RTE DSE – Protection Demonstration

Final Project Report

T-59G

Power Systems Engineering Research Center
Empowering Minds to Engineer
the Future Electric Energy System

RTE DSE – Protection Demonstration

Final Project Report

Project Team
Sakis Meliopoulos, Project Leader
George Cokkinides
Georgia Institute of Technology

Graduate Students
Jiahao Xie
Yuan Kong
Georgia Institute of Technology

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For information about this project, contact:

Sakis A.P. Meliopoulos
Georgia Institute of Technology
School of Electrical and Computer Engineering
Dept Mail Code: 0250
777 Atlantic Dr NW
Atlanta, GA 30332
Phone: 404-894-2926
E-mail: sakis.m@gatech.edu

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For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
527 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-727-2052

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Executive Summary

This report describes the application of setting-less relay on the RTE digital substation. We describe the model developed to simulate various events, and then play back these events into the setting-less relays to assess their performance. Four protection zones have been identified within the RTE digital substation. Use cases for each one of these protection zones have been developed with multiple events. The protection of each one of these protection zones has been studied under multiple events. Sample use cases of this testing is included in this report. A new methodology for correcting measurement errors from the instrumentation has been also developed and tested.

The basic idea of the setting-less protection relay has been inspired from the differential protection function which has a very important characteristic: it does not require coordination with any other protection functions. The differential protection monitors the validity of Kirchhoff's current law (KCL) within a protection zone. The setting-less protection can be considered as an extension and generalization of differential protection, because it can be viewed as monitoring the validity of all physical laws within the protection zone, i.e. KCL, KVL, thermodynamics, mechanical motion, etc. depending on the type of protection zone. The setting-less relay does not require coordination with any other protection function, a very big advantage. The setting-less relay replaces all the protection functions that are typically apply to a protection use using legacy protection systems.

Four protection zones have been identified within the RTE digital substation. The protection of these four zones has been studied extensively with numerical experiments as well as in the laboratory with hardware in the loop. In these studies we used a number of simulated test events. For the generation of the test events, a model of the RTE digital substation and the interconnected 220 kV and 90 kV system has been modeled with equivalent sources at the ends of the 220 kV and 90 kV transmission circuits. The model has been developed in WinIGS-T format (time domain). The report provides an overview of the model and the parameters of the major devices and the definition of the protection zones. The majority of the model parameters were provided by RTE. For missing parameter values, typical values were used. The model has been used to develop a large number of events for the purpose of testing the setting-less relay application on various protection zones of the RTE digital substation. A small number of these events are documented in a number of use cases which are included in this report.

For secure and reliable protection of power components such as a generator, line, transformer, etc. a new approach has emerged based on component health dynamic monitoring. The proposed method uses dynamic state estimation, based on the dynamic model of the component, which accurately reflects the nonlinear characteristics of the component as well as the loading and thermal state of the component.

The performance of any protection system is always dependent upon the quality and validity of the measurements, i.e. the input data into the relay. This has been recognized for any protective system and it is valid for the setting-less relays. The introduction of merging units offers a powerful way of correcting the measured sampled values in real time. Specifically, the model of the instrumentation channel can be used in a dynamic state estimation procedure to provide the estimated values of the primary quantities from the secondary quantities. This task can be

performed on each one of the instrumentation channels independently from any other channel, i.e. it is a distributed computation process and it does not affect the operation of the relay other than a small latency that is only a fraction of the sampling period. The process provides the best estimate of the primary sampled values. The report describes the implementation of the method and demonstrates the method on an example test system. It is shown that the method performs remarkably well even in cases of severe saturation of instrument transformers.

Project Publications:

[1] A. P. Sakis Meliopoulos, George Cokkinides, Jiahao Xie, and Yuan Kong, "Instrumentation Error Correction within Merging Units", Proceedings of the *2018 Georgia Tech Fault and Disturbance Analysis Conference*, Atlanta, Georgia, April 30-May 1, 2018.

[2] A. P. Sakis Meliopoulos, G. J. Cokkinides, Hussain Albinali, Paul Myrda and Evangelos Farantatos, “Integrated Centralized Substation Protection”, *Proceedings of the of the 51th Annual Hawaii International Conference on System Sciences*, Hawaii, HI, January 3-6, 2018.

Student Theses:

[1] Yuan Kong. *Instrumentation Error Correction and its Effects on Transmission*, PhD, Georgia Institute of Technology, 2019 (expected).

[2] Jiahao Xie. *Centralized Substation Protection*, PhD, Georgia Institute of Technology, Expected Graduation: 2019 (expected).

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1. Introduction

1.1 Background

Georgia Tech and EPRI, over the last few years, they have been developing the Dynamic State Estimation based protection method (a.k.a. setting-less protection). This technology has been demonstrated in the laboratory and also a demonstration project with NYPA under NYSERDA sponsorship is in progress. The objective of the proposed project is to demonstrate the technology on the digital substation that RTE is developing. A DSE based relay has been developed for the protection of selected protection zones of the RTE's digital substation and factory tested at the Georgia Tech laboratory. The plan is to install this relay to an RTE substation. As of the end of this project, this installation has not been completed due to schedules beyond the control of the investigators. The plan is to install the relay in the field when the conditions will permit in the future.

This report describes the application of setting-less relay on the RTE digital substation. The report describes the model developed to simulate various events, and then play back these events into the setting-less relays to assess their performance. Four protection zones have been identified within the RTE digital substation. Use cases for each one of these protection zones have been developed with multiple events. The protection of each one of these protection zones has been studied under multiple events. Sample use cases of this testing are included in this report.

1.2 Overview of the Problem

For the generation of the test events, a model of the RTE digital substation and the interconnected 220 kV and 90 kV system has been modeled with equivalent sources at the ends of the 220 kV and 90 kV transmission circuits. The model has been developed in WinIGS-T format (time domain). The report provides an overview of the model and the parameters of the major devices and the definition of the protection zones. The majority of the model parameters were provided by RTE. For missing parameter values, typical values were used. The model has been used to develop a large number of events for the purpose of testing the setting-less relay application on various protection zones of the RTE digital substation. A small number of these events are documented in a number of use cases which are included in this report.

1.3 Report Organization

The report is organized as follows:

Section 2 provides a brief description of setting-less protection relay.

Section 3 introduces the sample data correction method for the instrumentation channel.

Section 4 together with Appendices A, B, C, D, E and F provides the parameters of the major devices included in the model. The EBP setting-up is also included in Section 4.

Section 5 and section 6 present a number of events for protection zones. The events include various fault and non-fault conditions and they are used for laboratory evaluation of the setting-less relays.

Appendix G provides detailed description of protection zones of the BLOCAUX substation to be considered for implementation of the setting-less relay. It does not include all the protection zones of the substation.

2. The Setting-less Protective Relay

For secure and reliable protection of power components such as a generator, line, transformer, etc. a new approach has emerged based on component health dynamic monitoring. The proposed method uses dynamic state estimation, based on the dynamic model of the component, which accurately reflects the nonlinear characteristics of the component as well as the loading and thermal state of the component.

The basic idea of the setting-less protection relay has been inspired from the differential protection function which has a very important characteristic: it does not require coordination with any other protection functions. The differential protection monitors the validity of Kirchhoff's current law (KCL) within a protection zone. The setting-less protection can be considered as an extension and generalization of differential protection, because it can be viewed as monitoring the validity of all physical laws within the protection zone, i.e. KCL, KVL, thermodynamics, mechanical motion, etc. depending on the type of protection zone. The setting-less relay does not require coordination with any other protection function, as it is illustrated in Figure 2-1.

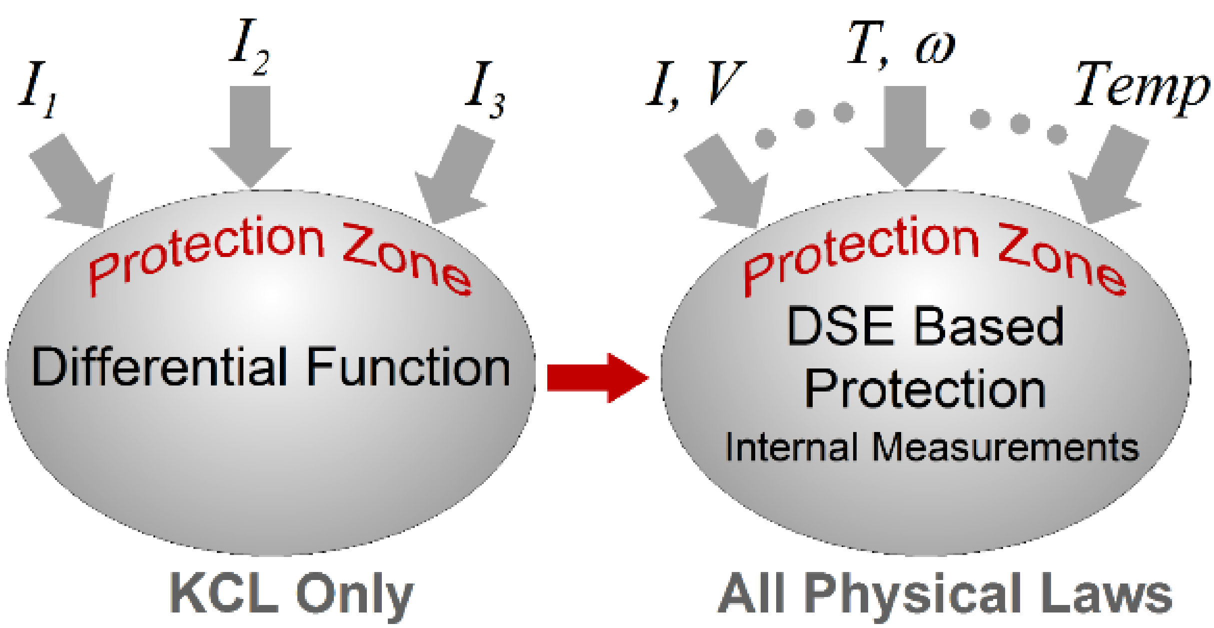


Figure 2-1: Conceptual Description of the Estimation Based Protection

In differential protection the electric currents at all terminals of a protection zone are measured and their weighted sum must be equal to zero (generalized Kirchhoff's current law). As long as the sum is zero or near zero no action is taking. Note that there are possible internal faults in a protection zone that will result in satisfaction of Kirchhoff's current law for the currents at the terminals of the protection zone. In this case the differential protection will not detect these faults, i.e. differential protection fails in this case. In DSE based protection, all existing measurements in the protection zone are utilized. Specifically, currents and voltages at the terminals of the protection zone, as well as voltages, currents inside the protection zone (as in capacitor protection) or speed, temperature and torque in case of rotating machinery or any other internal measurements. Then, the dynamic model of the device (consisting of physical laws such as KCL, KVL, motion laws, thermodynamic laws, etc.) is used to provide the inter-relationships among all measured quantities. When there is no fault within the protection zone, the measurements should satisfy the dynamic model of the protection zone. A dynamic state estimation procedure provides a systematic and mathematically rigorous way to verify that the measurements satisfy the mathematical model. When an internal fault occurs, the measurements do not fit the mathematical model of the protection zone and a protection action is triggered. The resulting method is a Dynamic State **E**stimation **B**ased **P**rotective relay (**EBP** relay). When an internal fault occurs, even high impedance faults or faults along a coil, etc., the dynamic state estimation reliably detects the abnormality and a trip signal can be issued. Three distinct dynamic state estimation algorithms (Extended Kalman Filter, Constraint Optimization and Unconstraint Optimization) have been developed and tested. Each algorithm requires the mathematical model of the protection zone, including instrumentation and the measurements. This basic approach has been extensively tested in the laboratory for several protection zones and presented in technical papers. It was named setting-less protection because of the simplicity of use and its lack of coordination issues with other relays, in the same way as differential protection does not require coordination.

In addition, setting-less relays have been extensively tested in the laboratory with hardware in the loop.

2.1 Setting-less Relay Testing with Hardware in the Loop

Prototype setting-less protective relays have been developed in the laboratory, connected to a system represented with a simulator, digital to analog conversion, amplifiers and data acquisition systems (merging units). This setup enables testing with hardware in the loop. The setup consists of (a) merging units to perform data acquisition, (b) a process bus, and (c) a personal computer attached to the process bus and performing the protection functions (the personal computer "runs" the setting-less protection). The setting-less protective relay block diagram, as implemented in the laboratory is illustrated in Figure 2-2.

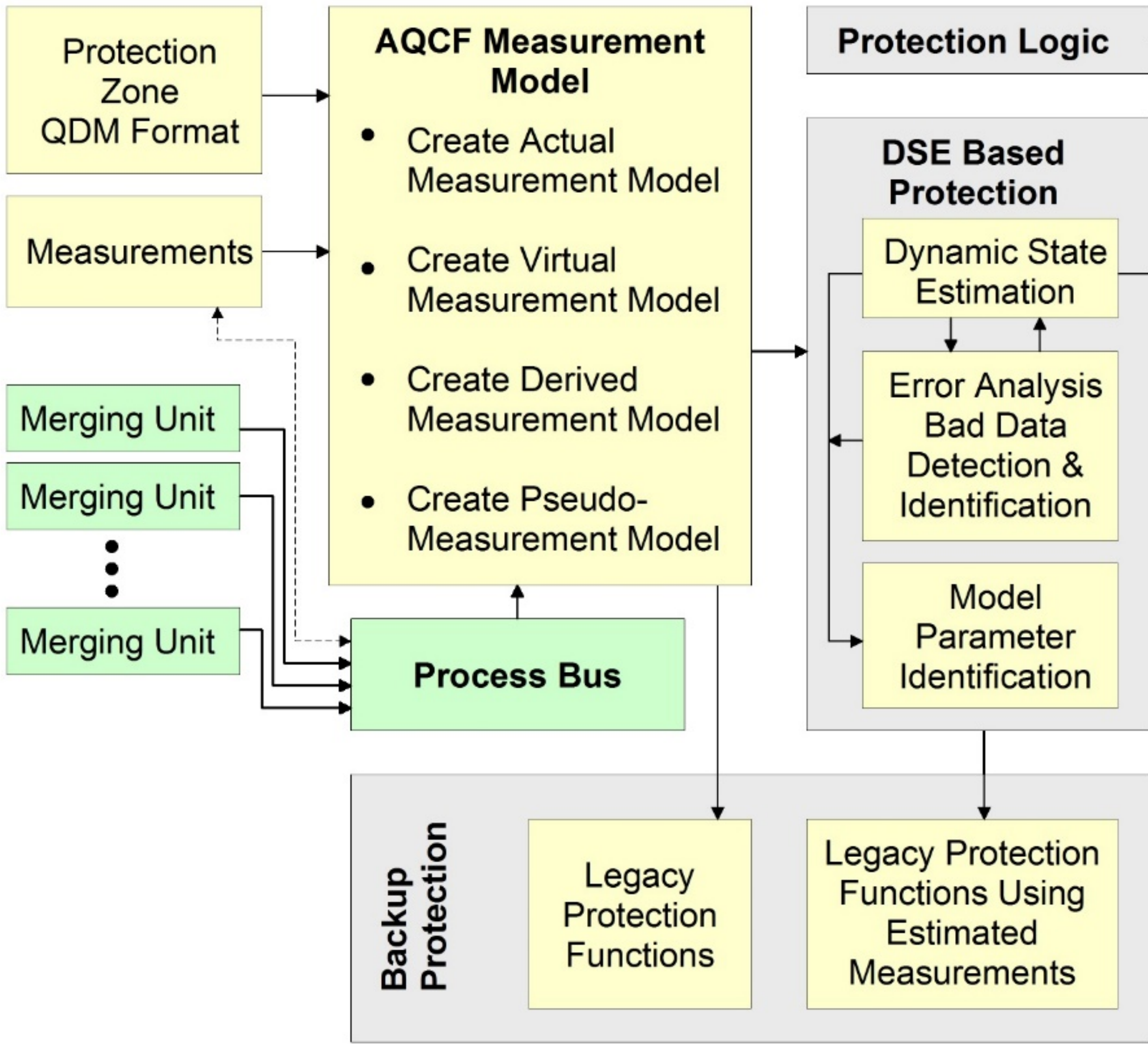


Figure 2-2: Block Diagram of Estimation Based Relay

The physical system under protection (not shown in the figure) is simulated in the laboratory via a computer controlled system of digital to analog converters, amplifiers (we use Omicron amplifiers) that amplify the signal to relay instrumentation levels and then the signals are injected into the merging units, shown in Figure 2-2. From that point on, the setup uses actual equipment. The merging units are GE Hardfiber, Siemens or Reason (we can include more manufacturers of merging units as they become available). Merging units are connected to a process bus. A personal computer is connected to the process bus and retrieves the streaming data as they are reported by the merging units. The personal computer performs the setting-less protection functions and optionally displays the results or selective visualizations. The physical construction of the laboratory is shown in the photograph below.

