. Comp.	Trip	100%	0%	0%	0%
10	Symm. Comp.	Fault Loc.	100%	0%	0%	0%

TABLE 8

Manufacturer C: Relay 4

Percentage of Correct Operations and Fault Locations
Fault resistance = 5 Ohms

			A-G	B-C-G	A-C	A-B-C-G
1	Freq. Model	Trip	100%	0%	35%	0%
2	Freq. Model	Fault Loc.	100%	0%	35%	0%
3	Bergeron Model	Trip	100%	0%	30%	0%
4	Bergeron Model	Fault Loc.	100%	0%	30%	0%
5	Distr. Pi	Trip	100%	0%	50%	0%
6	Distr. Pi	Fault Loc.	100%	0%	50%	0%
7	Coupled Pi	Trip	100%	0%	0%	0%
8	Coupled Pi	Fault Loc.	100%	0%	0%	0%
9	Symm. Comp.	Trip	100%	0%	12%	0%
10	Symm. Comp.	Fault Loc.	100%	0%	60%	0%

CONCLUSIONS

<u>Analyzing the previous results, with a fault resistance R = 0, it was observed:</u>

1) With the Symmetrical Components Model, all the relays tripped without too much of a problem (when they operated).

2) With the Symmetrical Components Model, it was observed that all the relays had quite a few "No Op" (less than with the Coupled Pi, though).

3) All the relays seemed to have the worst behavior with the Coupled Pi Model. Greater number of No Op (More than 75%).

4) Even though the Distributed Pi had a number of "No Op", they were less than with the Symmetrical Components and the Coupled Pi Models.

5) For the case of the Distributed Pi, the Standard Deviation was smaller due to the reduced number of "No Op".

6) With the Bergeron Model, Relays 1, 2 and 3 had a better performance, showing a smaller number of "No Op", which it did not occur for Relay 4.

7) For the Bergeron Model there was a greater Trip Standard Deviation. There were cases in which the relay required more than 80 msec to operate.

8) The Frequency Dependent Model shows more "No Op" than the Bergeron and the Distributed Pi. An indication that the relays were more challenged with the Freq. Dependent than with the Bergeron and Distributed Pi.

9) With the Frequency Dependent Model it was when the relays showed more errors in locating the faults.

10) With the Frequency Dependent Model, in most of the cases most relays failed to report correctly the fault location.

In reference to the Fault Resistance, the following was noticed:

<u>Analyzing the previous results, with a Fault Resistance R = 5, it was observed:</u>

11) With the Symmetrical Components Model, all the relays tripped without too much of a problem (when they operated).

12) With the Symmetrical Components Model, it was observed that all the relays had quite a few "No Op".

13) All the relays seemed to have the worst performance with the Coupled Pi Model.

14) Even though the Distributed Pi had a number of “No Op”, they were less than with the Symmetrical Components and the Coupled Pi Models.

15) Fort he case of the Distributed Pi, the Standard Deviation was smaller due to the reduced number of “No Op”.

16) With the Bergeron Model, Relays 1, 2 and 3 had a better performance, showing a smaller number of “No Op”, This did not occurred for Relay 4.

17) For the Bergeron Model there was a greater Trip Standard Deviation. There were cases in which the relay required more than 150 msec to operate.

18) The Frequency Dependent Model shows more “No Op” than the Bergeron and the Distributed Pi. An indication that the relays were more challenged with the Freq. Dependent than with the Bergeron and Distributed Pi.

19) With the Frequency Dependent Model it was when the relays showed more errors in locating the faults.

20) With the Frequency Dependent Model, in the majority of the cases, most relays failed to report correctly the fault location.

In summary, it appears the Frequency dependent Model is the one, which challenges the most the relay’s operations. The one which challenges the least the relays is the Symmetrical Components Model.

A few possible explanations: In our opinion, there are a number of reasons for the relay performance noted in this paper among them:

1) Those related to the signal conditioning, sampling and filtering of the relay input waveforms (voltages and currents) and,

2) Those related to different algorithms used for the determination of the faulted phase (s) and the fault location.

3) Even though the experience of a number of past blackouts has determined that about 70% of them have been originated by relay failures and that previous investigators [7] and [8] have amply demonstrated that relay testing using steady state carries a significant amount of uncertainties, up to now there has been little noticeable movement towards the implementation of transient waveforms for relay testing.

4) NERC has required their members to implement a number of measures to try to control the number of relay failures and their impact to the power system. Some of these measures have been reporting requirements when:
R3.2: “Changes in the reach or pickup of any protection system (e.g. increasing the reach of a distance relay or increasing the pickup of an overcurrent relay)
Changes in the clearing time of a protection system (e.g. changing the time delay of a distance relay or the time dial of an overcurrent relay)” [9].

5) The results of this paper and others indicate that “The Random behavior of the relay is related to transients that occur in real power systems. When applying input signals with transients, the relay behavior may not match the one observed for phasor-based test waveforms. In particular the relay response and the operating time are variable depending on the content of the fault transient” [8]. The above has been corroborated once more by the results of this paper.

FIGURES OF THE POWER SYSTEM MODELS USED IN THIS PAPER

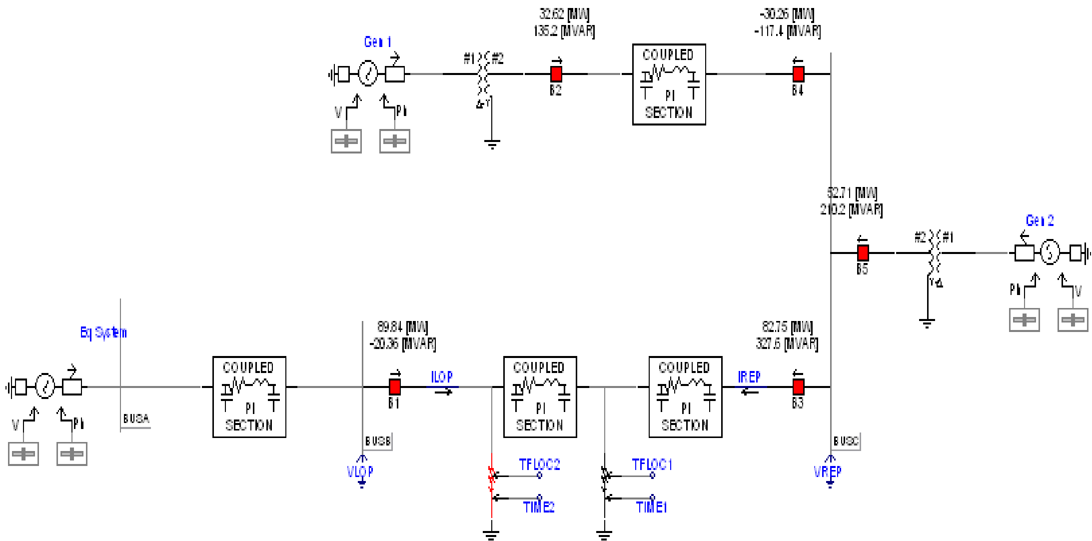


Fig.10 – Coupled Pi Mode

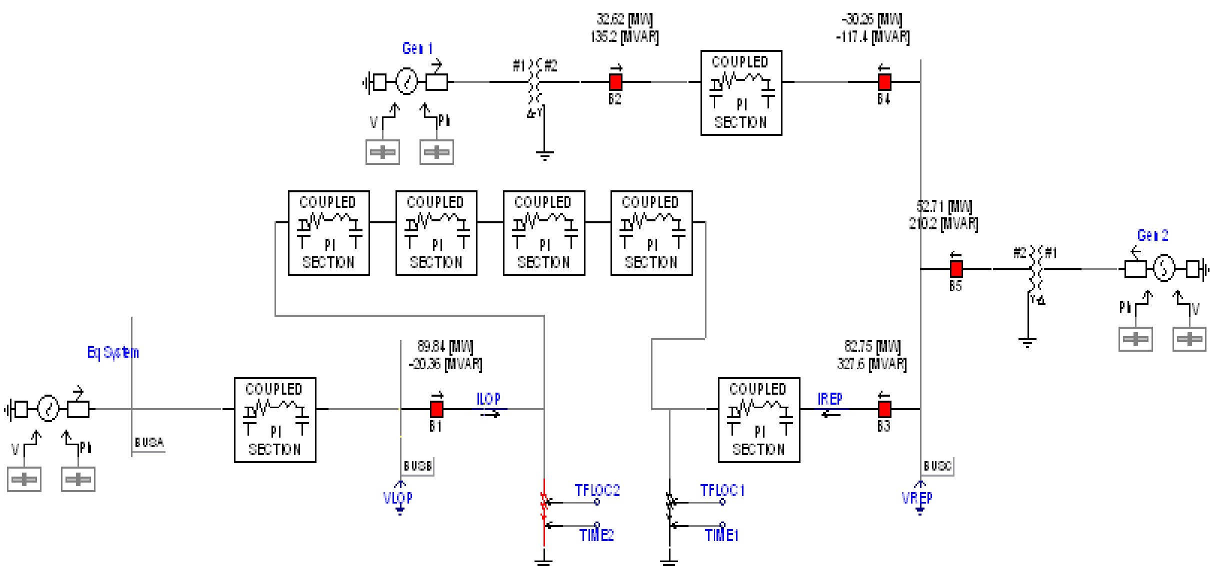


Fig. 11– Distributed Pi Model

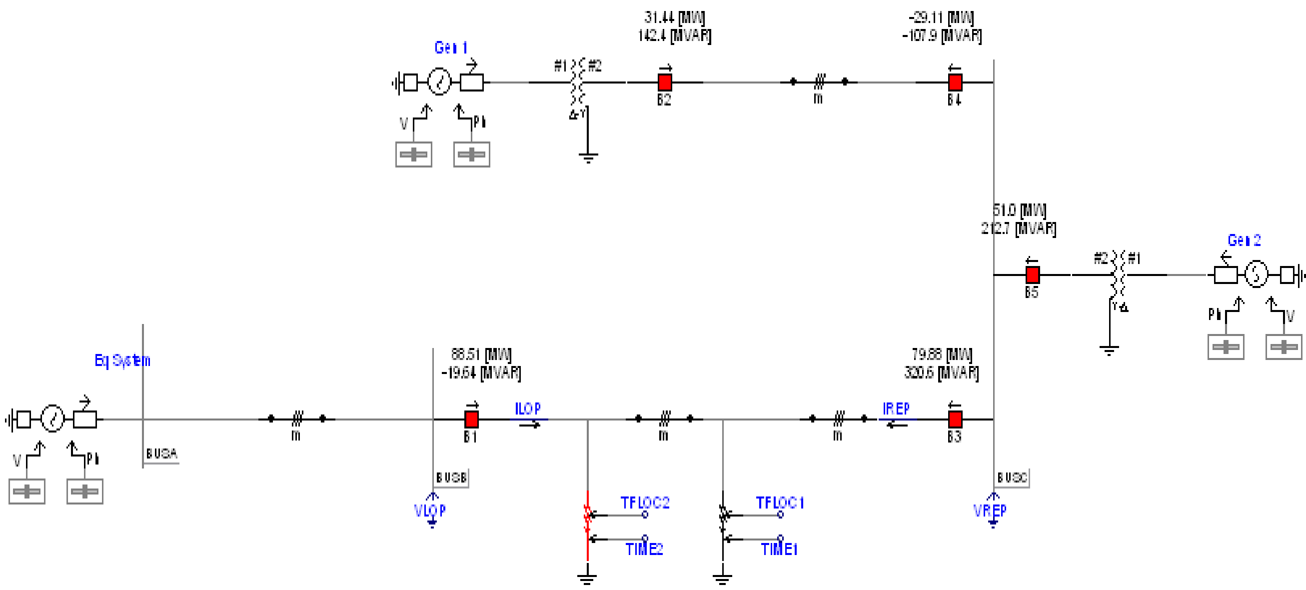


Fig. 12 – Symmetrical Components Model

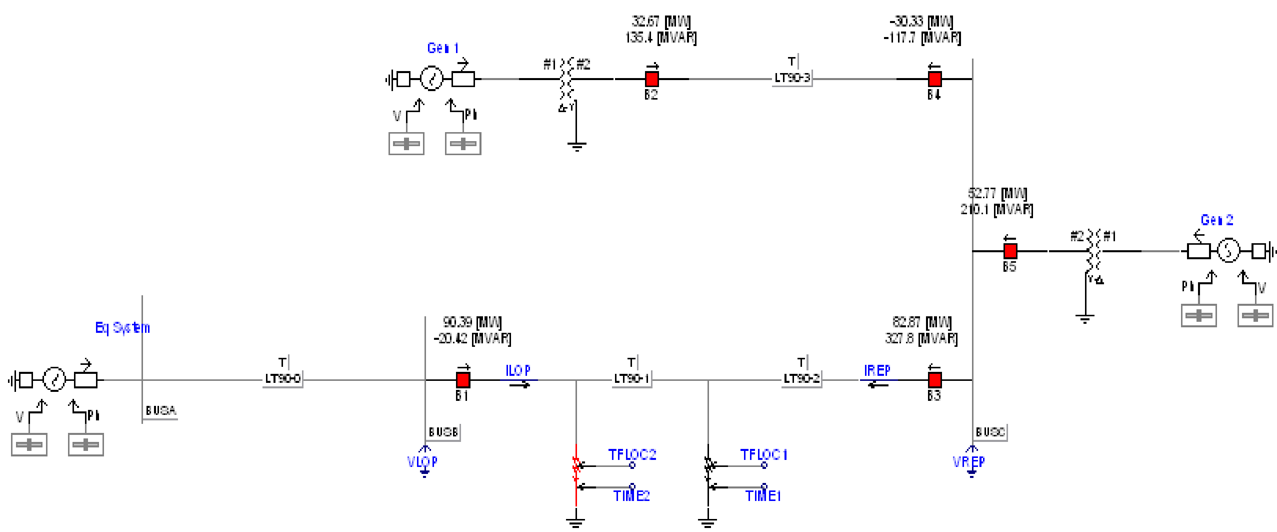


Fig. 13 – Bergeron Model

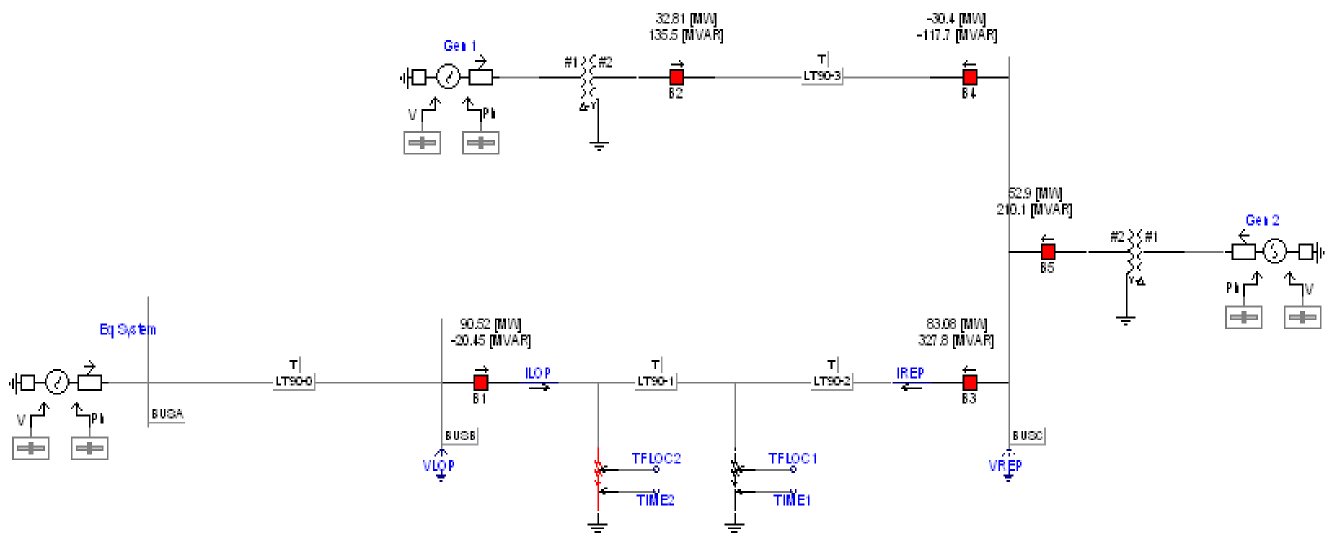


Fig. 14 – Frequency Dependent function Model (phase)