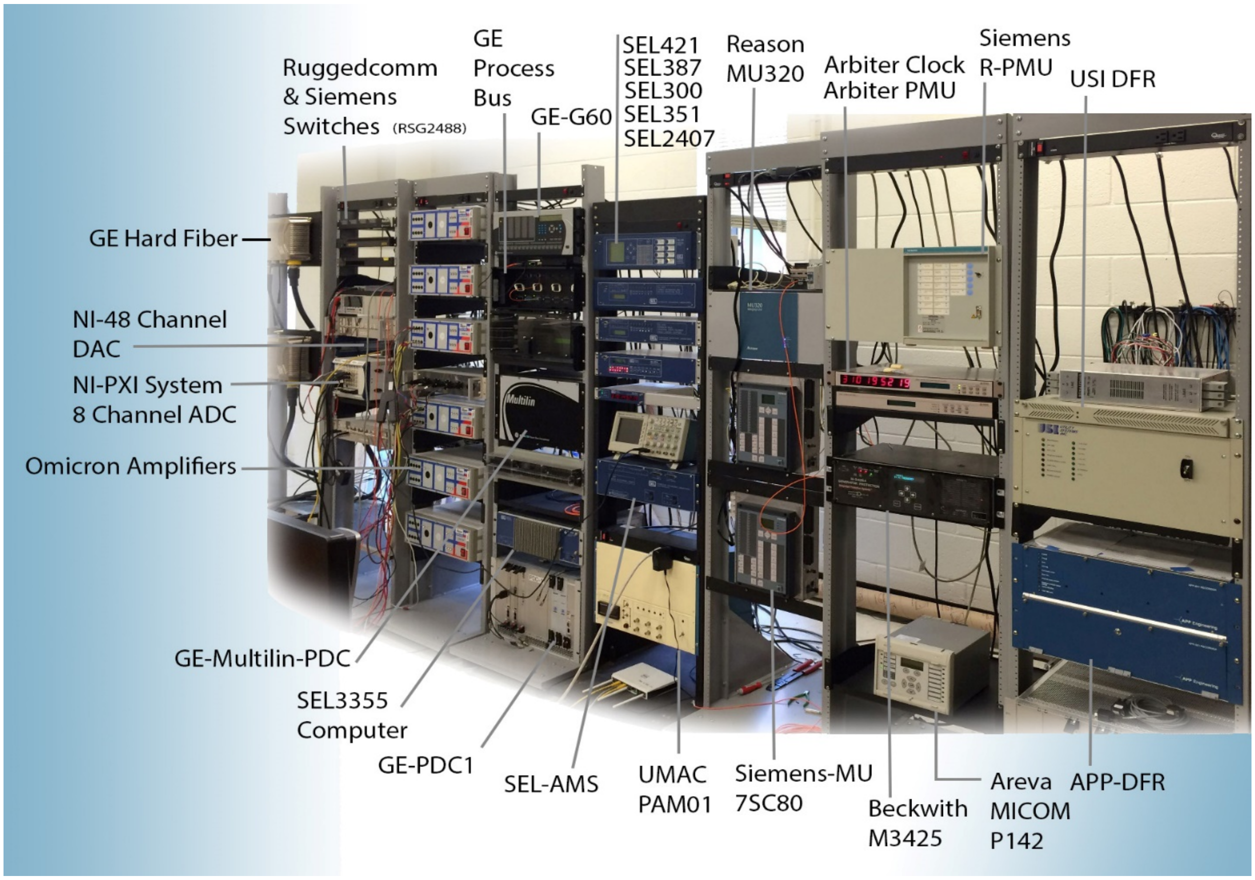


Figure 2-3 Photograph of the PSCAL (Power System Control and Automation Laboratory)

The laboratory experiments indicate that the analytics of the setting-less protection function can be performed within the time period between two successive sets of streaming data, i.e. the setting-less protection can operate in real time as any other numerical relay by simply using a standard high end personal computer. In the tests we used sampling rates of 80 samples per cycle (IEC standard). In this case the available time between two successive executions of the dynamic state estimator is 416 microseconds. This is plenty of time to perform the computations for most protection zones. For complex protection zones, such as unit protection of a generator and transformer, higher power computers may be needed or the algorithms must be parallelized and be running on multiple core computers.

The setting-less relay has been also named the EBP relay, standing for **E**stimation **B**ased **P**rotection.

Many visualizations have been developed which provide real time view of the operation of the estimation based relay. Figure 2-4 shows two example visualizations from an EBP applied to a three phase delta-wye connected transformer. Many other visualizations are possible and are typically customized to specific protection zones.

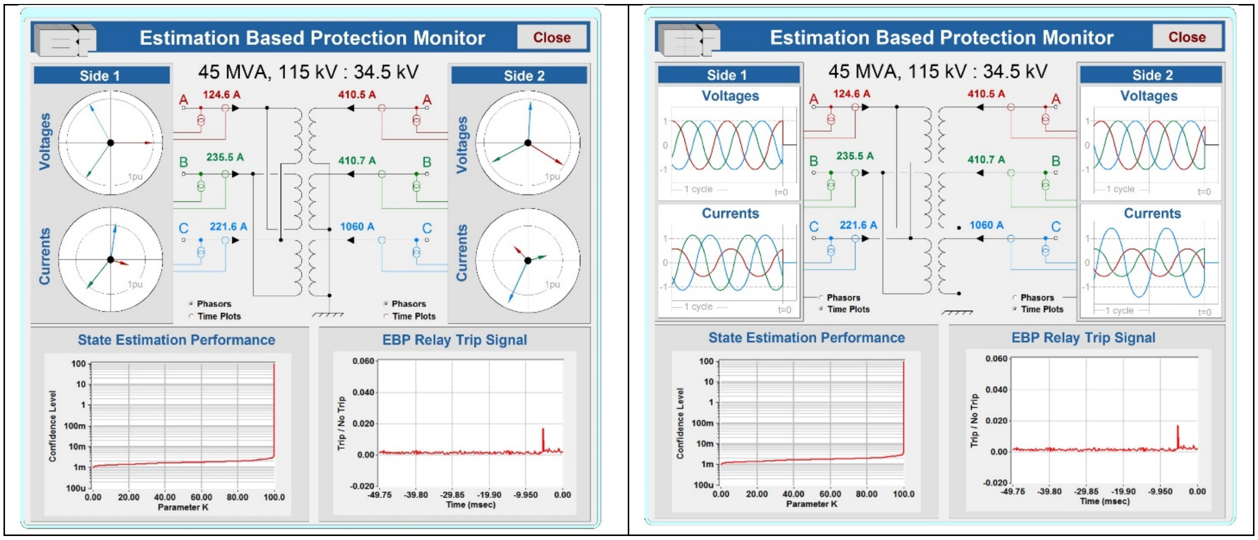


Figure 2-4: Example Visualizations of a Setting-less Relay Applied to a Transformer

The development of the EBP relay faced several challenges. A partial list of the challenges is given below. These challenges can be overcome with present technology. The project has demonstrated that these challenges are met.

1. Ability to perform the dynamic state estimation in real time
2. Initialization issues
3. Communications in case of a geographically extended component (i.e., lines)
4. New modeling approaches for components - connects well with the topic of modeling
5. Requirement for GPS synchronized measurements in case of multiple independent data acquisition systems.

The modeling issue is fundamental in this approach. For success the model must be dynamic and high fidelity so that the component dynamic state estimator will reliably determine the operating status (health) of the component. For example, consider a transformer during energization. The transformer will experience high in-rush current that represent a tolerable operating condition and therefore no relay action should occur. The component state estimator should be able to "track" the in-rush current and determine that they represent a tolerable operating condition. This requires a transformer model that accurately models saturation and in-rush current in the transformer. We foresee the possibility that a high-fidelity model used for protective relaying can be used as the main depository of the model which can provide the appropriate model for other applications. For example, for EMS applications, a positive sequence model can be computed from the high-fidelity model and send to the EMS data base. The advantage of this approach will be that the EMS model will come from a field validated model (the utilization of the model by the relay in real time provide the validation of the model). Since protection is ubiquitous, it makes economic sense to use relays for distributed model data base that provides the capability of perpetual model validation.

For this project, dynamic high fidelity models were developed for the four protection zones of the RTE substation. These protection zones include the following components: (a) three-phase 90 kV cables, (b) three winding transformers, and (c) three phase reactors. Dynamic high fidelity models of these components have been developed.

2.2 Data Correction within Merging Units

The technology used in the implementation of the setting-less relays provides another possibility. Specifically, merging units sample voltages and currents and transmit the sample values to the process bus and upstream applications. It is possible to provide intelligence to the merging units to make error correction on these measurements. Specifically, the instrumentation channel model is known. The instrumentation channel model together with the measurement at the burden of the channel at the merging unit can be used in a dynamic stat estimation procedure to provide the best estimate of the primary quantity. Note this process can be applied to any instrumentation channel independently of how many channels exist. It is also performed at the merging unit level so that the merging unit will stream the estimated values of the primary quantities. The implementation of this approach is shown in Figure 2-5. The details of the method and results are presented in section 3.

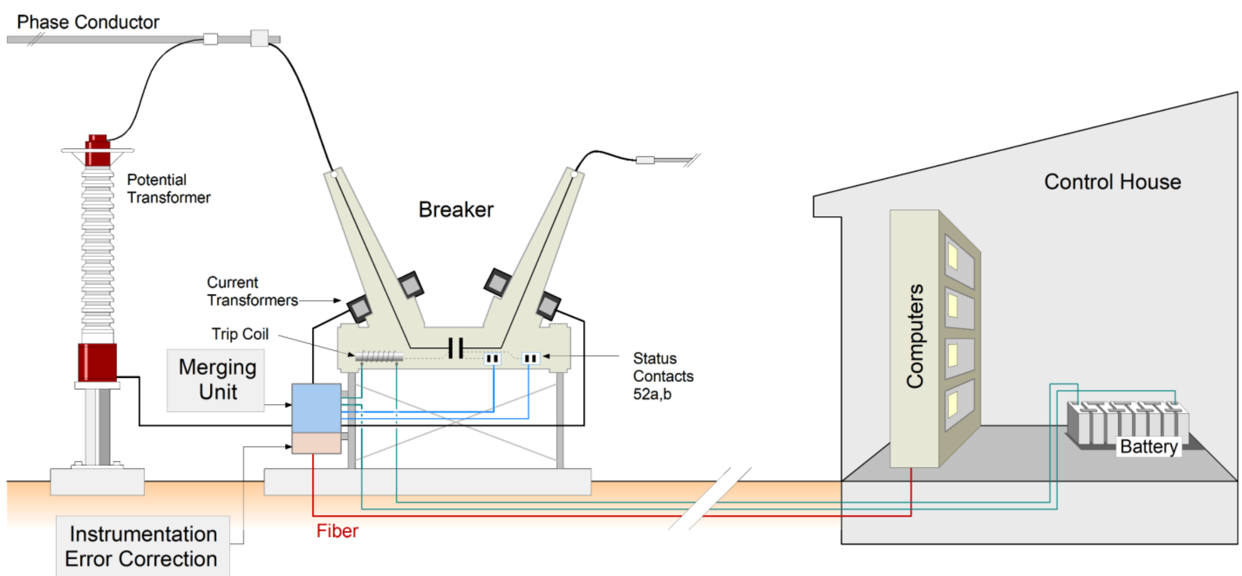


Figure 2-5: Error Correction within Merging Units

We have demonstrated the feasibility of the method and the results are very good. The algorithm practically removes the errors from the non-ideal instrumentation components (instrument transformers, cables, burdens, etc.) and the estimated primary quantities are practically identical to the actual primary quantities. The study has been performed with a series of computational experiments. It is expected that in the future these algorithms will be impeded in merging units. This feature will have a very favorable impact on the performance of the setting-less relays as the quality of the data will drastically improve.

3. Sample Value Data Correction

The performance of any protection system is always dependent upon the quality and validity of the measurements, i.e. the input data into the relay. This has been recognized for any protective system. The introduction of merging units offers a powerful way of correcting the measured sampled values in real time. Specifically, the model of the instrumentation channel can be used in a dynamic state estimation procedure to provide the estimated values of the primary quantities from the secondary quantities. The dynamic state estimation has the inherent capability to correct the errors introduced by the instrumentation channel. While this approach works, it generates a very large dynamic model for the setting-less relay application. The dynamic model consists of the protection zone and all the instrumentation channel models. The dimensionality of this model is very large and impacts the ability of the setting-less relay to perform the computations within the time step between sampled values. One way to avoid this problem is to distribute the computations. Specifically, the instrumentation channel modeling and error correction can be performed for each individual instrumentation channel separately. This process can provide the best estimate of the primary sampled values. This approach is presented here.

3.1 Method Description

The instrumentation subsystem is to provide the proper interface between the high voltage electric power system and the relays that operate at relatively low voltage. In this report, we focus on instrumentation subsystems that are based on Merging Units (MU). In this case, the instrumentation subsystem consists of instrument transformers that convert the high voltage and/or high current of the power system into instrumentation level voltages and currents that can be fed into the Merging Unit. Standard voltages for Merging Units are 69 V and 115 V and standard currents are 5A and 1A.

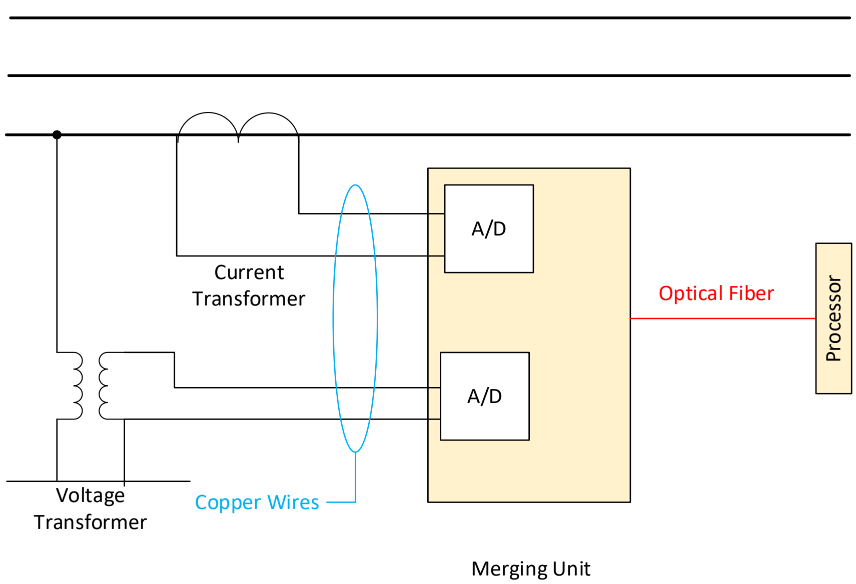


Figure 3-1: Instrumentation Channel Subsystem – Voltage and Current Instrumentation Channel

As shown in Figure 3-1, in general, the instrumentation subsystem consists of instrument transformers (voltage transformers and current transformers), copper wires and the merging unit/relay input circuit. The analog to digital conversion stage is contained in the Merging Unit. Ideally, these voltages and currents should be scaled replicas of the high voltages and currents of the electric power system. Practically, however, the instrumentation channels introduce errors that can distort the waveforms of the high voltage and currents. In some cases, these errors will even cause the mal-operation of the relay. Therefore, to make the protection scheme reliable, it is essential to correct the errors introduced by the instrumentation channels.
We define instrumentation error as follows:

Current Instrumentation Channels:

$$\varepsilon = \frac{\left| k \cdot i_S(t) - i_P(t) \right|}{I_{range}}$$

Where :

$i_S(t)$ is the secondary instantaneous current value

$i_P(t)$ is the primary instantaneous current value

I_{range} is the CT's primary current range

Voltage Instrumentation channels:

$$\varepsilon = \frac{\left| k \cdot v_S(t) - v_P(t) \right|}{V_{range}}$$

Where:

$v_P(t)$ is the primary instantaneous voltage value

$v_S(t)$ is the secondary instantaneous voltage value

V_{range} is the PT's primary voltage range

There are four parts in the instrumentation channel introducing errors to the primary voltage and current:

Instrument Transformers
Copper Wires
Merging unit/relay input circuit
Analog to Digital Converter

In the following analysis, we will focus on the error introduced by the instrument transformers, copper wires and the merging unit/relay input circuit in the following analysis. As for error introduced by a N bit Analog to Digital Converter (ADC), which is called the "Quadratuer Error", it is typically very small for today's IEDs and can be calculated as:

$$Quadratuer\ Error = 0.5 * \frac{V_{\max}}{2^N}$$

Where Vmax is the scale voltage for the ADC.

A typical Current Instrumentation Channel configuration is shown in Figure 3-2. It has three components: the current transformer, the instrumentation cable and the burden resistor. The problem is stated as follows: a measurement is taken of the voltage or current through the burden to estimate the electric current in the primary of the CT. As shown in Figure 3-2, the measurement we have is the voltage across the burden resistor, which is “Vout”. The current we are going to compute is the current transformer primary current, which is i_1. Then, the dynamic state estimation method will be used to compute i_1.