APPENDIX I

SOME OF THE COMTRADE WAVEFORMS USED DURING THE EVALUATIONS

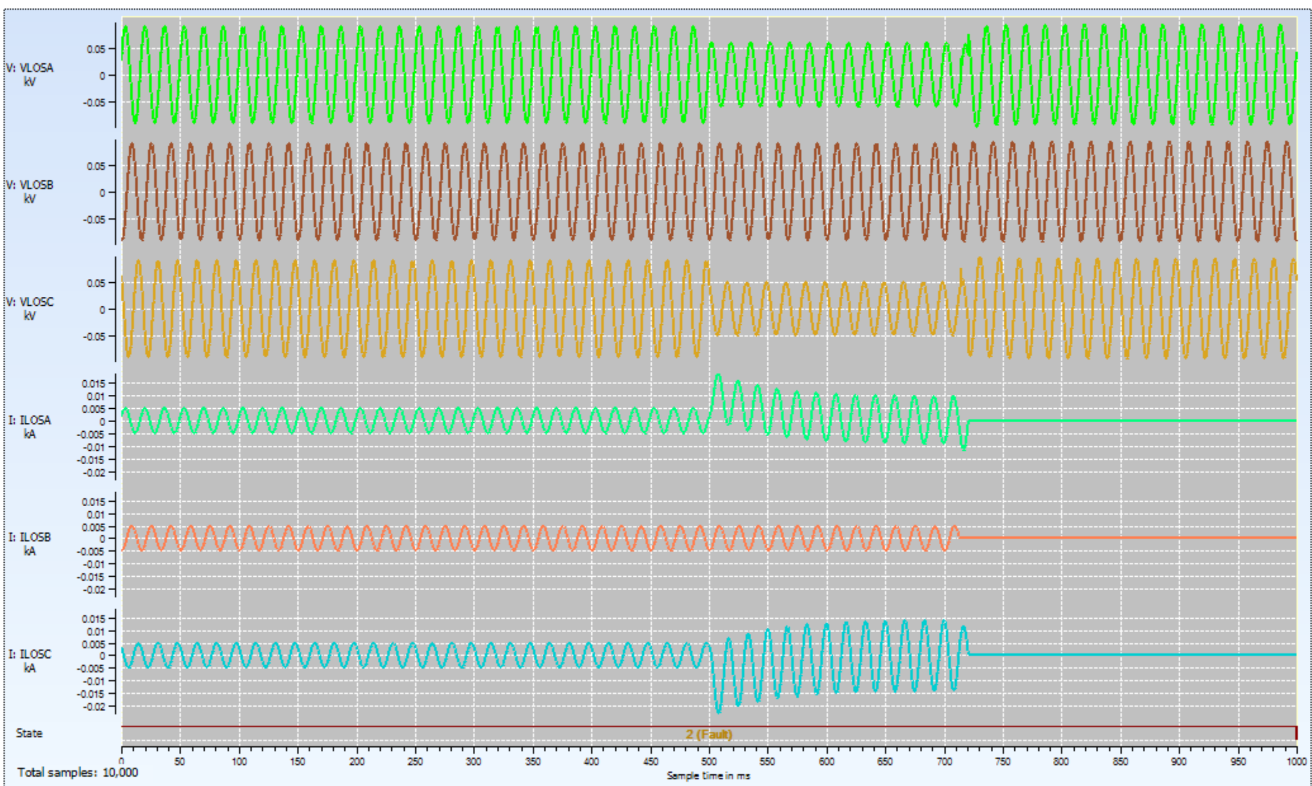


Fig. 19 – Symmetrical Components Model - A-C Fault, Rf =0 Ohms

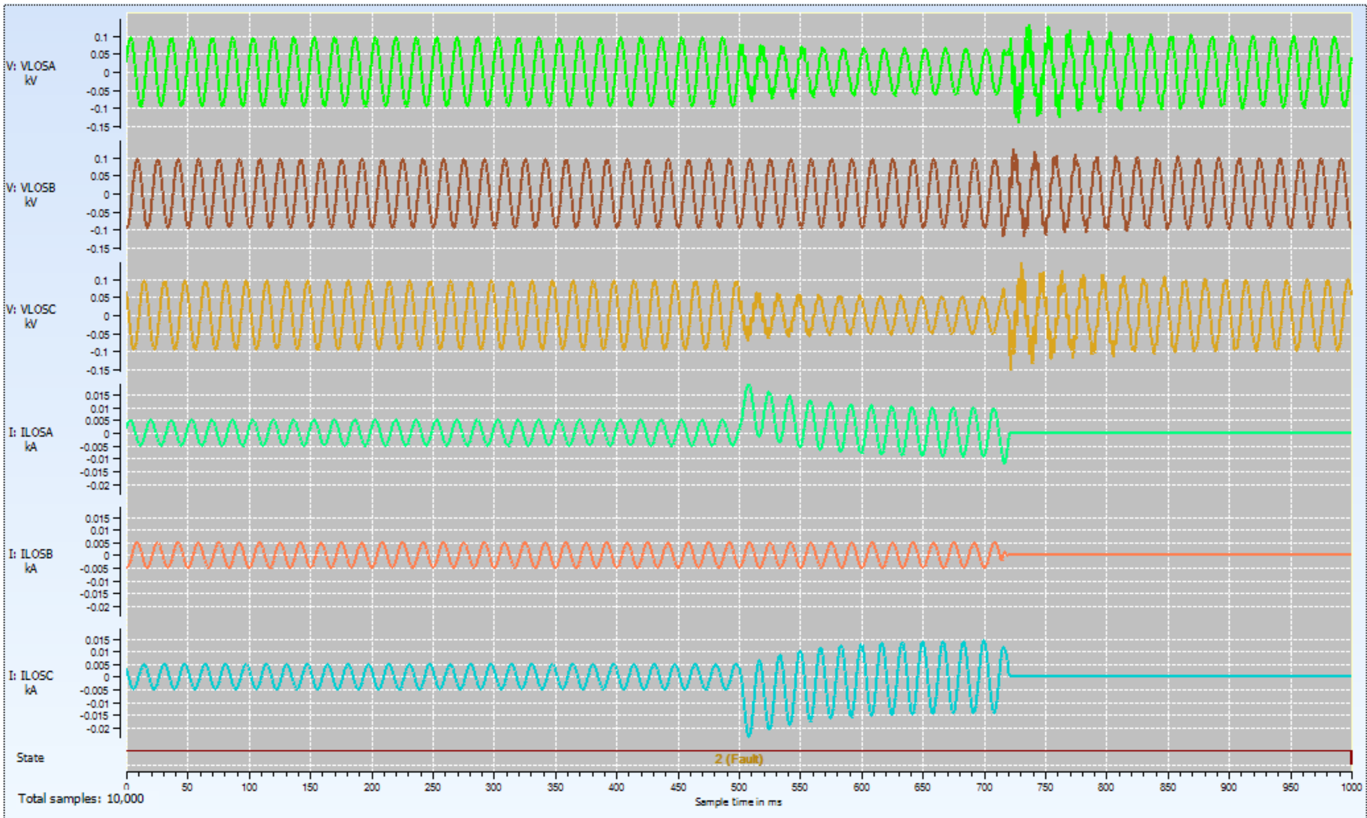


Fig. 20 – Coupled Pi Model - A-C Fault, Rf =0 Ohms

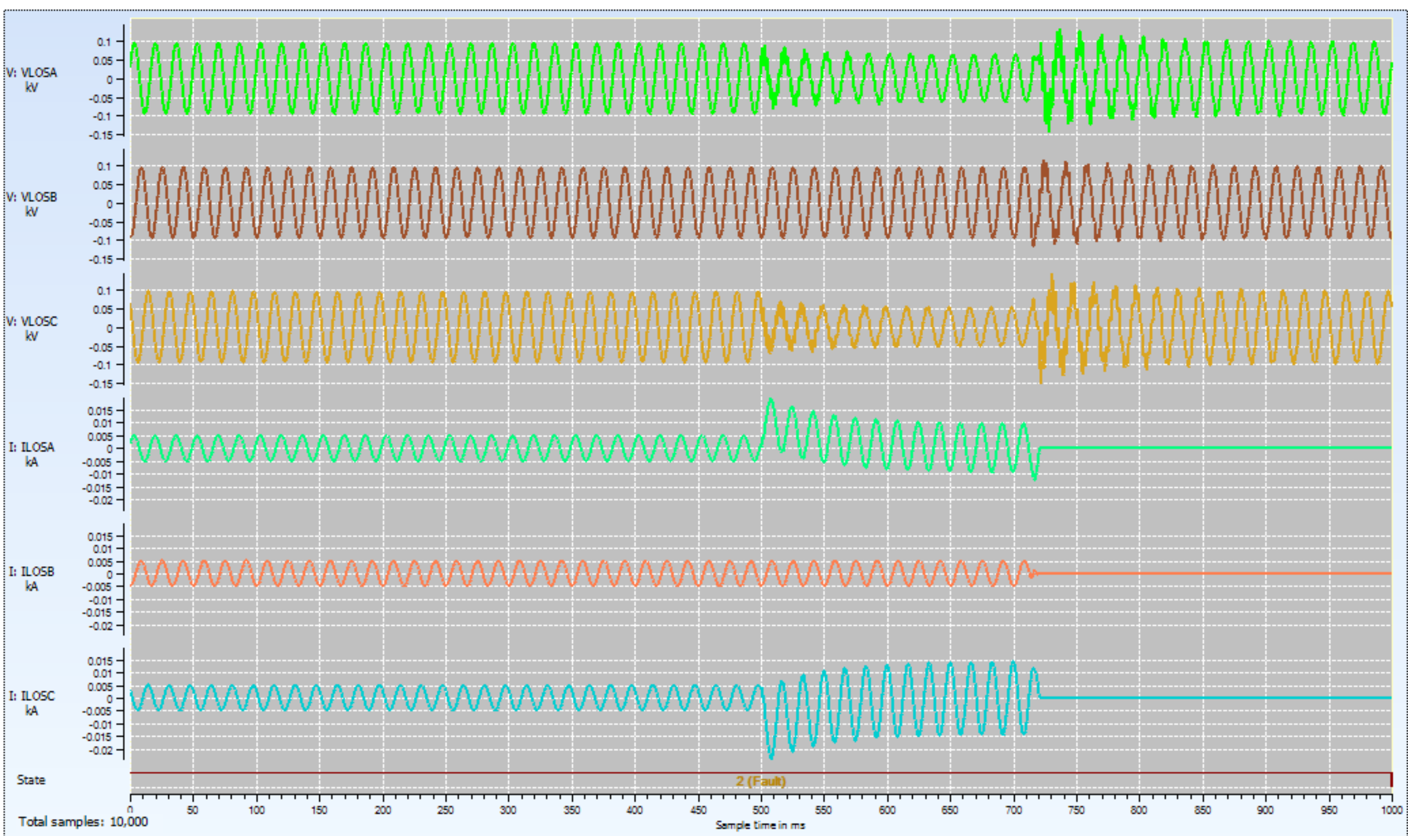


Fig. 21 – Distributed Pi Model - A-C Fault, Rf =0 Ohms

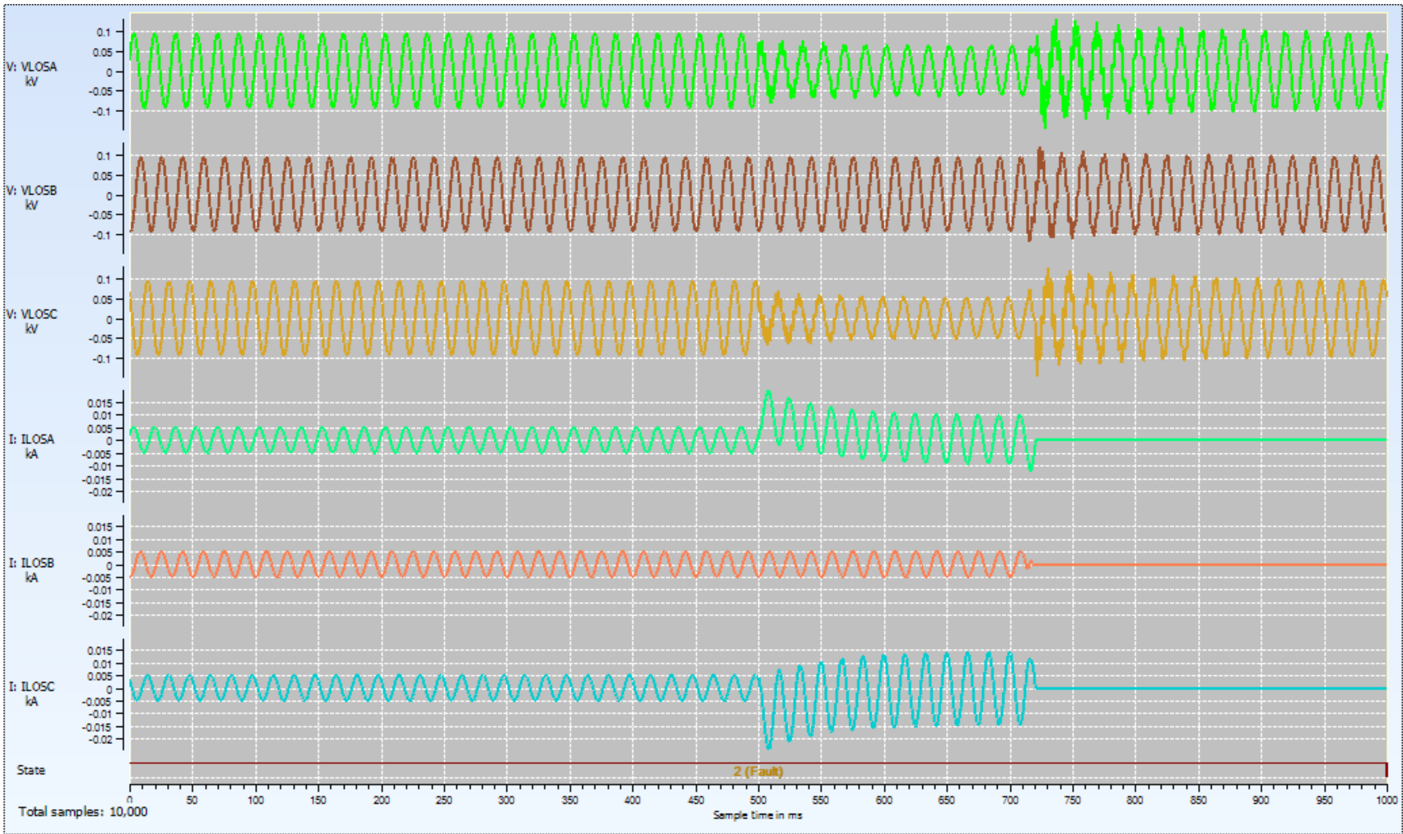


Fig. 22 – Bergeron Model - A-C Fault, Rf =0 Ohms

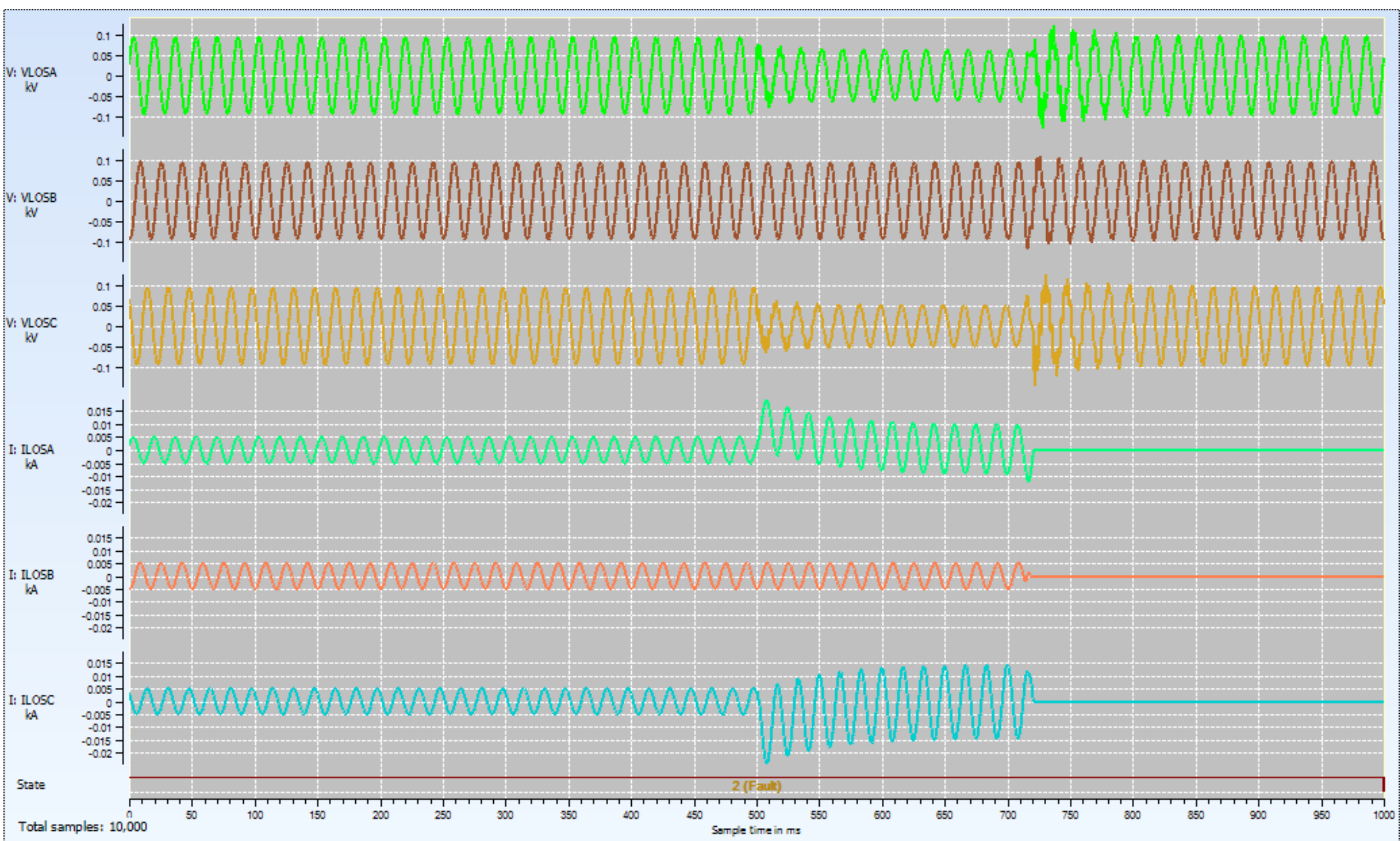


Fig. 23 – Frequency Dependent Model - A-C Fault, Rf =0 Ohms