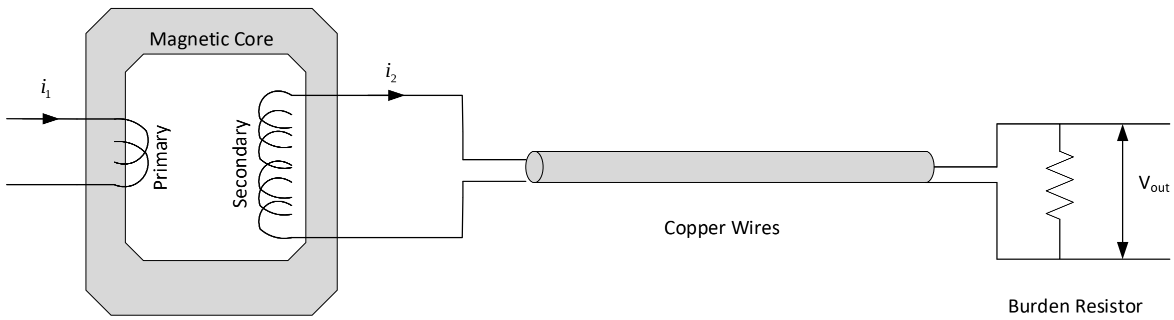


Figure 3-2: Typical Current Instrumentation Channel Configuration

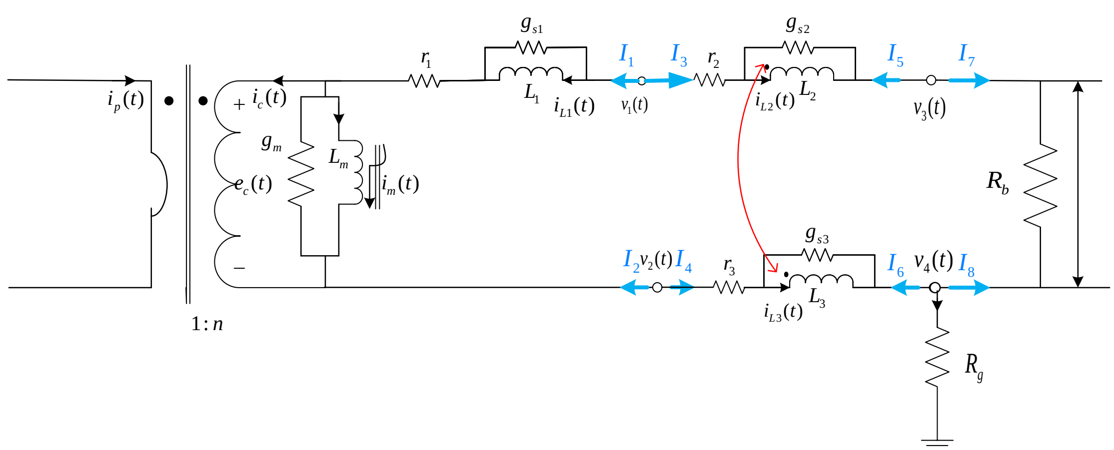


Figure 3-3: Equivalent Circuit of CT’s Primary Current Estimation

The equivalent circuit of CT’s primary current estimation is shown in Figure 3-3. To estimate the CT’s primary current, the measurement model will be constructed. The measurement model has 19 states, which is:

$$
\begin{aligned}
X = [&v_1(t) \quad v_2(t) \quad v_3(t) \quad v_4(t) \\
&i_p(t) \quad i_{L_1}(t) \quad i_c(t) \quad e_c(t) \quad i_m(t) \quad \lambda(t) \\
&i_{L_2}(t) \quad i_{L_3}(t) \quad v_{s2}(t) \quad v_{s3}(t) \\
&y_1(t) \quad y_2(t) \quad y_3(t) \quad y_4(t) \quad y_5(t)\ ]^T
\end{aligned}
$$

In the measurement model, there are 24 measurements, including 1 actual measurement, 8 derived measurements, 1 pseudo measurement, and 14 virtual measurements.

One approach to achieve the robustness of setting-less protection is to get the estimation of primary current (voltage) from the secondary current (voltage). Then, this estimated current and voltage will be used in the setting-less protection scheme. The weighted least square (WLS) method is used for the estimation. WLS method provides a solution that minimizes the sum of squares of the residuals for each single measurement equation. For the nonlinear measurement model, a local optimal solution can usually be reached using the Newton's method.
Taking the instrument transformer as an example, any measurement (actual, derived, pseudo or virtual measurement) can be expressed in terms of the transformers states and the transformer dynamic model in AQCF form:

$$\mathbf{z}(t) = \mathbf{h}_t(\mathbf{x}(t),\mathbf{x}(t_m)) = Y_{t,x}\begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix} + \begin{Bmatrix}\vdots\\ \begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix}^T F^i_{t,x}\begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix}\\ \vdots\end{Bmatrix} + N_{t,x}\mathbf{x}(t-h) + M_t\mathbf{i}(t-h) + K_t + \eta_t$$

$$\mathbf{z}(t_m) = \mathbf{h}_{tm}(\mathbf{x}(t),\mathbf{x}(t_m)) = Y_{tm,x}\begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix} + \begin{Bmatrix}\vdots\\ \begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix}^T F^i_{tm,x}\begin{bmatrix}\mathbf{x}(t)\\ \mathbf{x}(t_m)\end{bmatrix}\\ \vdots\end{Bmatrix} + N_{tm,x}\mathbf{x}(t-h) + M_{tm}\mathbf{i}(t-h) + K_{tm} + \eta_{tm}$$

Where z is the measurement (actual, derived, pseudo or virtual measurement), x is the state variables.

Mathematically, the WLS method can be written in the following way:

$$Min\ J = \sum_{i=1}^{n}\left(\frac{h_i(x) - z_i}{\delta_i}\right)^2 = \sum_{i=1}^{n} s_i^{\ 2} = \eta^T W \eta$$

Where $\eta = h(x) - z$, $s_i = \dfrac{\eta_i}{\delta_i}$ and $W = diag(\cdots,\dfrac{1}{\delta_i^{\ 2}},\cdots)$ and δ_i is the standard deviation of the meter by which the corresponding measurement z is measured.
The best estimate of the system is obtained from the Gauss-Newton iterative algorithm:

$$\hat{x}^{v+1} = \hat{x}^{v} - (H^T W H)^{-1} H^T W (h(\hat{x}^{v}) - z)$$

Where $\hat{x}^v$ refers to the best estimate of the state vector x, and H is the Jacobian matrix of the measurement equations: $H = \dfrac{\partial h(x)}{\partial x}$
The goodness of fit is defined as the probability that the distribution of the measurement errors are within the expected bounds. Consider the normalized residuals computed at the solution $\hat{x}$, we have postulated that the normalized residuals are Gaussian random variables with zero mean and standard deviation 1.

Now the goodness of fit is defined as the probability that the distribution of the measurement errors is within the expected bounds. This probability is computed as follows. Assume that the state estimate has been computed with the least square approach. Consider the normalized residuals computed at the solution $\hat{x}$. We have postulated that the normalized residuals s_i are Gaussian random variables with zero mean and standard deviation 1. Now consider the following variable

$$\chi^2 = \sum_{i=1}^{m} s_i^2$$

The probability distribution function of a general chi-square distributed random variable

$\Pr(\zeta, v) = \Pr\left[x^2 \leq \zeta\right]$, with v degrees of freedom, where $\zeta = \sum_{i=1}^{m} s_i^2(\hat{x}) = \sum_{i=1}^{m} \left(\frac{h_i(\hat{x}) - b_i}{\sigma_i} \right)^2$.

We will call this probability the confidence level of the state estimate. The confidence level is computed as follows. The confidence level is computed as follows. Consider the least squares solution $\hat{x}$, this solution minimizes the sum of the squares of s_i , i.e. any other state vector x will result in a larger value of χ^2 . The probability of above event, $x^2 \geq \zeta$ is given by the chi-square distribution

$$\Pr\left[x^2 \geq \zeta\right] = 1 - \Pr\left[x^2 \leq \zeta\right] - 1 - \Pr(\zeta, v)$$

3.2 Example Results

An example test system is utilized to model instrumentation channels and merging units to create simulated data of primary currents and measured values at the merging units. Subsequently, the measured values at the merging unit are used in the dynamic state estimation to provide the best estimate of primary current. Since the primary current is known form the simulation, the absolute error of the method can be computed, thus providing and excellent measure of performance of the proposed method.

The example test system is presented in Figure 3-4. It comprises a 115-kV transmission system. A current transformer measures phase A current of the line that is located on the left hand side of the figure. The CT ratio is 800:5A, and the error class for the CT is 10C100. The instrumentation cable is #10 cable with the length 96 meters. The burden resistance is 0.1 Ω.

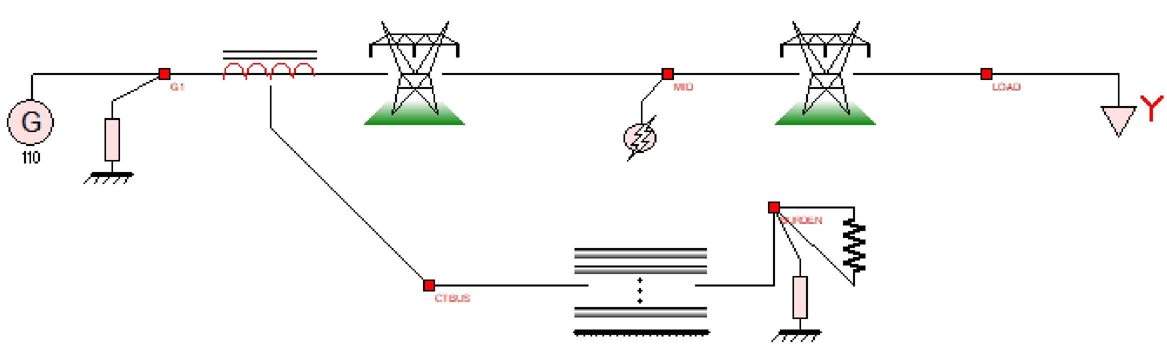


Figure 3-4: Example System for Current Instrumentation Channel Error Correction

Event 1: Low CT saturation: A phase A to ground fault at bus MID (middle of Figure 3-4) was simulated. This fault yields fault current that causes low CT saturation of the instrumentation channel. The merging unit measures the CT secondary current through the burden resistor, as shown in Figure 3-5. It can be seen in Figure 3-5 that the CT secondary current is moderately distorted.

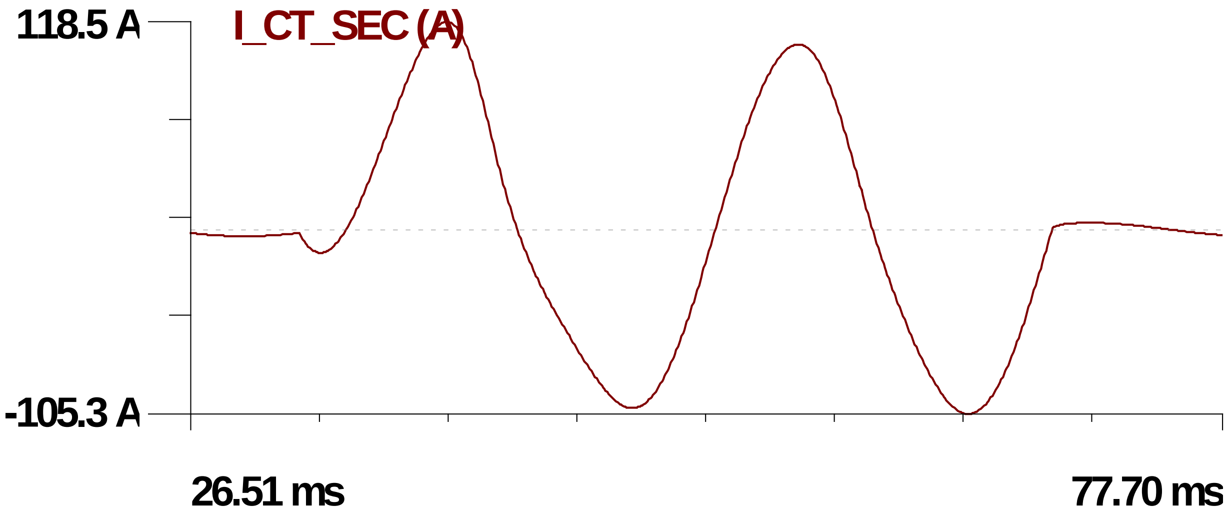


Figure 3-5: CT Secondary Current through the Burden Resistor

Application of the current instrumentation channel error correction algorithm provides the best estimate of the CT primary current. Figure 3-6, top set of traces, provides a graph of the estimated primary current, the actual primary current and the primary current computed by simply multiplying the measurement secondary current time the transformation ratio. The last quantity is referred to as “Ratio*CT Secondary Current”. Note a sizable difference between the last quantity and the actual primary current. On the other hand the estimated primary current tracks very well the actual primary current. The bottom set of traces of Figure 3-6 provides the error between the uncorrected primary current and the actual primary current as well as the error between the estimated and actual primary current. Note that without error correction the error reaches 50% while with error correction the error is below 1%.

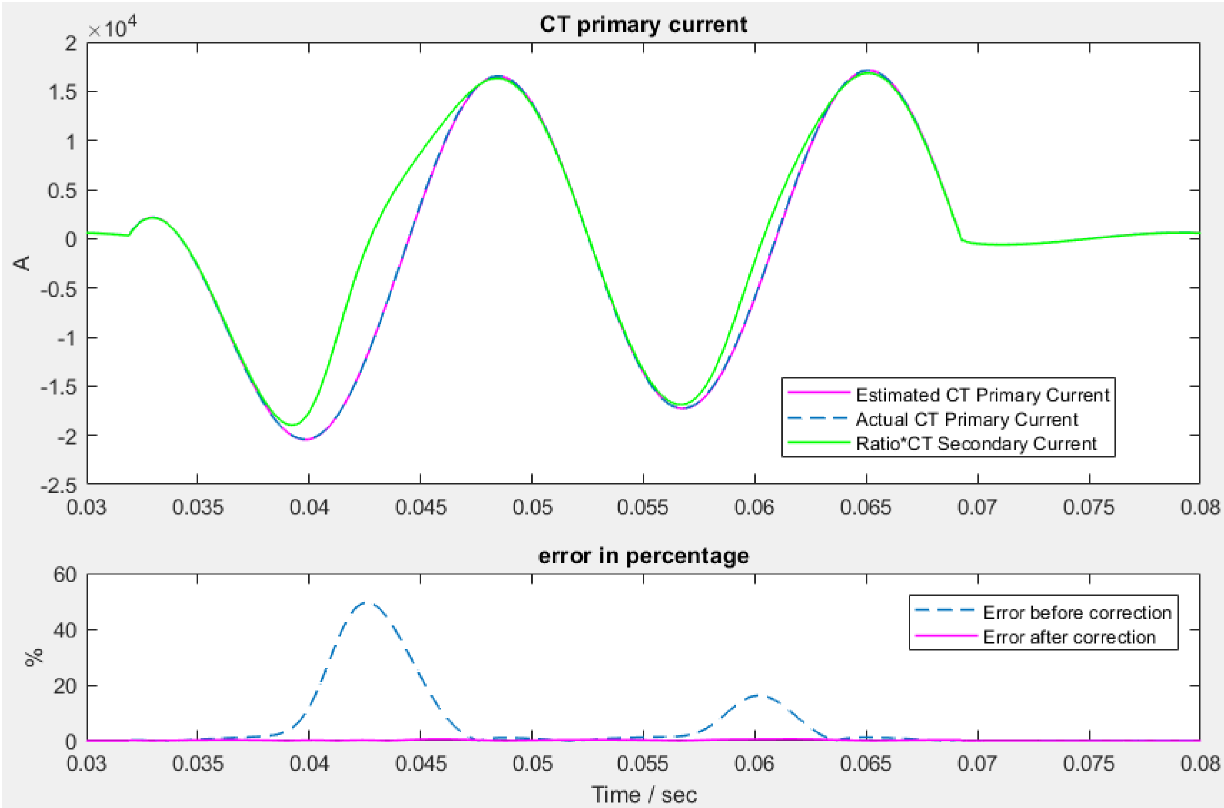


Figure 3-6: Comparison between the CT Primary Current before and after Correction

Event 2: Deep CT Saturation: A phase A to phase C fault at bus MID (middle of Figure 3-4) was simulated. This fault yields fault current that causes high CT saturation of the instrumentation channel. The merging unit measures the CT secondary current through the burden resistor, as shown in Figure 3-7. It can be seen in Figure 3-7 that the CT secondary current is highly distorted.