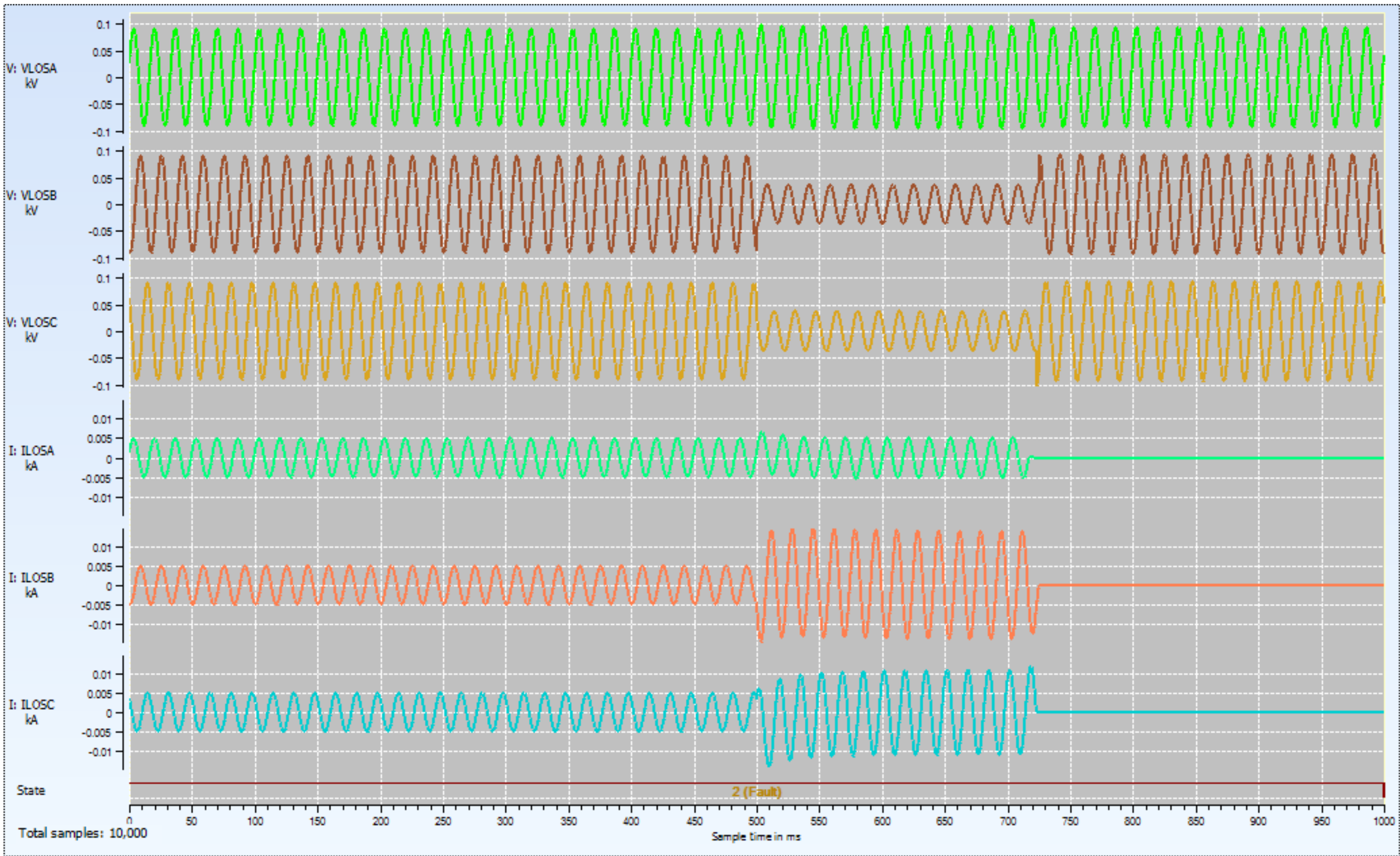


Fig. 24 – Symmetrical Components Model - B-C-G Fault, Rf =0 Ohms

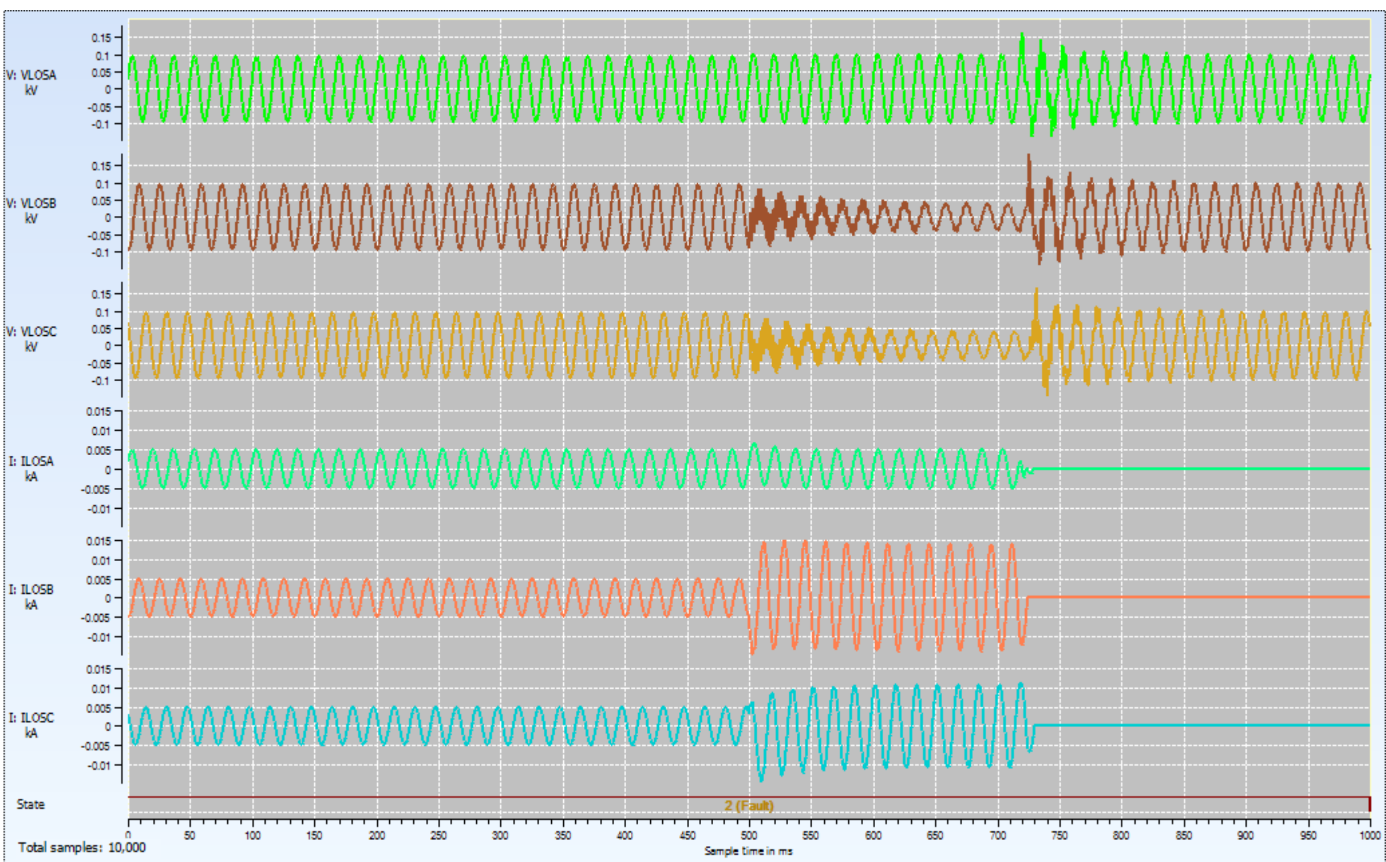


Fig. 25 – Coupled Pi Model - B-C-G Fault, Rf =0 Ohms

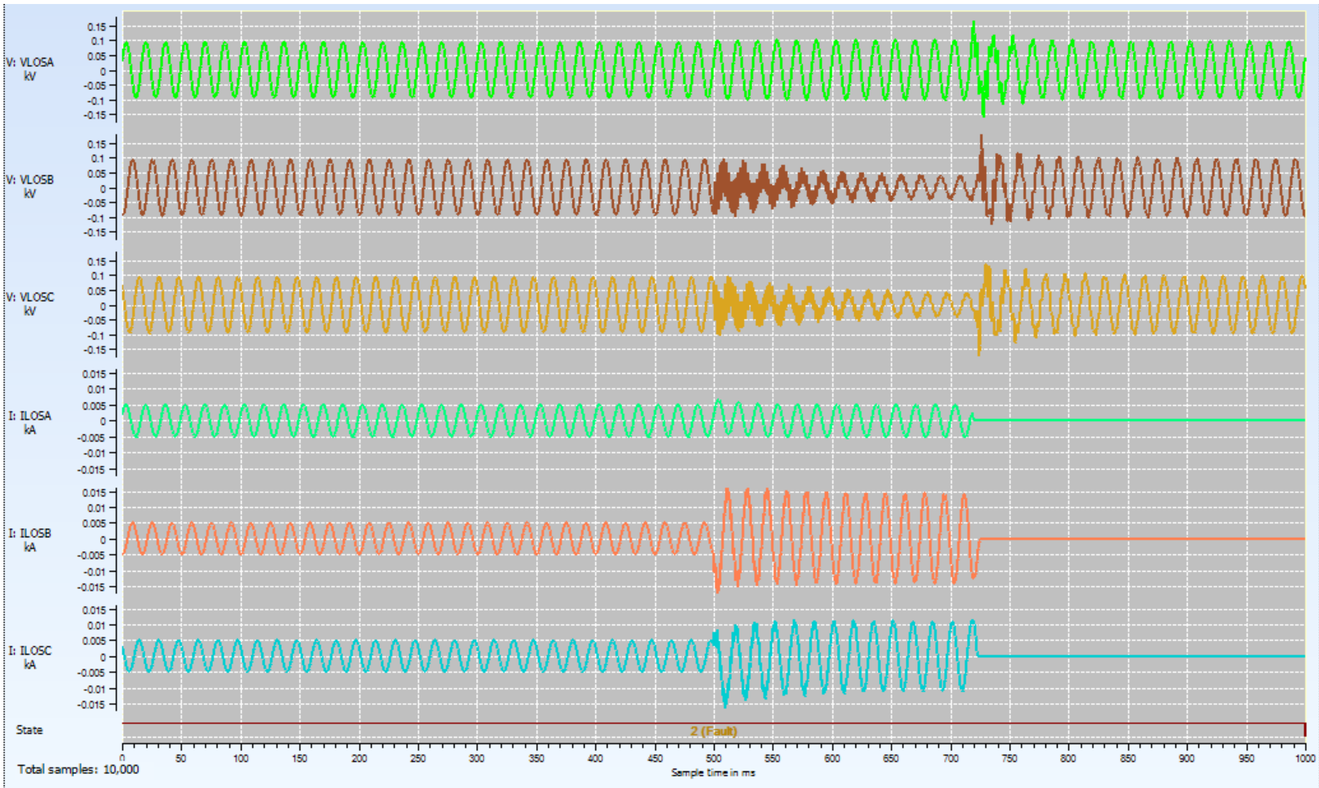


Fig. 26 – Distributed Pi Model - B-C-G Fault, Rf =0 Ohms

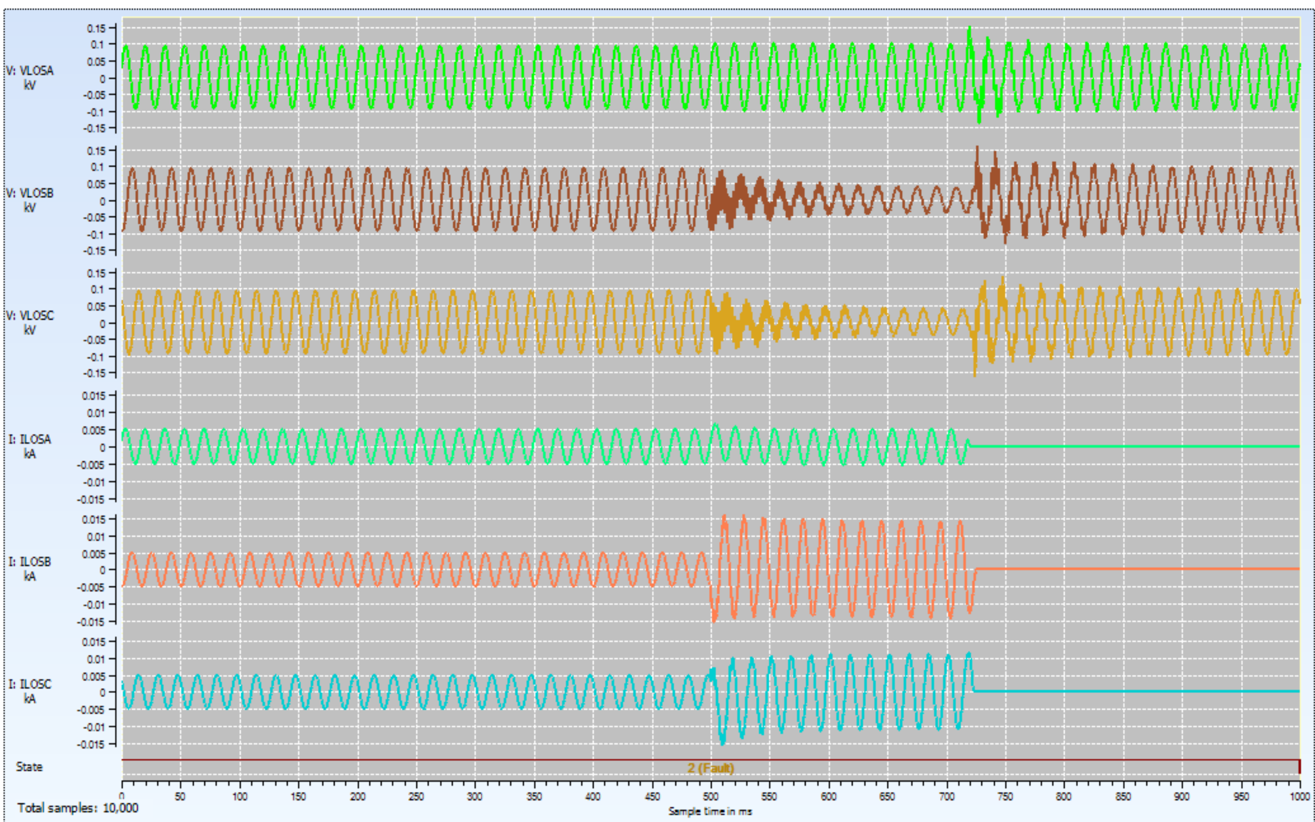


Fig. 27 – Bergeron Model - B-C-G Fault, Rf =0 Ohms

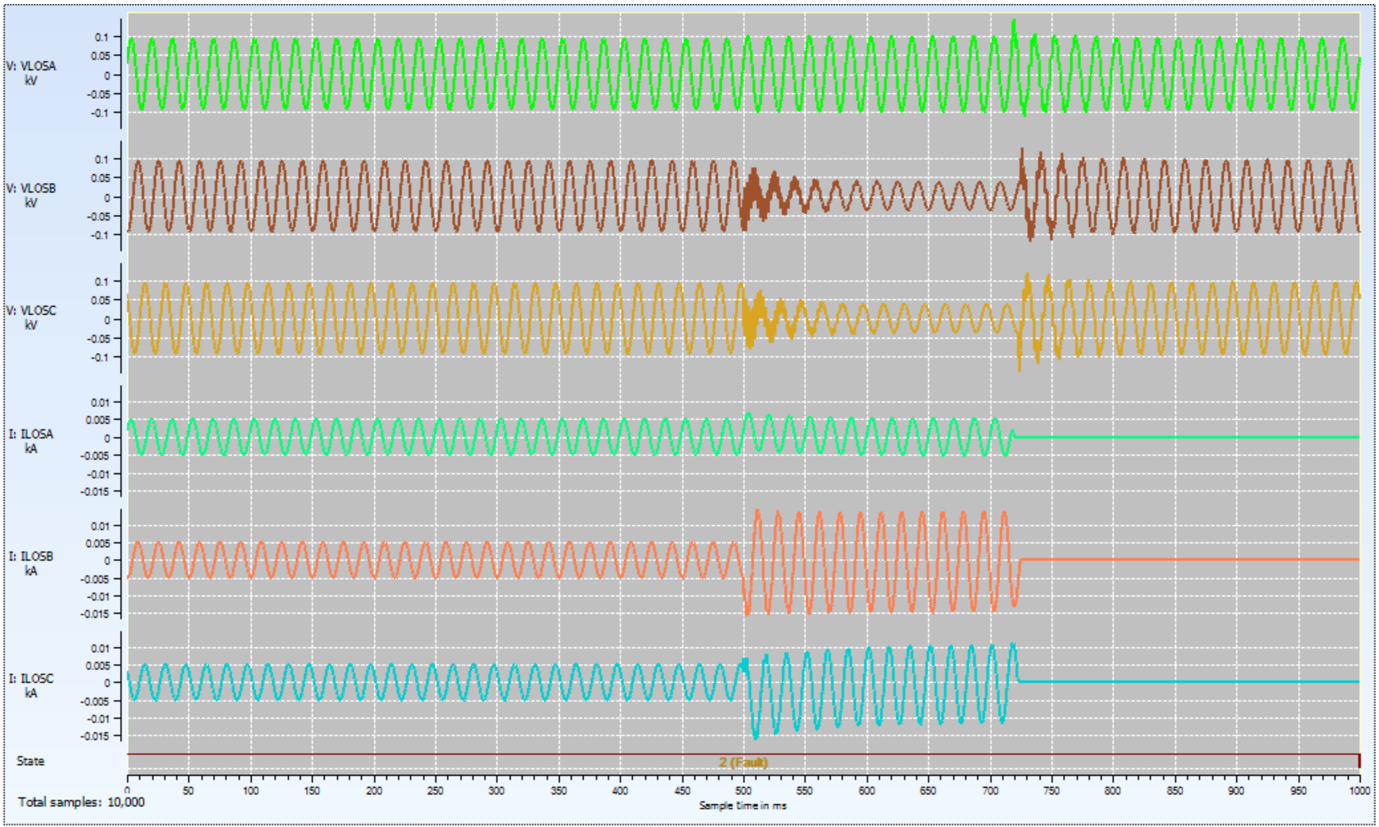


Fig. 28 – Frequency Dependent Model - B-C-G Fault, Rf =0 Ohms

APPENDIX II