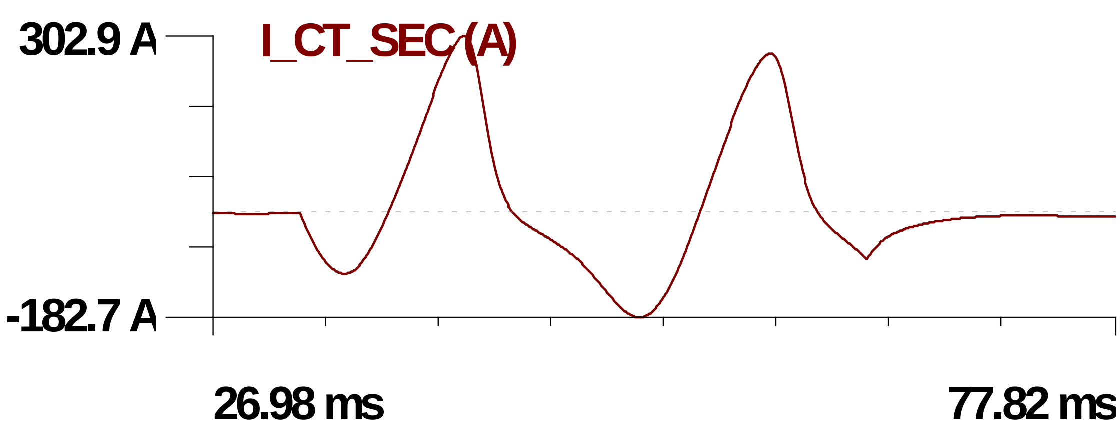


Figure 3-7: CT Secondary Current through the Burden Resistor

Application of the current instrumentation channel error correction algorithm provides the best estimate of the CT primary current. Figure 3-8, top set of traces, provides a graph of the estimated primary current, the actual primary current and the primary current computed by simply multiplying the measurement secondary current time the transformation ratio. The last quantity is referred to as "Ratio*CT Secondary Current". Note a large difference between the last quantity and the actual primary current. On the other hand the estimated primary current tracks very well the actual primary current. The bottom set of traces of Figure 3-8 provides the error between the uncorrected primary current and the actual primary current as well as the error between the estimated and actual primary current. Note that without error correction the error exceeds 200% while with error correction the error is below 2.5%.

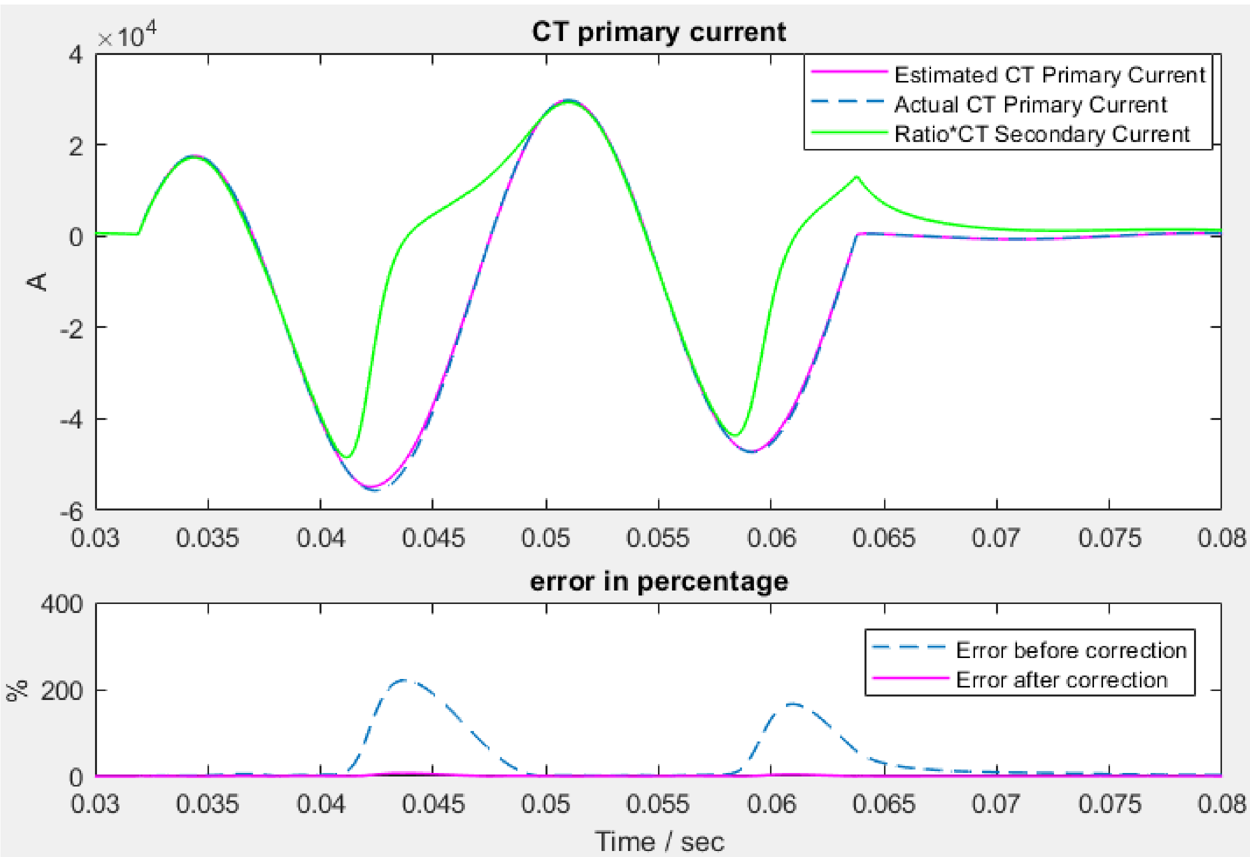


Figure 3-8: Comparison between the CT Primary Current before and after Correction

This section presented an on-line current instrumentation channel error correction method using dynamic state estimation. The method can be integrated with the merging units so that they directly provide corrected values of the primary quantities. The method has been demonstrated on current instrumentation channels. It can reliably reproduce the primary current under various saturation conditions of the CT. The computation of the method can be performed within a fraction of one sampling interval of merging units. This additional latency does not cause any problems in the streaming of the data from the merging units. The method can be applied equally well on voltage instrumentation channels.

4. Application to the RTE System

This section describes the relay setup and laboratory tests with hardware in the loop for the eventual installation of the DSE based relays (aka setting-less relays) in an RTE substation.

In order to prepare for the installation of the DSE-protection method to the RTE system, the RTE system has been modeled in the software WinIGS for the purpose of simulating a variety of faults and examining the performance of the relay with hardware in the loop. A single line diagram of the modeled system is given in Figures 4-1, 4-2 and 4-3.

Figure 4-1 shows the single line diagram of the modeled power system which includes the BLOCAUX substation and its external links to a 225 kV and 90 kV system. Specifically the BLOCAUX substation is connected to the power grid which is represented with equivalent sources at the next substations. There are two 225 kV circuits and several 90 kV circuits.

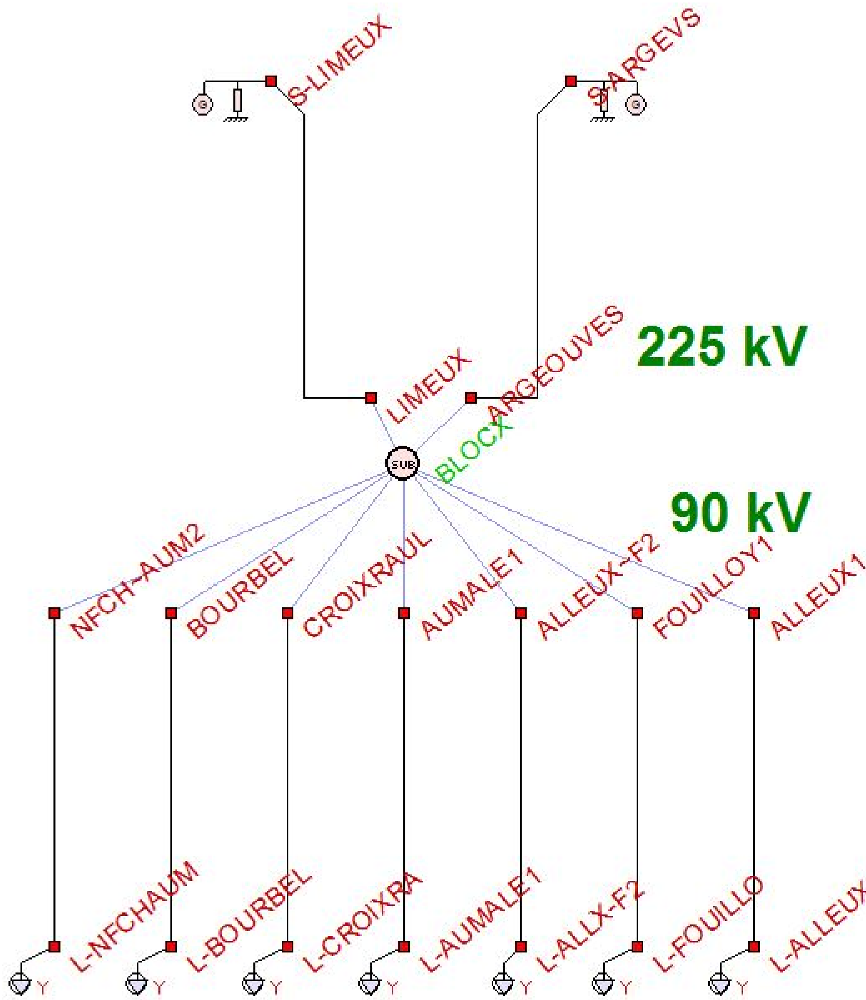


Figure 4-1: The RTE Subsystem Single Line Diagram

The substation BLOCAUX consists of the 225 kV section and the 90kV section, which are interconnected via transformers and short cables inside the substation. The 225 kV and 90 kV bus configurations of the substation are shown in Figure 4-2 and Figure 4-3, respectively.

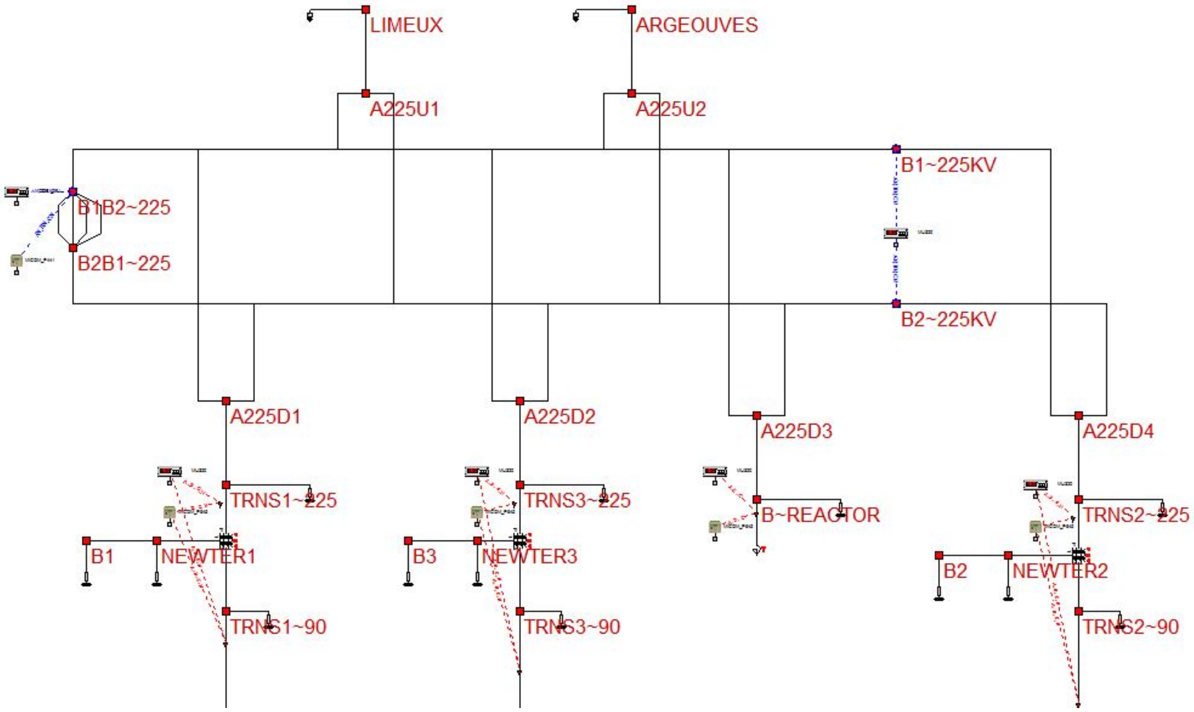


Figure 4-2: Single Line Diagram of 225 kV Section

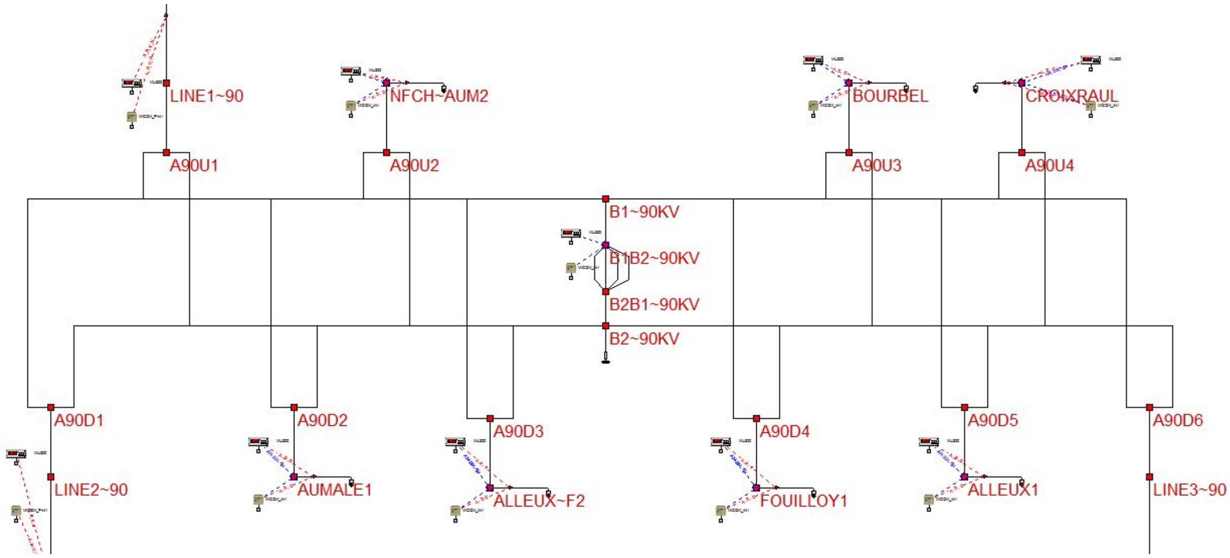


Figure 4-3: Single Line Diagram of 90 kV Section

The BLOCAUX substation has many protection zones. For the purpose of this project four protection zones have been selected for laboratory testing and eventual installation in the substation. In other words, these zones are targeted for application of the setting-less protective relay.

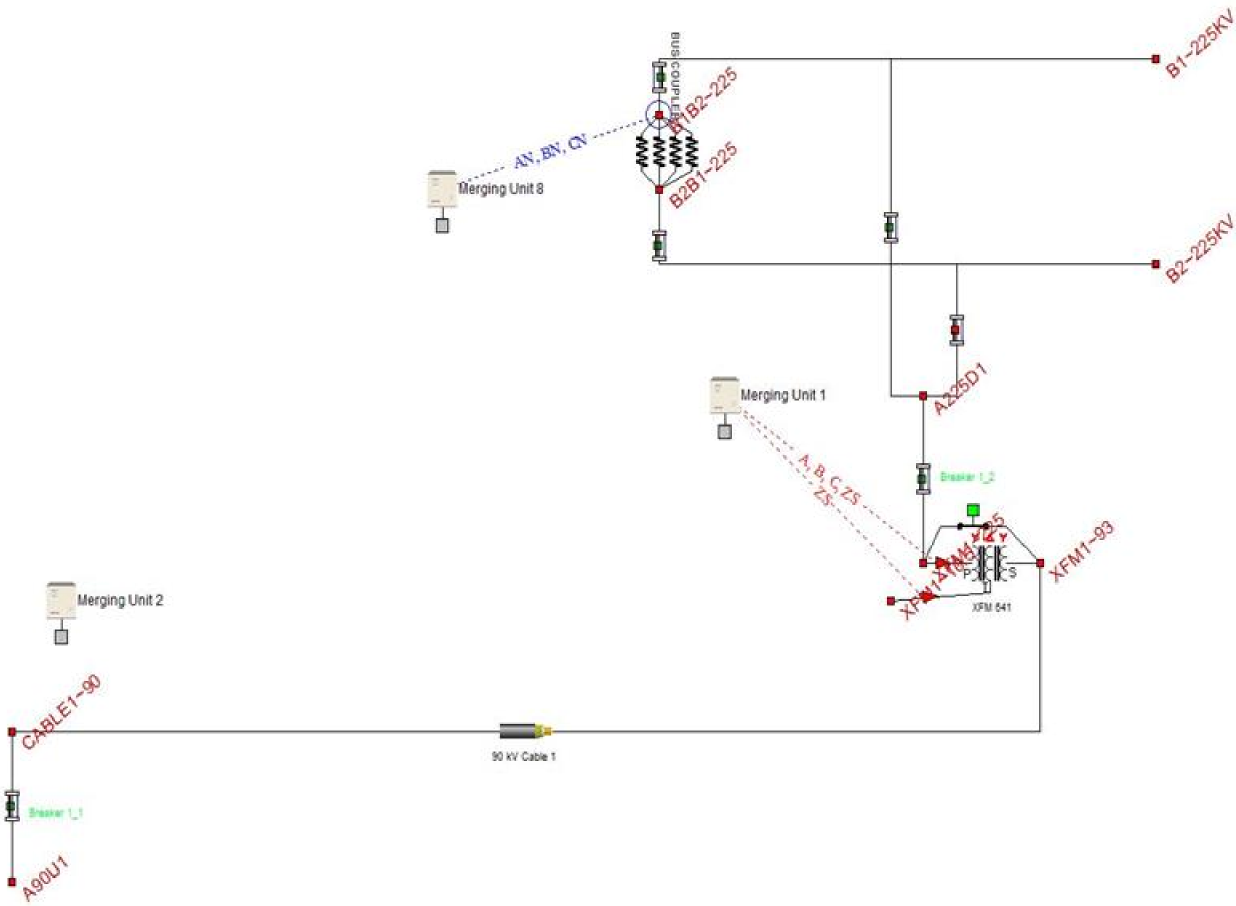


Figure 4-4: RTE – BLOCAUX Substation – Protection Zone 1

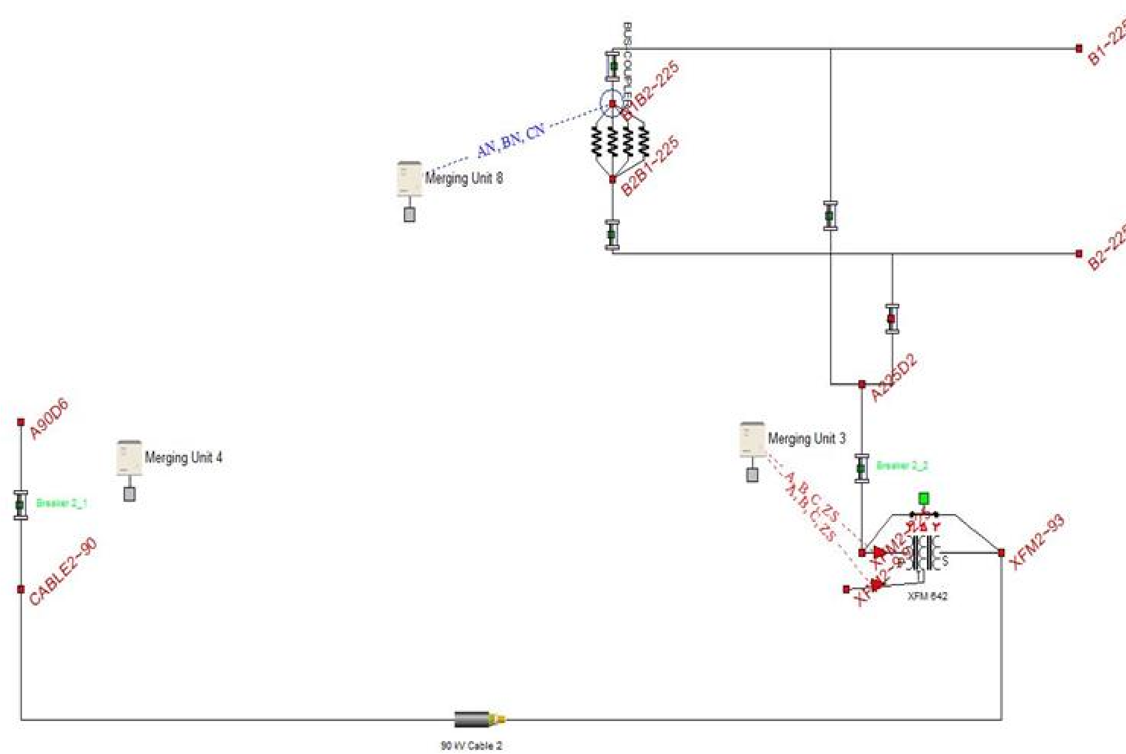


Figure 4-5: RTE – BLOCAUX Substation – Protection Zone 2

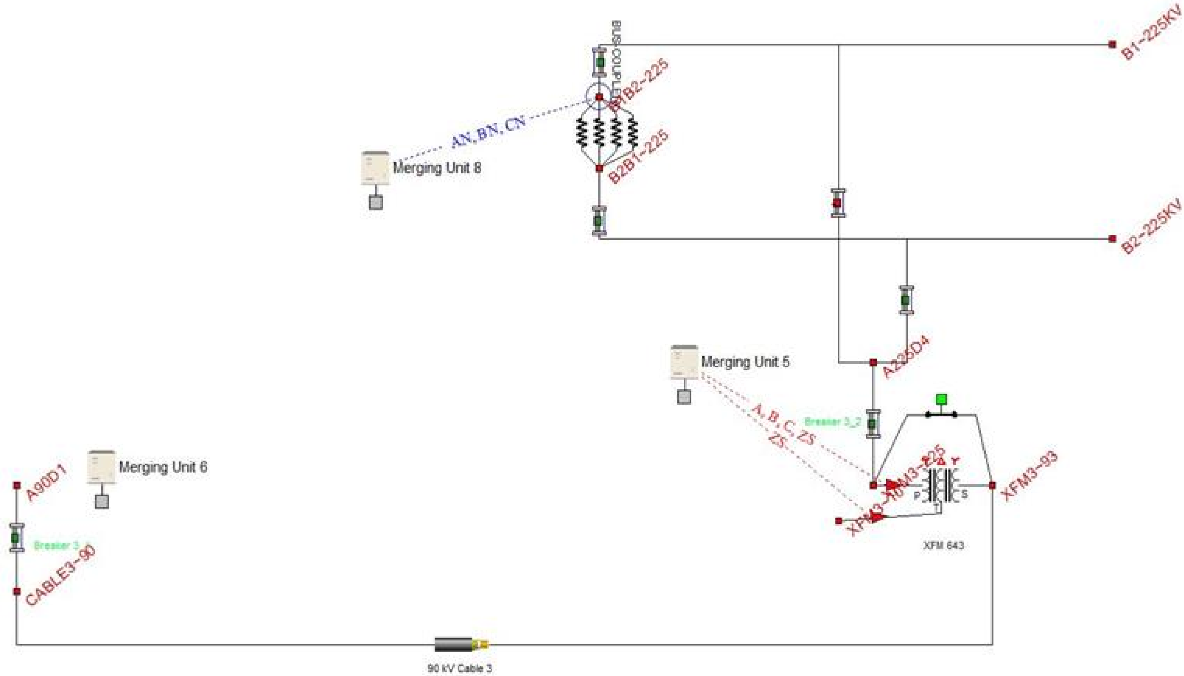


Figure 4-6: RTE – BLOCAUX Substation – Protection Zone 3

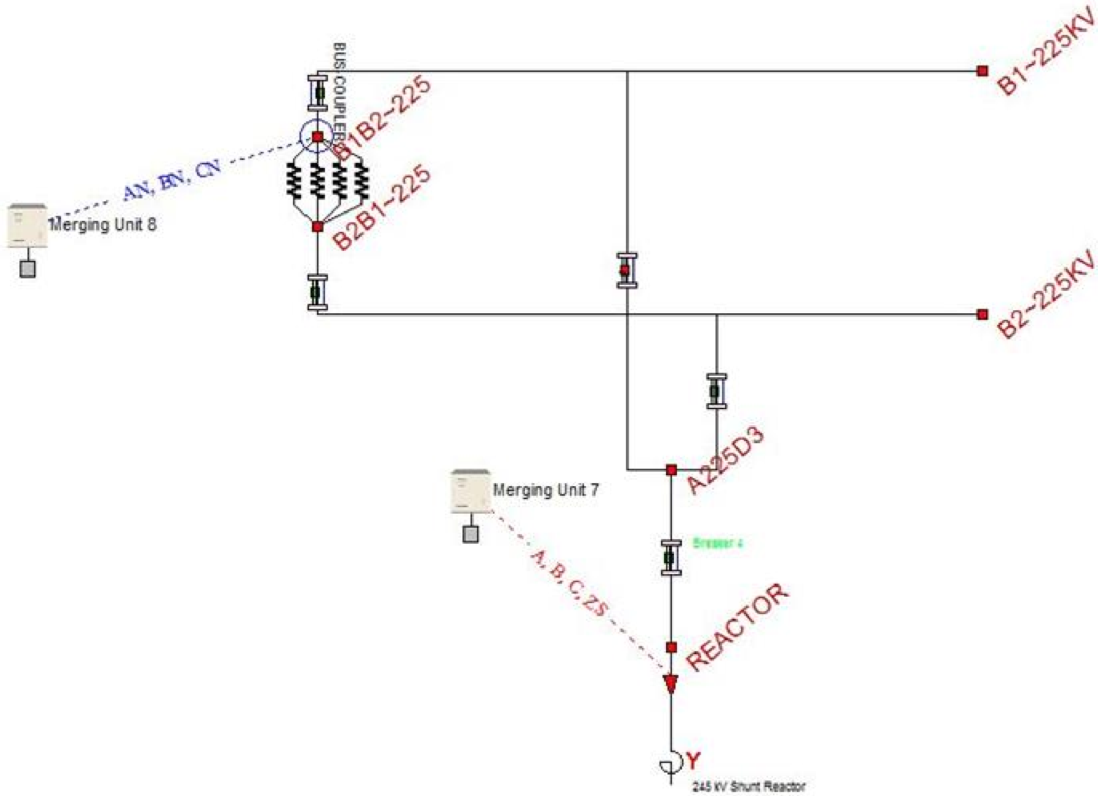


Figure 4-7: RTE – BLOCAUX Substation – Protection Zone 4

A detailed description of the four protection zones is provided in Appendix G. The detailed description of each protection zone includes (a) The physical system to be protected. The protection zone is connected to the rest of the system with interrupting devices (breakers), (b) the merging units with the data acquisition system (instrumentation channels) that perform measurements; and the definition of the output measurements by the merging units.

In the next section we present the overall process for setting up and installing the EBP relay for each one of the protection zones. We also provide example test results with several test events. We refer to these descriptions and results as use cases. Note that protection zones 1, 2 and 3 comprise a three-phase three-winding transformer and a three-phase cable. Since protection zones 1, 2 and 3 are similar, we present a use case for protection zone 1 and a use case for protection zone 4.

5. Example Test Results, RTE Protection Zone 1

This section describes a use case for preparing and running the setting-less relay for the specific protection zone 1 of the RTE substation BLOCX. Protection Zone 1 consists of a **three-phase three-winding transformer XFM641** (225 kV/90 kV/10.5 kV), a **90-kV cable 1**, four breakers, and two switches.

First, the protection zone model is developed in the program WinIGS-T. Once the protection zone model has been defined, it is exported into two files that are readable by the **E**stimation **B**ased **P**rotection (***EBP***) program. The first file contains the model of the protection zone power components. Note that a protection zone may include one or more components, for example protection zone 1 contains a transformer, a cable and breakers. Each protection zone component model is represented in its **SCPAQCF** format (**S**tate, **C**ontrol, and **P**arameter **A**lgebraic **Q**uadratic **C**ompanion **F**orm). The second file contains the definition of the measurements. The measurements definition provides the IED , Merging unit providing the measurement, type of measurement, and where on the protection zone the measurement was taken. The measurement definition is key-word oriented.

A number of events have been simulated with the program WinIGS-T, using the RTE BLOCAUX substation model. The results of the simulation provided by the merging units of the Protection Zone 1 are stored in COMTRADE format. These files are used for playback through a series of conversions and amplifiers into merging units connected to the EBP relay in the laboratory.

The use case demonstrates the EBP setup and testing procedure consisting of the following steps:

- Read model and measurement files
- Read event data (COMTRADE files)
- Run the setting-less relay.

This report includes several simulated events as well as the EBP results.

5.1. Creating Protection Zone Models for EBP Relays

WinIGS-T includes a tool which automatically generates the model of the user selected protection zone in the **SCPAQCF** syntax. The protection zone can be a single component protection zone or it may comprise several components and/or breakers. The estimation based protective relay (EBP, a.k.a. setting-less relay) requires the model of the protection zone in SCPAQCF standard. The user should select the components that constitute the protection zone and which must be exported in the **SCPAQCF** syntax into a file. In addition, the user must specify the merging units providing data to the EBP relay in order to generate a second file describing the measurement parameters. These two files are read by the WinXFM-EBP program that executes the estimation based protective relay algorithm.

5.1.1 Creating the Network Time Domain Model

The procedure to generate the EBP model file begins by building a system model in WinIGS-T. The WinIGS-T model could include the entire or part of the large system (for simulation studies and for generating events) and must also include the models of the protection zone under study. Specifically:

- The power devices comprising the EBP protection zone.
- The instrumentation channels available to the EBP relay via merging units.
- The breakers/switches that enable the protection of the zone.

The WinIGS-T model for the RTE system, including the necessary merging unit information is provided along with this document. The single line diagram of the interested protection zone (i.e., Protection Zone 1) is illustrated in Figure 5-1. Protection Zone 1 contains a three-phase three-winding transformer, a cable, four breakers, and two switches. The diagram also includes three Merging Units that capture the voltages and currents from the transformer and the cable.

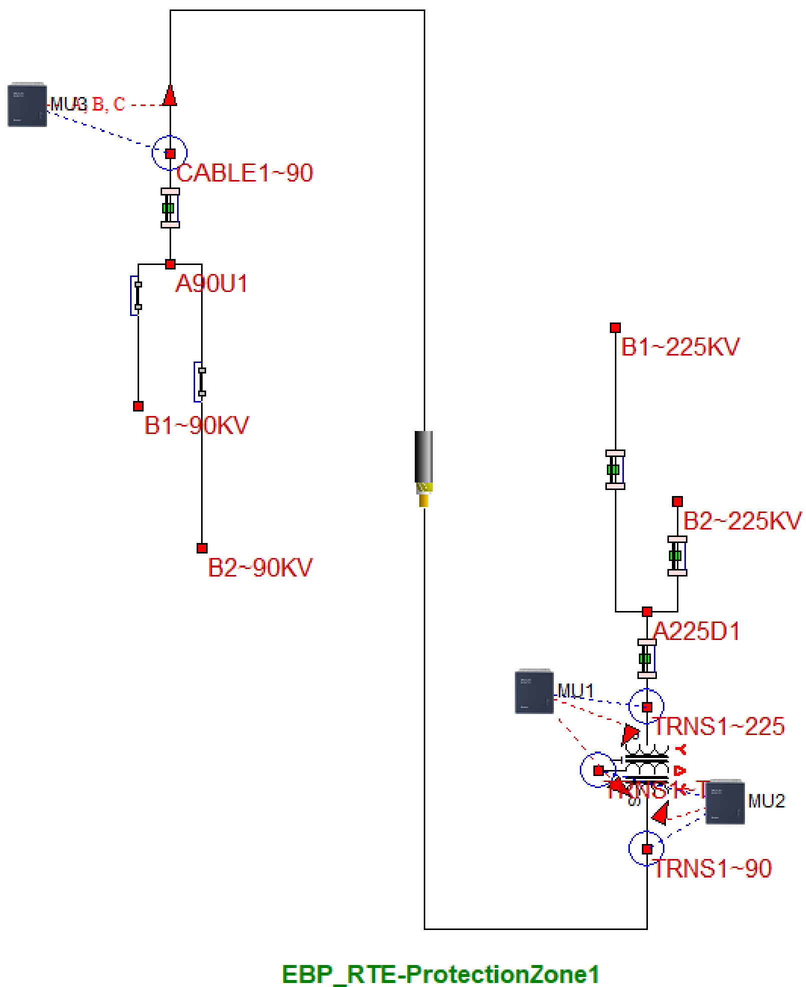


Figure 5-1: Single Line Diagram of Protection Zone 1

The parameter dialog of the three-phase three-winding transformer and the cable are illustrated in Figure 5-2 and Figure 5-3, respectively. This dialog can be accessed via left button double clicking on the device icon.