TEST RESULTS – PERFORMANCE STATISCAL EVALUATION

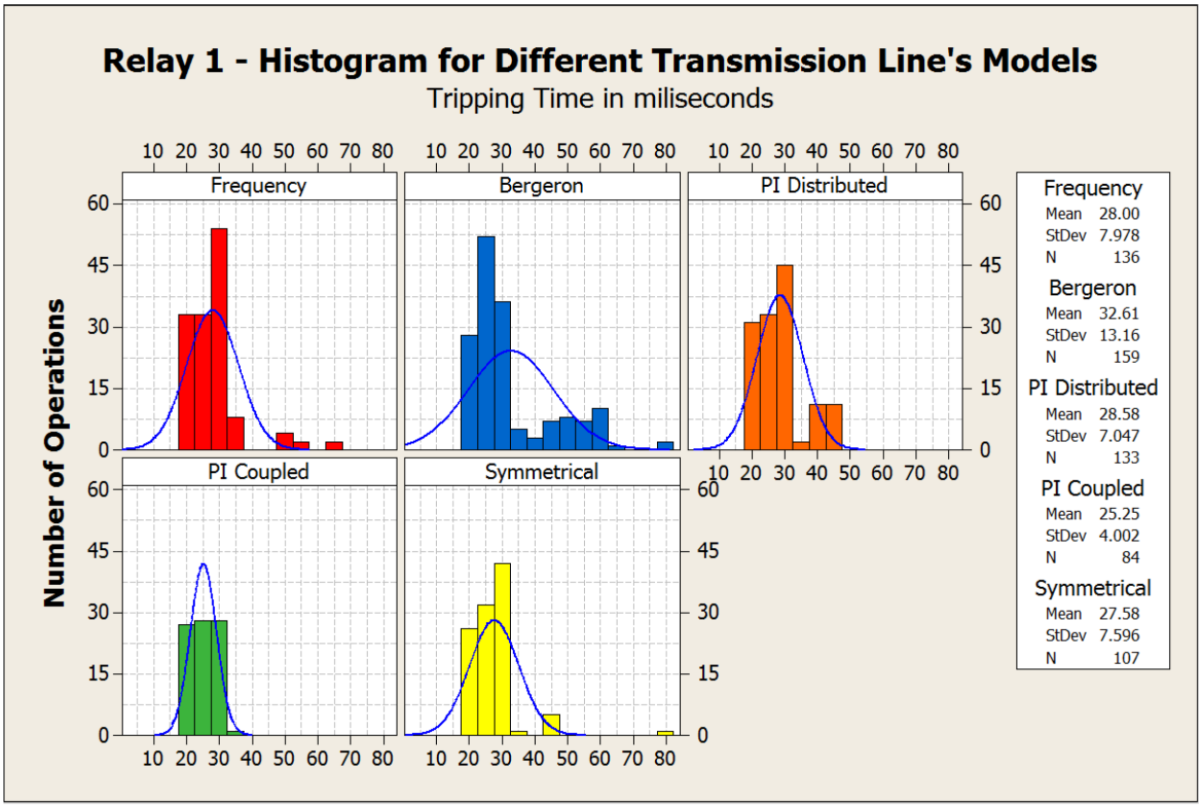


Fig. 29 – Relay 1 – Tripping Times while using different Transmission Line Models

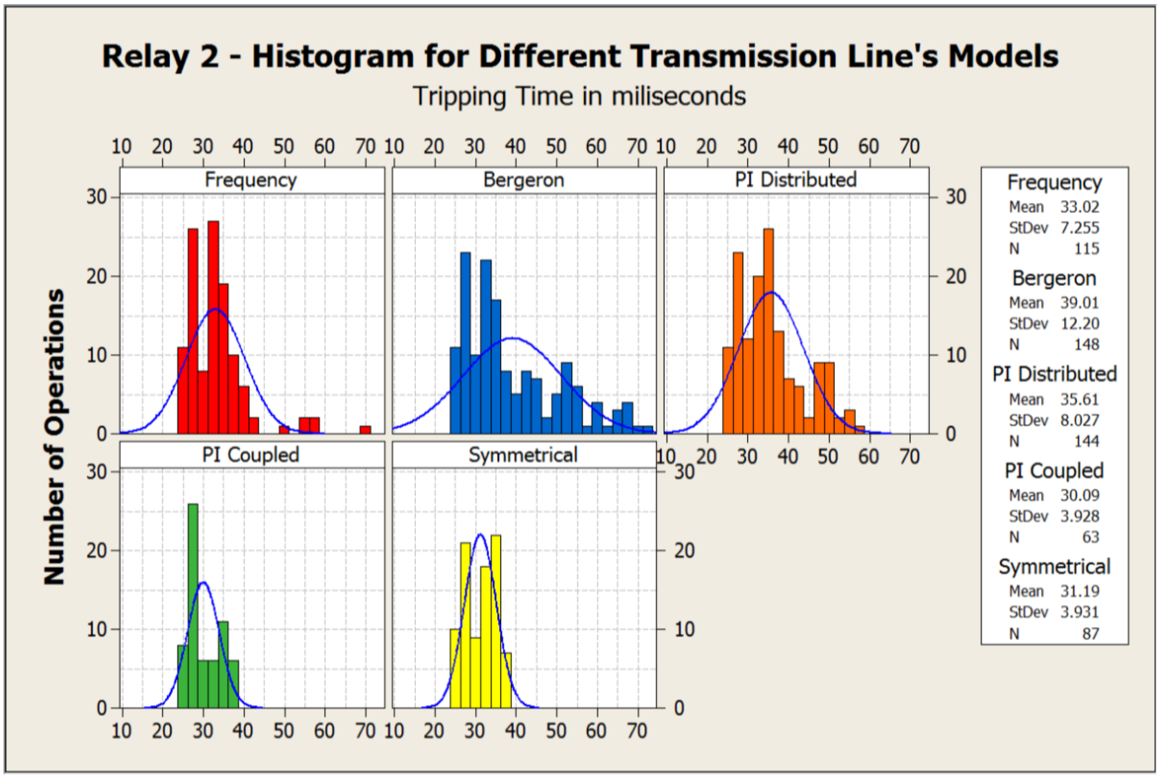


Fig. 30 – Relay 2 – Tripping Times while using different Transmission Line Models