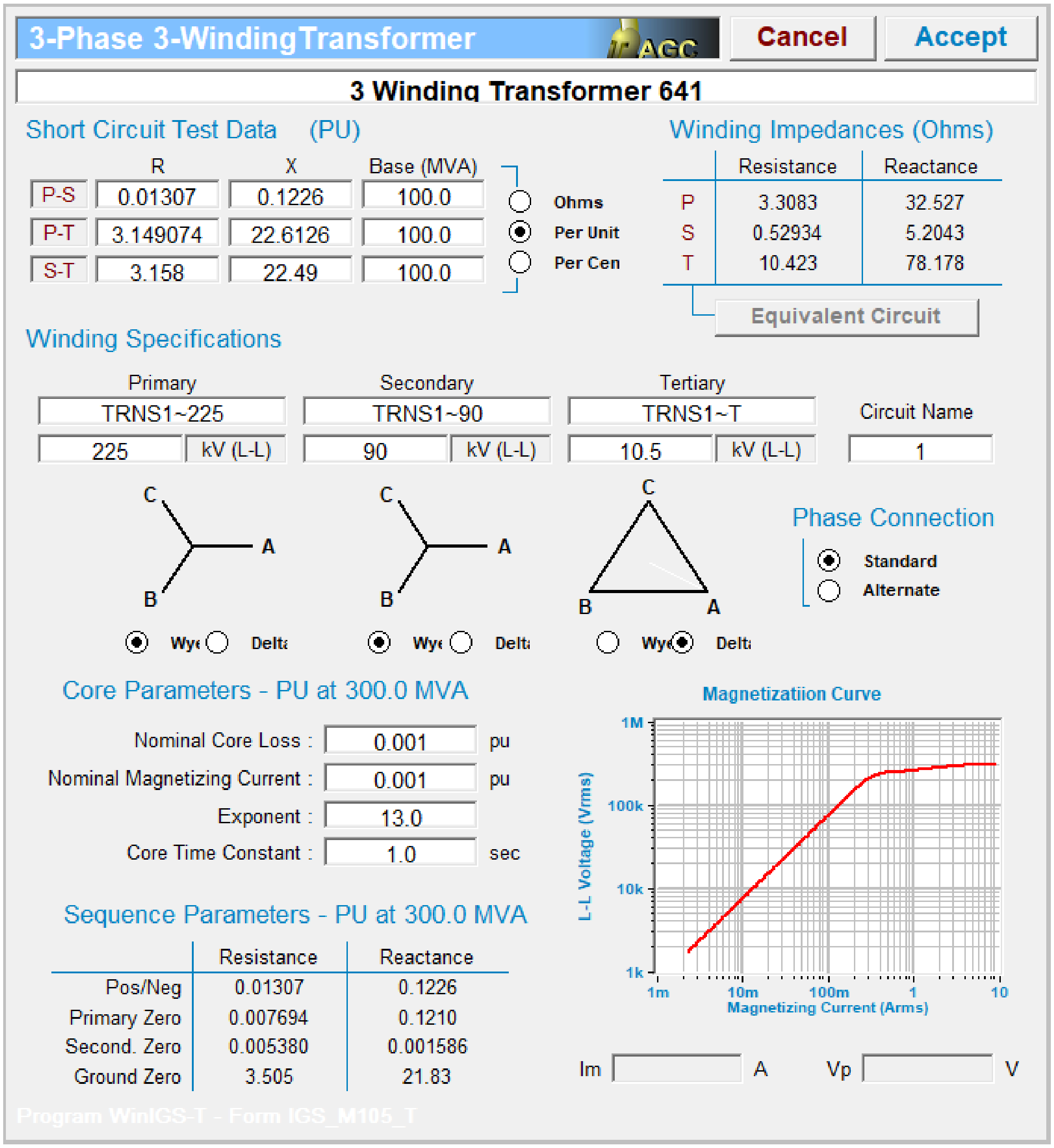


Figure 5-2: Parameters of the Three-Phase Three-Winding Transformer

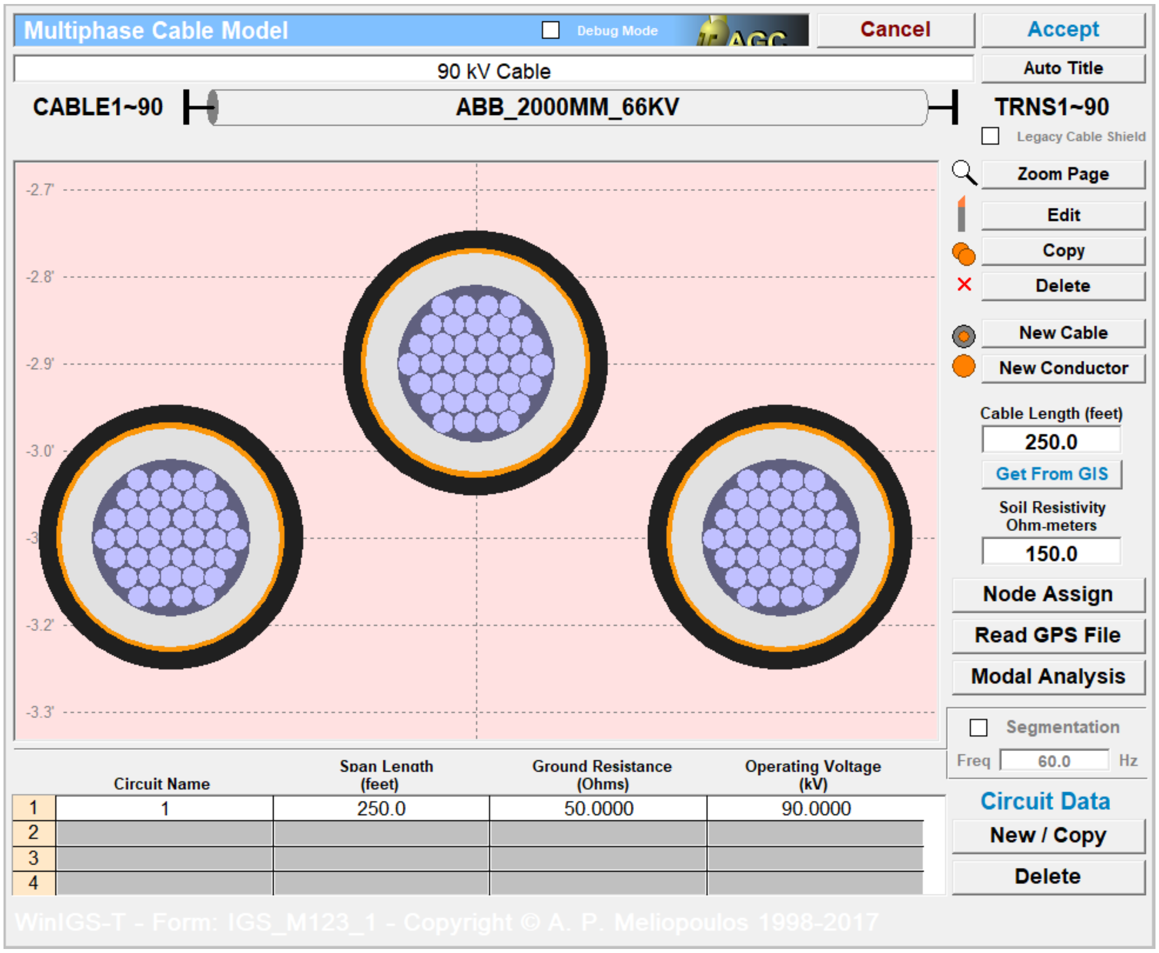


Figure 5-3: Parameters of the Three-Phase Cable

5.1.2 Creating Measurement Models for Merging Units

The instrumentation channel and measurement parameters to be used by the EBP relay for the Protection Zone 1 are modeled in the Merging Unit (see MU icon in Figure 5-1). In this example, three merging units are set up to monitor the phase currents and voltages in the protection zone. The total number of measurements obtained from merging units is 24 at time t.

The merging unit model parameters and instrumentation channel list can be edited by clicking on the merging unit icon. This action will bring the user interface illustrated in Figure 5-4. Click on the Instrumentation button to open the instrumentation channel list dialog, illustrated in Figure 5-5.

Double-click on each list table entry to inspect the instrumentation channel parameters. Figures 5-6 and 5-7 illustrate examples of a voltage and a current channel, respectively. Note that a WinIGS-T instrumentation channel model includes models of the instrument transformer, instrumentation cable, burdens, and data acquisition device.

A short description of the instrumentation channel parameters is presented in Table 5-1.

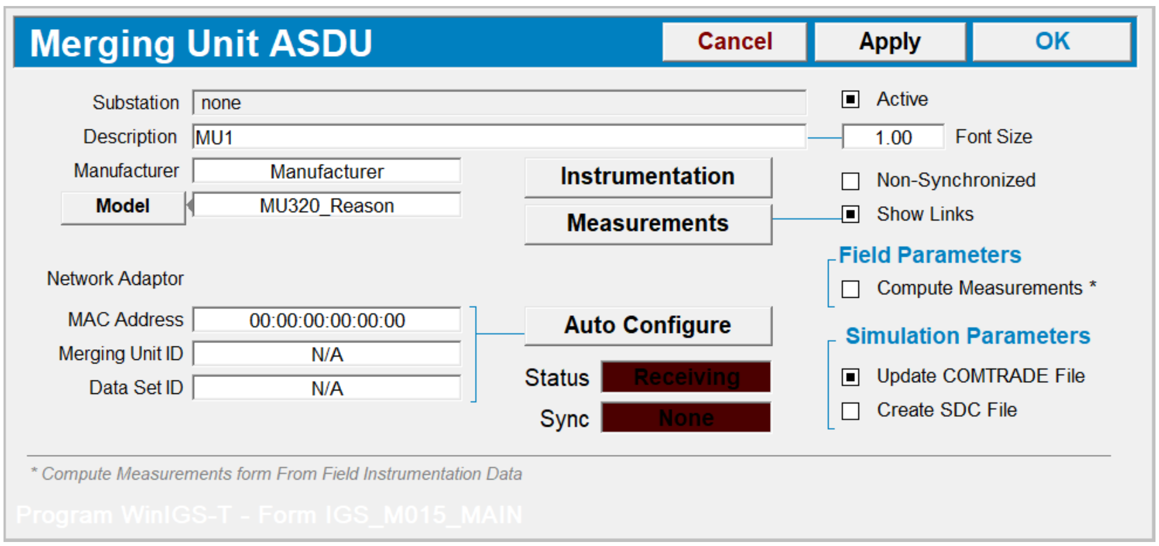


Figure 5-4: Merging Unit Main Parameter Dialog

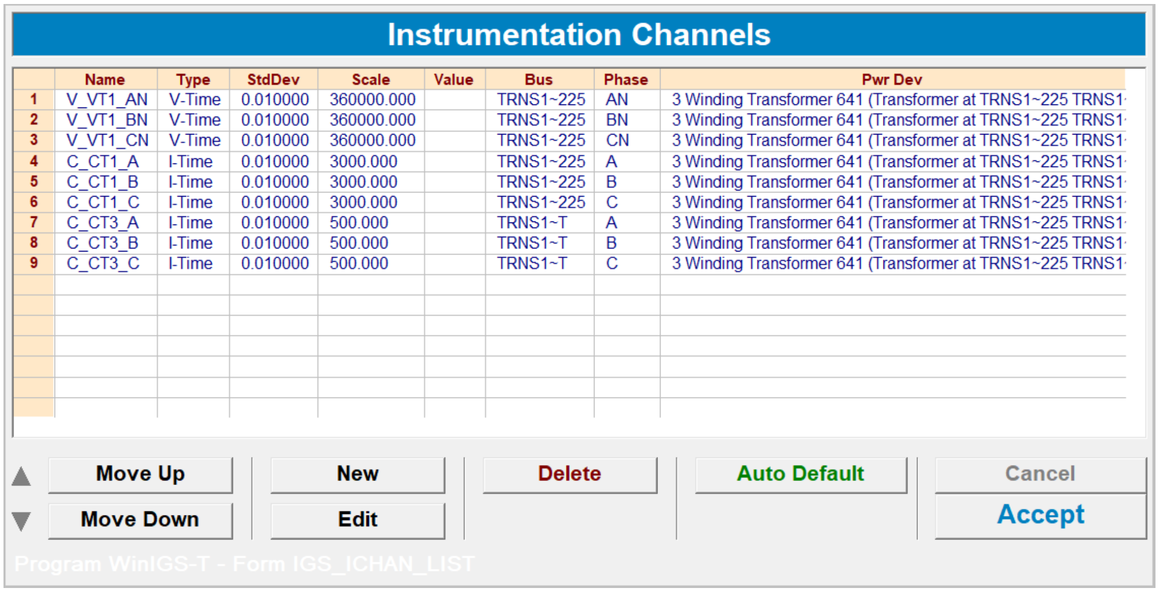


Figure 5-5: Merging Unit Instrumentation Channel List Dialog

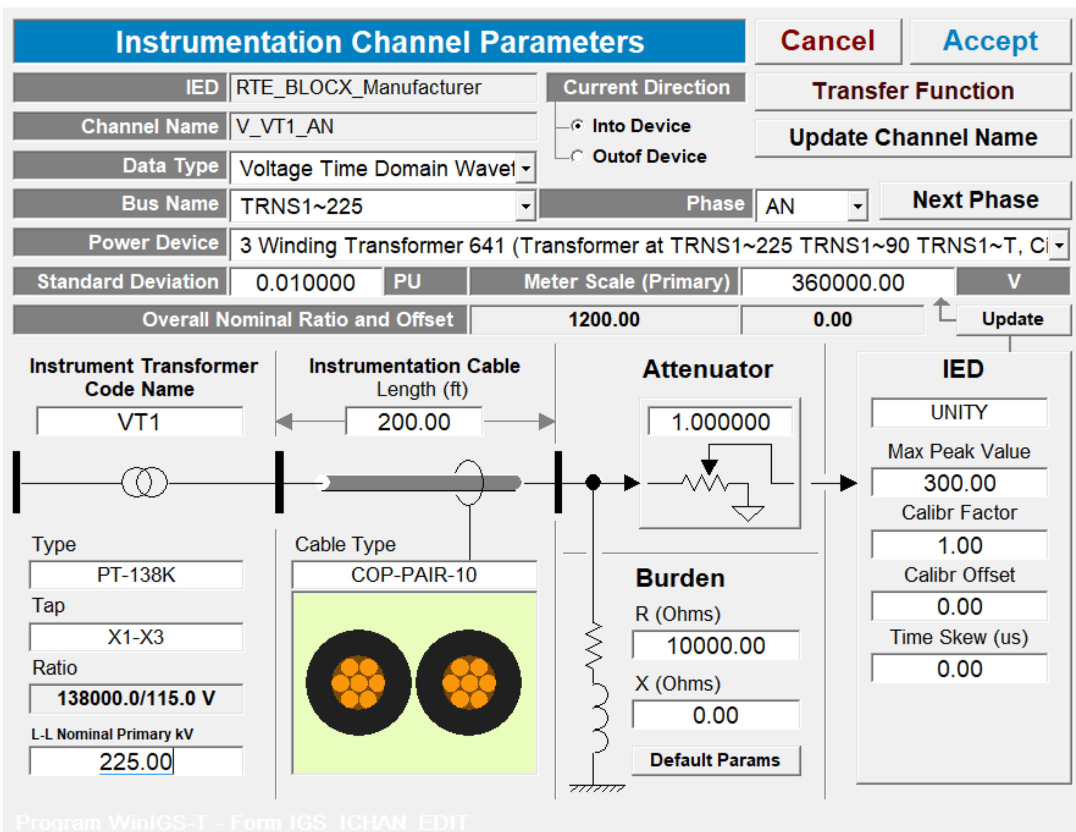


Figure 5-6: Example of a Voltage Instrumentation Channel Dialog

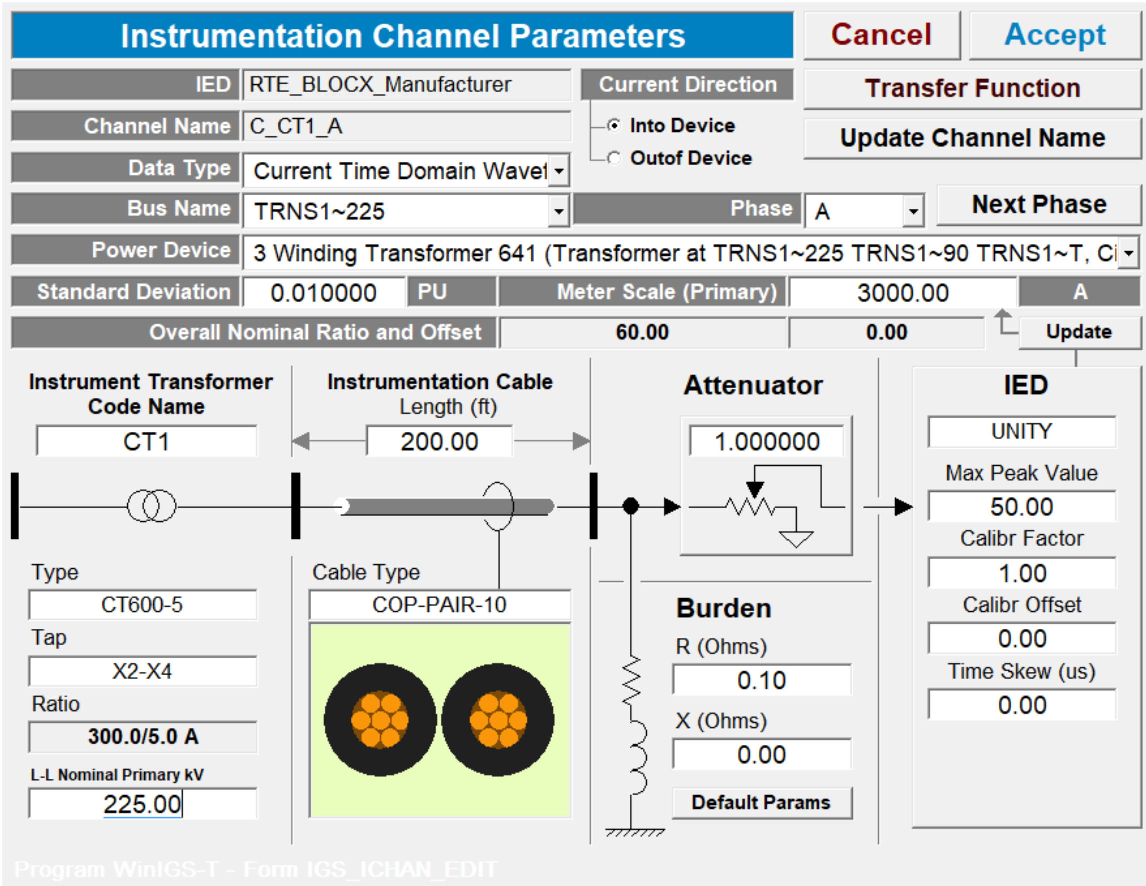


Figure 5-7: Example of a Current Instrumentation Channel Dialog

Table 5-1: Instrumentation Channel Parameters – User Entry Fields

Parameter	Description
Data Type	Specifies the type of the measured quantity. Valid options for merging units are Voltage Time Domain Waveform and Current Time Domain Waveform.
Bus Name	The bus name where the measurement is taken
Power Device	Identifies the power device into which the current is measured (not used for voltage measurements)
Phase	The phase of the measured quantity (A, B, C, N, etc.)
Current Direction	The direction of current flow which is considered positive. For example, checking into device indicates that the positive current flow is into the power device terminal (See also Power Device parameter above)
Standard Deviation	Quantifies the expected error of the instrumentation channel in per unit of the maximum value that the channel can measure (See also channel scale parameter).
Meter Scale	The maximum peak value that the channel can measure defined at the instrument transformer primary side. Note that this value can be directly entered by the user, or automatically computed from the instrument transformer and data acquisition device characteristics. In order to automatically compute the, click on the **Update** button located below the Meter Scale field.
Instrument Transformer Code Name	An identifier of the instrument transformer associated with this channel. Note that WinIGS uses this identifier to generate the channel name. For example, the phase A voltage channel is automatically named V_VT1_AN, if the instrument transformer name is set to VT1.
Instrument Transformer **Type** and **Tap**	Selects instrument transformer parameters from a data library. The library includes parameters needed to create instrument channel models such as turns ratio, frequency response, etc. To select an instrument transformer model, click on the **type** or **tap** field to open the instrument transformer data library dialog (See also Figure 5-8)
L-L Nominal Primary Voltage	The line to line voltage at the instrument transformer primary side.
Instrumentation Cable Length	The length of the instrumentation cable connecting the instrument transformer secondary with the data acquisition device.
Cable Type	The instrumentation cable type and size. Clicking on this field opens the cable library selection window. Note that if the desired cable is not found in the library, a cable library editor is available allowing adding and modifying cable parameters (See WinIGS-T

	user's manual for details).
Attenuator	Attenuation value of any additional voltage or current reduction divider. Set to 1.0 if none.
Burden	The equivalent resistance of the burdens attached to the instrument transformer secondary.
IED	Selects data acquisition device from an IED library. This setting retrieved the data acquisition device frequency response for the purpose of applying error correction. Set to UNITY if this information is not available.
Maximum Peak Value	Set to the maximum instantaneous (peak) voltage or current value that will not saturate the data acquisition device input. This value can be found in data acquisition device specifications. For example, the GE Merging unit voltage and current max peak values can be derived from the voltage and current range specifications shown in Figure 5-9. Note that the range is specified in RMS so these Figures must be multiplied by $\sqrt{2}$ to obtain the peak values (i.e.: 325.3 Volts and 282.8 Amperes)
Calibration Factor	The channel output is multiplied by this value. Set to 1.0 if none required.
Calibration Offset	This value is added to the channel output. Set to 0.0 if none required.
Time Skew	Time delay in seconds of this channel with respect to time reference. Set to zero for no delay.

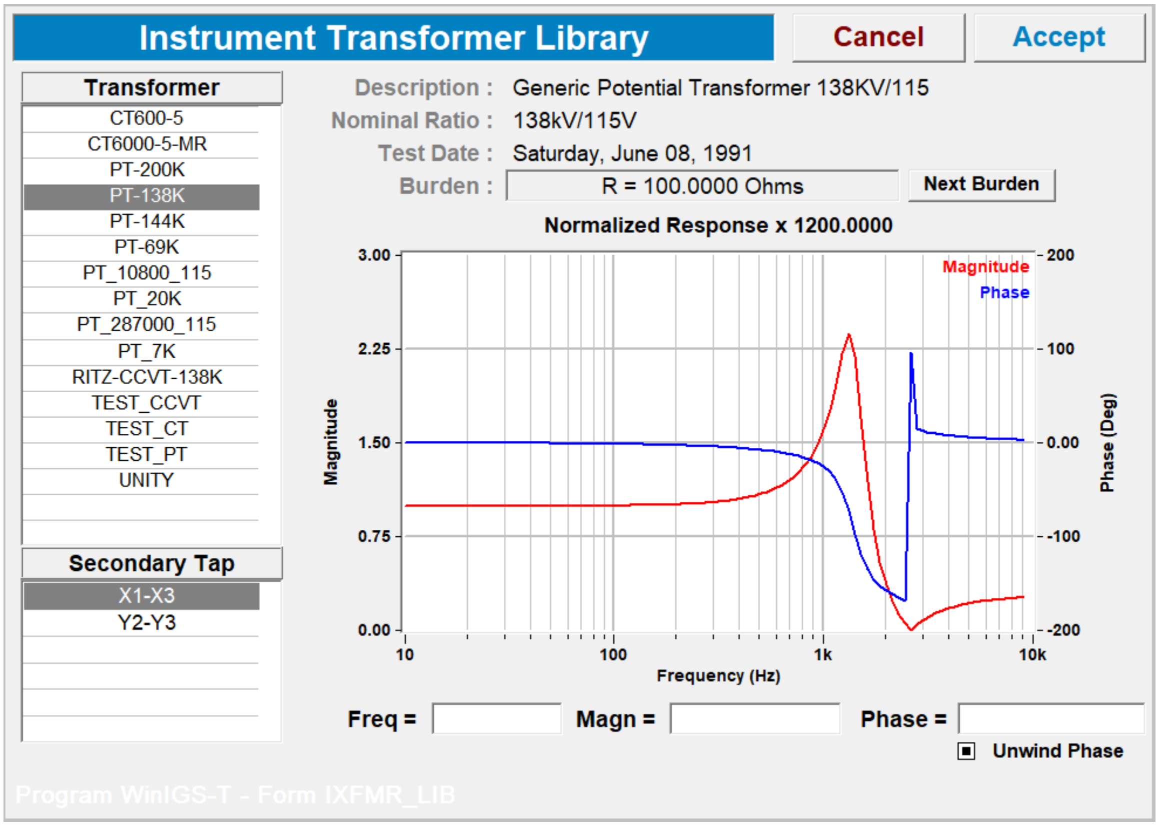


Figure 5-8: Instrument Transformer Library Dialog

CURRENT INPUTS

Nominal Current (In)	5 A	1 A
Nominal frequency	50/60Hz	50/60Hz
Current range (rms)	0.25 ... 200A	0.05 ... 40A
Accuracy	± 0.1 % F.S.	± 0.1 % F.S.
Impedance	3 m Ω	15 m Ω
Burden In	50 m VA	< 0.02 VA
Continuous overload	20A (4 x In)	4A (4 x In)
AC current thermal withstand 1 s (Ith rms)	320A (64 x In)	100A (100x In)
AC current thermal withstand 10 s (Ith rms)	100A (20 x In)	30A (30 x In)
Insulation	> 3.5 kV	> 3.5 kV
Bandwidth	3 k Hz	3 k Hz

VOLTAGE INPUTS

Nominal Voltage (Vn)	115 V
Nominal frequency	50/60Hz
Voltage range	0.02 ... 230 V
Accuracy	± 0.1 % F.S.
Impedance	> 210 k Ω
Burden Vn	< 0.1VA
Continuous overload	240 V
Maximum overload (1 s)	460 V (4 x Vn)
Bandwidth	3 k Hz

Figure 5-9: Example Input Specifications of a GE MU320 Merging Unit

Note that the order of the instrumentation channels can be modified using the **MoveUp** and **MoveDown** buttons of the instrumentation channel list dialog (Shown in Figure 5-5). Once the instrumentation channel parameter entry is completed, click on the **Accept** button of the instrumentation channel list dialog, to save the channel parameters. Note that the instrumentation channel parameters are saved in an ASCII file named:

CASENAME_Fnnnnn.ich

where CASENAME is the WinIGS-T network model file name root, and nnnnn is a 5-digit integer. These files are stored in the same directory as the WinIGS-T network model file.

The next step is to define the measurements to be used for the EBP relay, in terms of the defined instrumentation channels. This is accomplished by clicking on the **Measurement** button of the merging unit ASDU dialog (Shown in Figure 5-4). This action opens the Measurement List Dialog illustrated in Figure 5-10.

For most cases (including the protection zone 1 described in this document), the measurement parameters can be created automatically using the **Auto Create** button in the Measurement List Dialog.

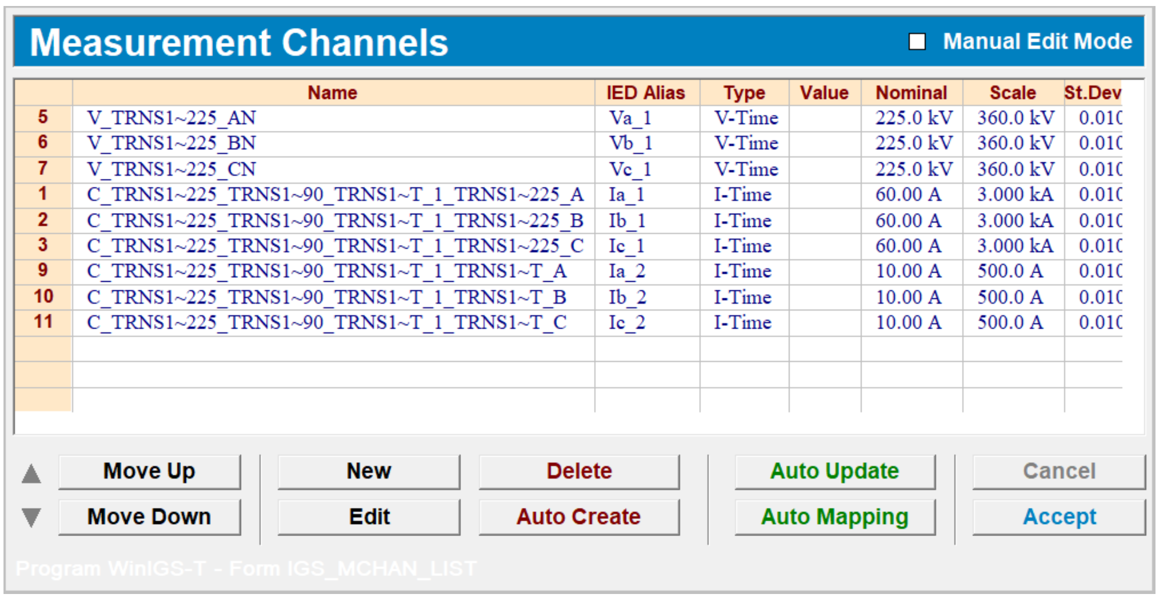


Figure 5-10: Measurement List Dialog

Measurement parameters can be manually created and edited using the **New** and **Edit** buttons of the Measurement List dialog (Figure 5-10), which open the measurement parameter dialog illustrated in Figures 5-11 and 5-12. The fields in this dialog are briefly described in Table 5-2.