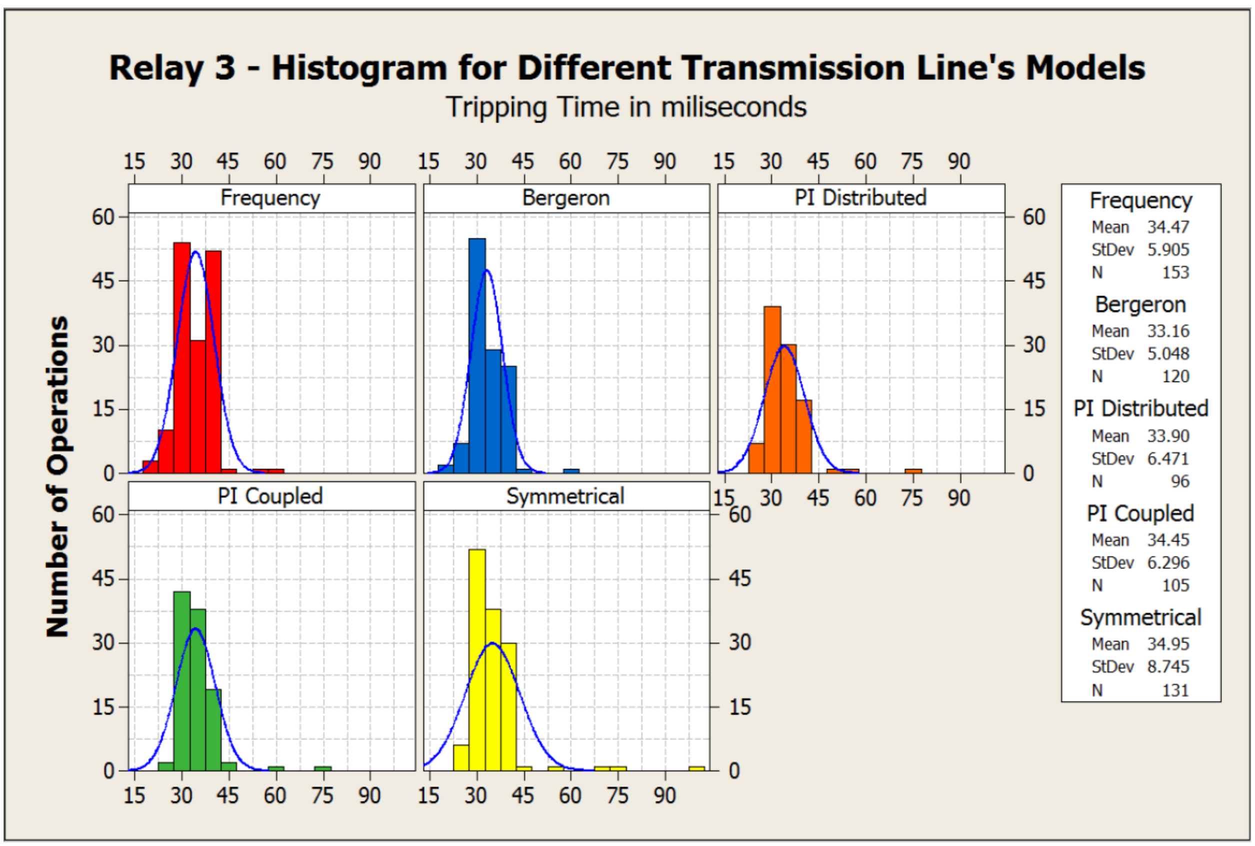
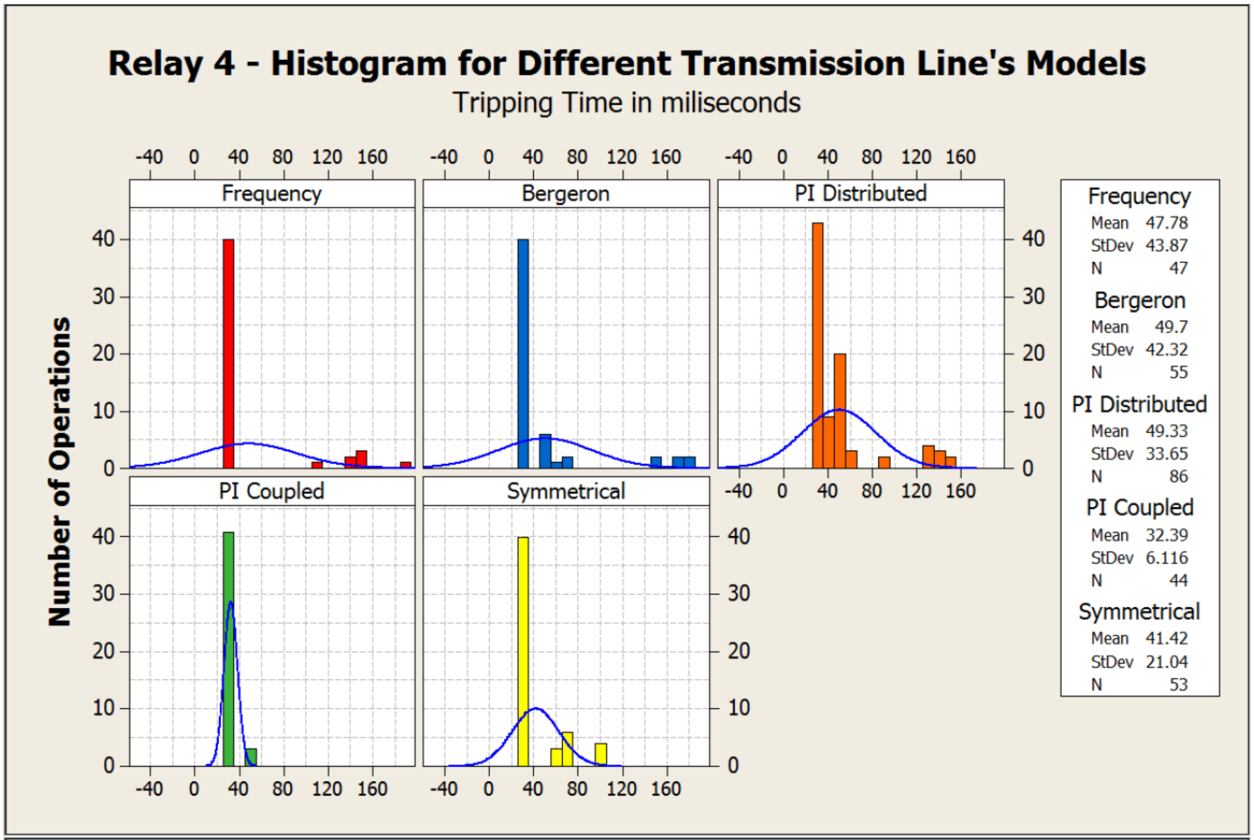


Fig. 31 – Relay 3 – Tripping Times while using different Transmission Line Models



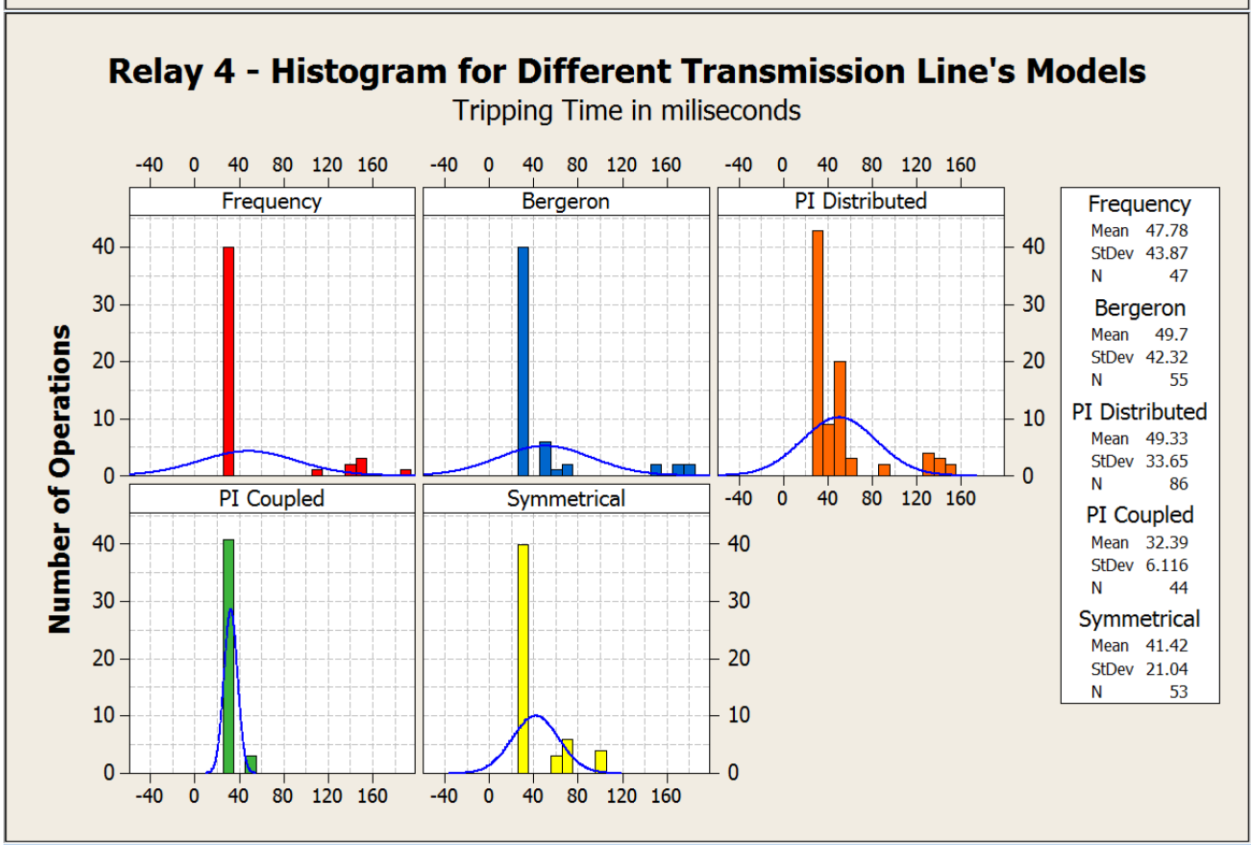


Fig. 32 – Relay 4 – Tripping Times while using different Transmission Line Models

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