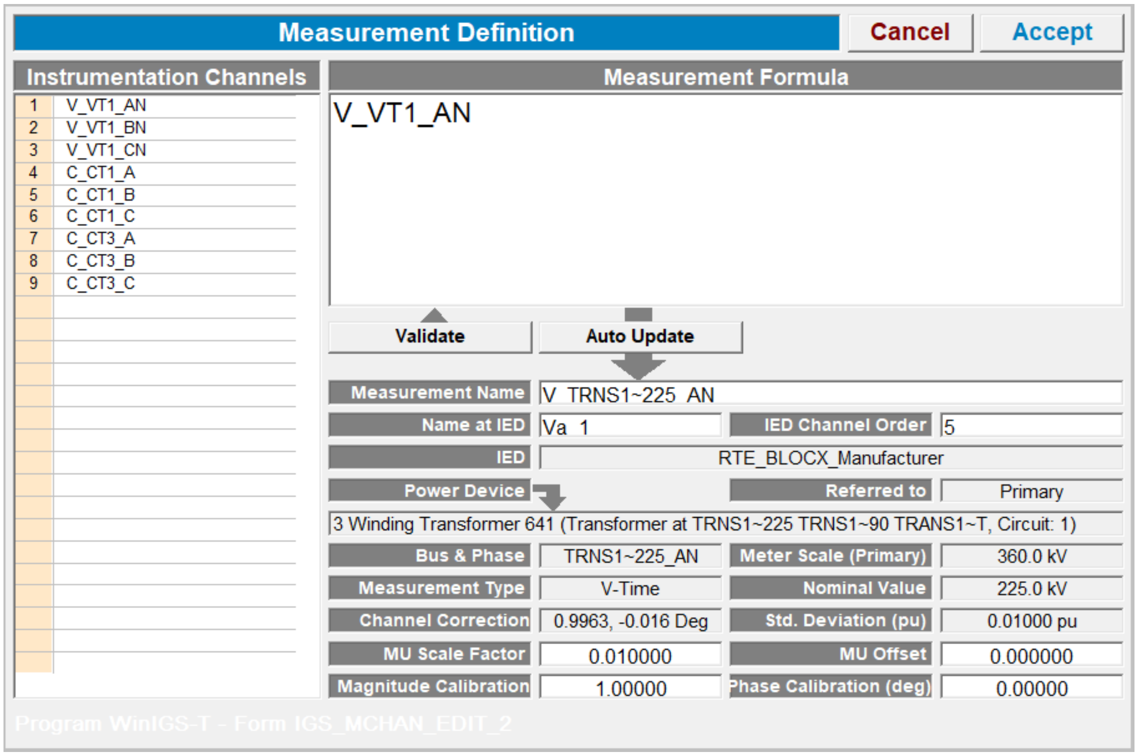


Figure 5-11: Voltage Measurement Parameters Dialog

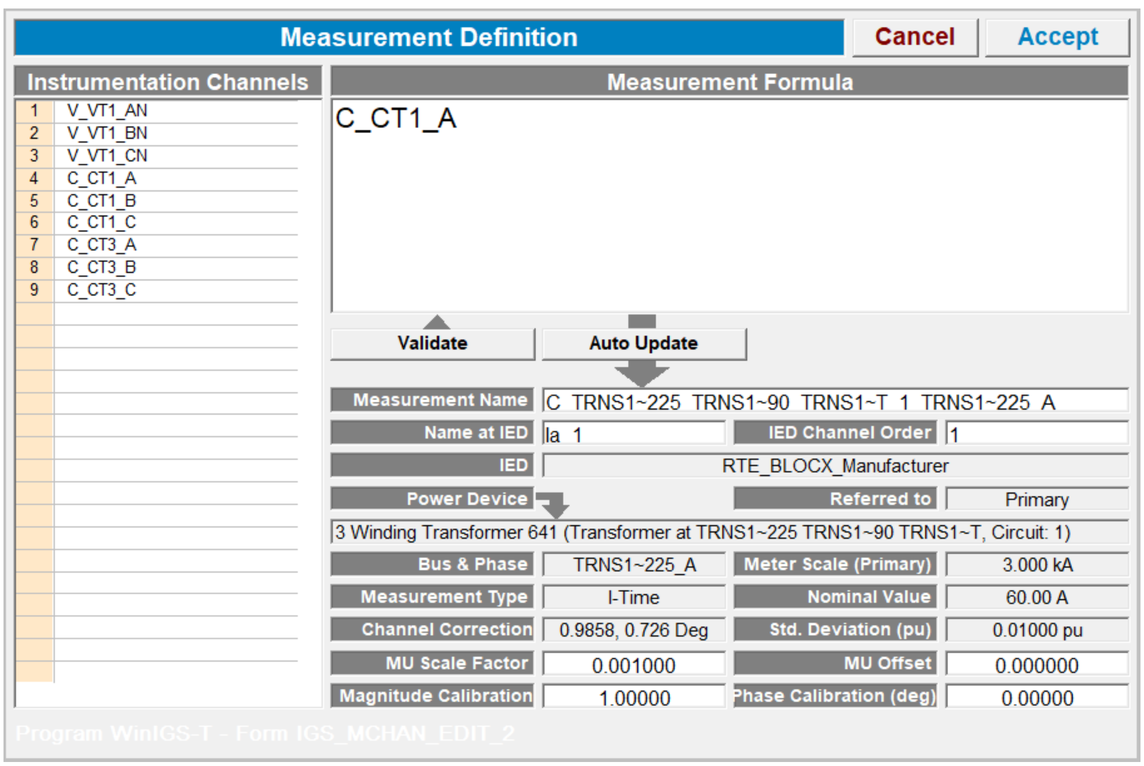


Figure 5-12: Current Measurement Parameters Dialog

Table 5-2: Measurement Parameters – User Entry Fields

Parameter	Description
Measurement Formula	Mathematical expression giving measurement value in terms of instrumentation channel values. Note that the measurement formula for automatically created measurements form instrument channels is simply the instrument channel name. However, a measurement can be manually defined as any expression involving all available instrument channels.
Measurement Name	***Voltage measurements*** names are automatically formed based on the bus name, phase and measurement type. For example, a phase A voltage measurement on Bus TRNS1~225 is automatically named V_TRNS1~225_AN. Similarly, ***current measurements*** are automatically formed by identifying a power device and a specific terminal into which the measured current is flowing. For example, the phase A current into the transformer at Bus TRNS1~225 is named C_TRNS1~225_TRNS1~90_TRNS1~T_1_TRNS1~225_A, where the part TRNS1~225_TRNS1~90_TRNS1~T_1 identifies the power device as circuit 1 connected to the bus TRNS1~225, and the last part _TRNS1~225 identifies the terminal into which the measured current is flowing. Note that the name part 1 is the user specified Circuit Name of the transformer.
Name at IED	The measurement name as defined by the merging unit or other IED used. The default channel names vary with IED manufacturers and IED types. For example, the GE MU320 merging units default channel names are Ia_1, Ib_1, Ic_1, for the current channels and Va_1, Vb_1, Vc_1, for voltage channels.
IED Channel Order	An order number (starting with 1) indicating the ordering of the channels in the Sample Value packets. For example, GE MU320 merging units SV packets have four current channels followed by four voltage channels. Thus, the current channel order numbers are 1, 2, 3, 4 for phase A, B, C N, and the voltage channel order numbers are 5, 6, 7, and 8 for phases A, B, C, and N.
Merging Unit Scale Factor and Merging Unit Offset	These values define the conversion from the 32 bit integer Sample Values to actual values in Volts and Amperes. Specifically: $V_k = a X_k + b$ where Vk is a voltage sample in volts, a is the Scale Factor, Xk is the sample value voltage sample (32 bit integer), and b is the Merging Unit Offset. The default merging unit scale factor for voltage channels is 0.01, while for current channels is 0.001. Default offsets are zero.

Magnitude Calibration and Phase Calibration	Measurement magnitude and a phase angle correction value. Default values are 1.0 and 0.0 respectively.

In this example, 3 merging units are placed in this protection zone for estimation based protection. The instrumentation channels of these merging units are listed in Table 5-3. The total number of these channels is 24.

Table 5-3: Instrumentation Channels of Merging Units in Protection Zone 1

MU Name	**Voltage Channels**	**Current Channels**	**# of channels of this MU**
MU1	AN, BN, CN at TRNS1~225	A, B, C at TRNS1~225 (into the XFMR) A, B, C at TRNS1~T (into the XFMR)	9
MU2	AN, BN, CN at TRNS1~90 AN, BN, CN at TRNS1~T	A, B, C at TRNS1~90 (into the XFMR)	9
MU3	AN, BN, CN at CABLE1~90	A, B, C at CABLE1~90 (into the cable)	6

5.1.3 Exporting Measurement and Protection Zone Models

In order to generate the estimation based protective relay files (to be used in the XFM program EBP feature), perform the following steps:

1. Select the power devices belonging to the protection zone of interest. In this example select the transformer, cable, and two breakers in the protection zone 1. (NOTE: to select multiple objects, hold down the CTRL key, and ***left-click*** on the elements to be selected).
2. Select the merging units monitoring the voltages and currents to be used in the EBP relay. In this example, select the merging unit named “MU1”, “MU2”, and “MU3” in Figure 5-2. (NOTE: to select multiple objects, hold down the CTRL key, and ***left-click*** on the elements to be selected).
3. Execute the SCAQCF Export command of the Tools menu, or click on the toolbar icon: 

(See also Figure 5-13).

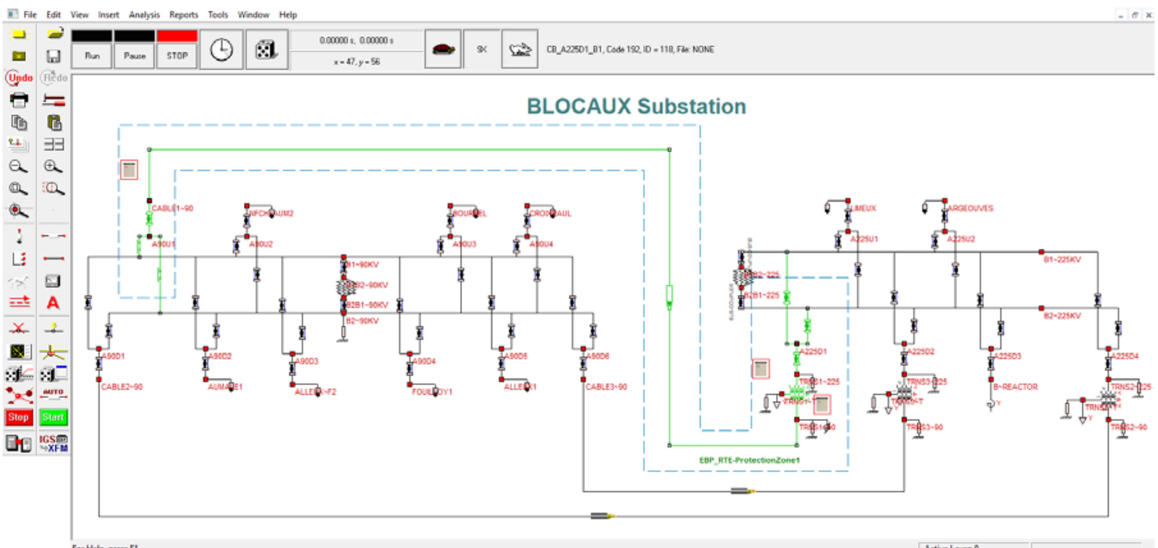


Figure 5-13: Selecting Zone Power Devices and Merging Units

This command/toolbar button opens the dialog window illustrated in Figure 5-14.

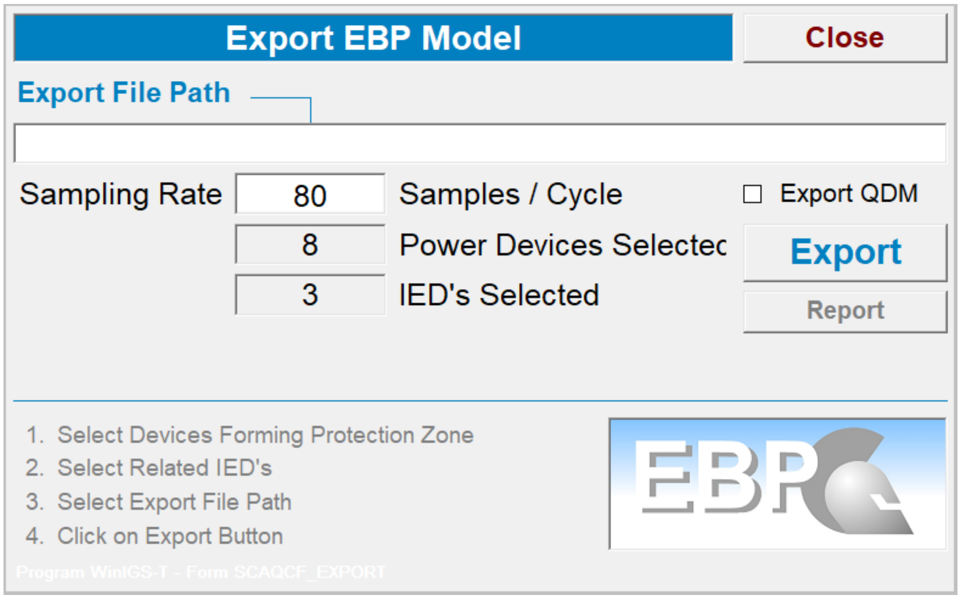


Figure 5-14: EBP Export Dialog

4. Click on the entry field under the Export File Path label in order to select the file path of the files to be generated.
5. Click on the **Export** button to generate the files. Optionally click on the Report button to verify that the process was completed successfully (See Figure 5-15)

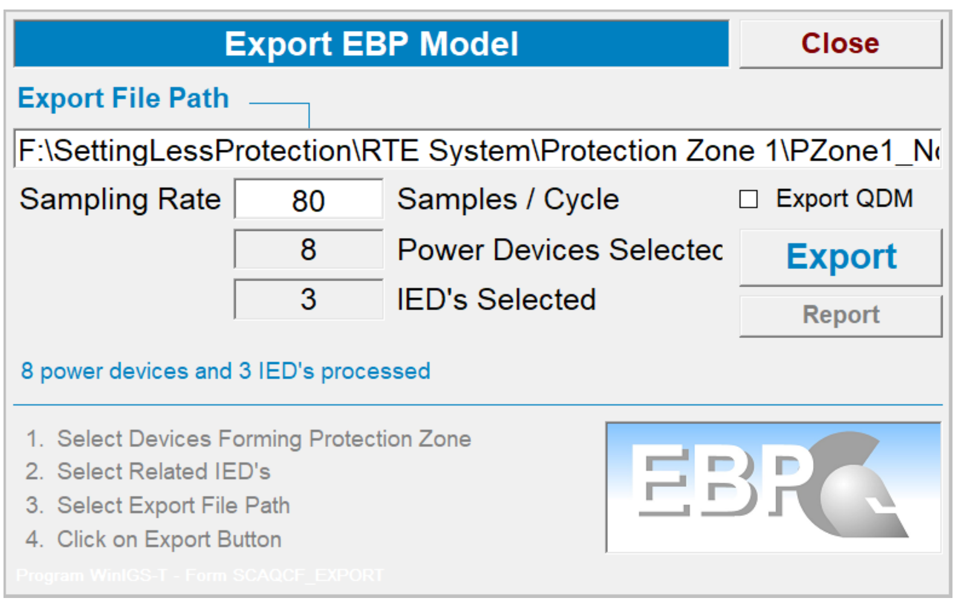


Figure 5-15: Message Window Indicating EBP File Creation Progress & File Paths

The generated files are next used to automatically setup the EBP relay in the XFM program.

5.2 Creating Events and Storing in COMTRADE

For the above stated purpose, we use WinIGS-T to define events, simulate the events and store the results in COMTRADE format. Two such events are described below.

5.2.1 Event A: UseCase_01.A

Event A is defined with a phase A to neutral fault at TRNS1~90 bus within the protection zone. Figure 5-16 shows the fault model and fault model parameters dialog. This is a fault occurring inside Zone 1 which should be cleared by opening the two breakers connected to this zone. The fault is initiated at 0.5 seconds from the start of the simulation.

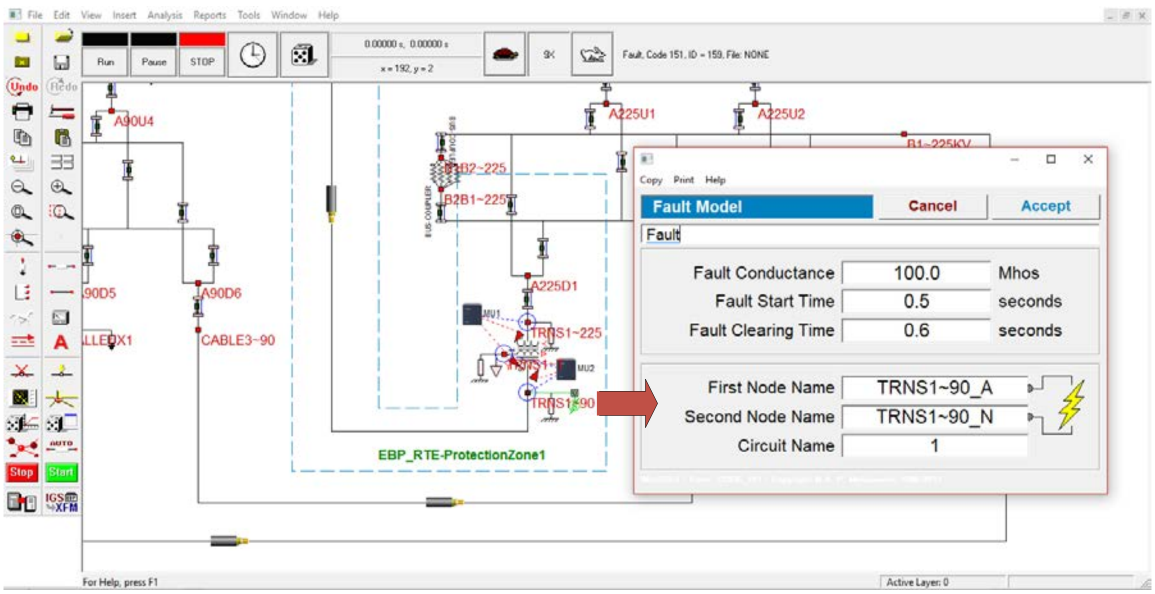


Figure 5-16: Network Model with Fault between Phase A and Neutral at Bus TRNS1~90

The simulation is executed for a period of one second. The measurements generated during the simulation are stored in a COMTRADE file. Figure 5-17 shows the time domain simulation parameters dialog where the simulation time step, duration, as well as the COMTRADE output is specified. Note that the time step is selected to match the standard merging unit sampling rate at 80 samples per cycle. For a 50 Hz system this is achieved by selecting the time step at:

Δt = 1,000,000 / (50 x 80) = 250 microseconds.

The voltages and currents captured by the three merging units are plotted in Figure 5-18 to Figure 5-20.

The WinIGS-T case files is named RTE_PZone1_EVENT_A.NMT and is provided with this report. The generated COMTRADE configuration and data files are named RTE_PZone1_EVENT_A_BLOCX.cfg and RTE_PZone1_EVENT_A_BLOCX.dat respectively.

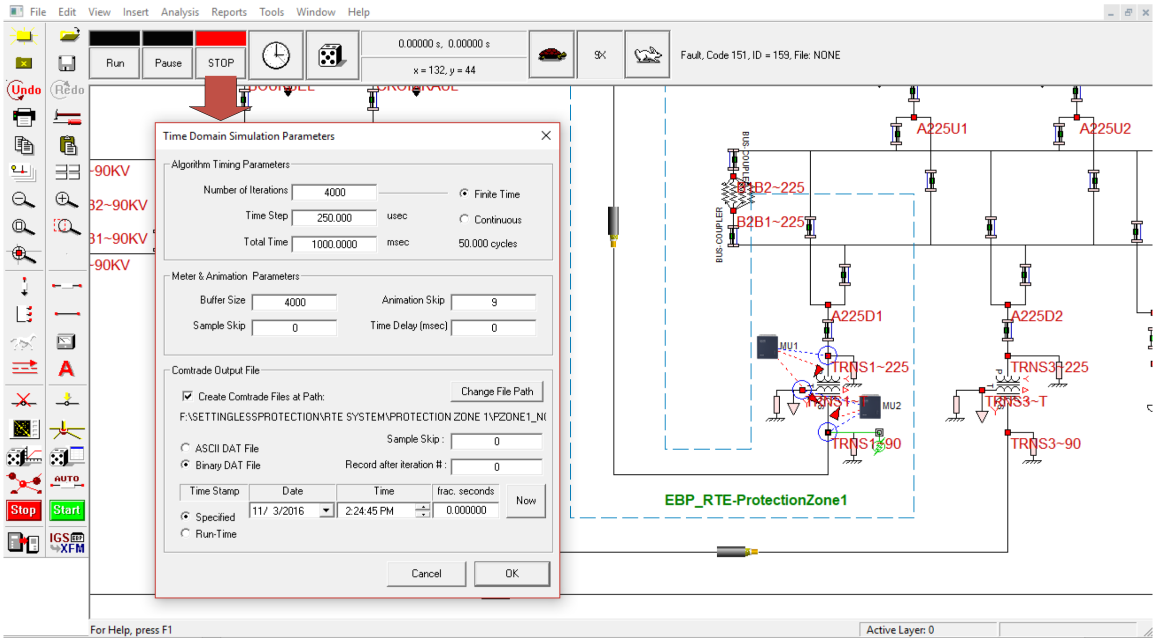


Figure 5-17: Time Domain Simulation Parameters Dialog

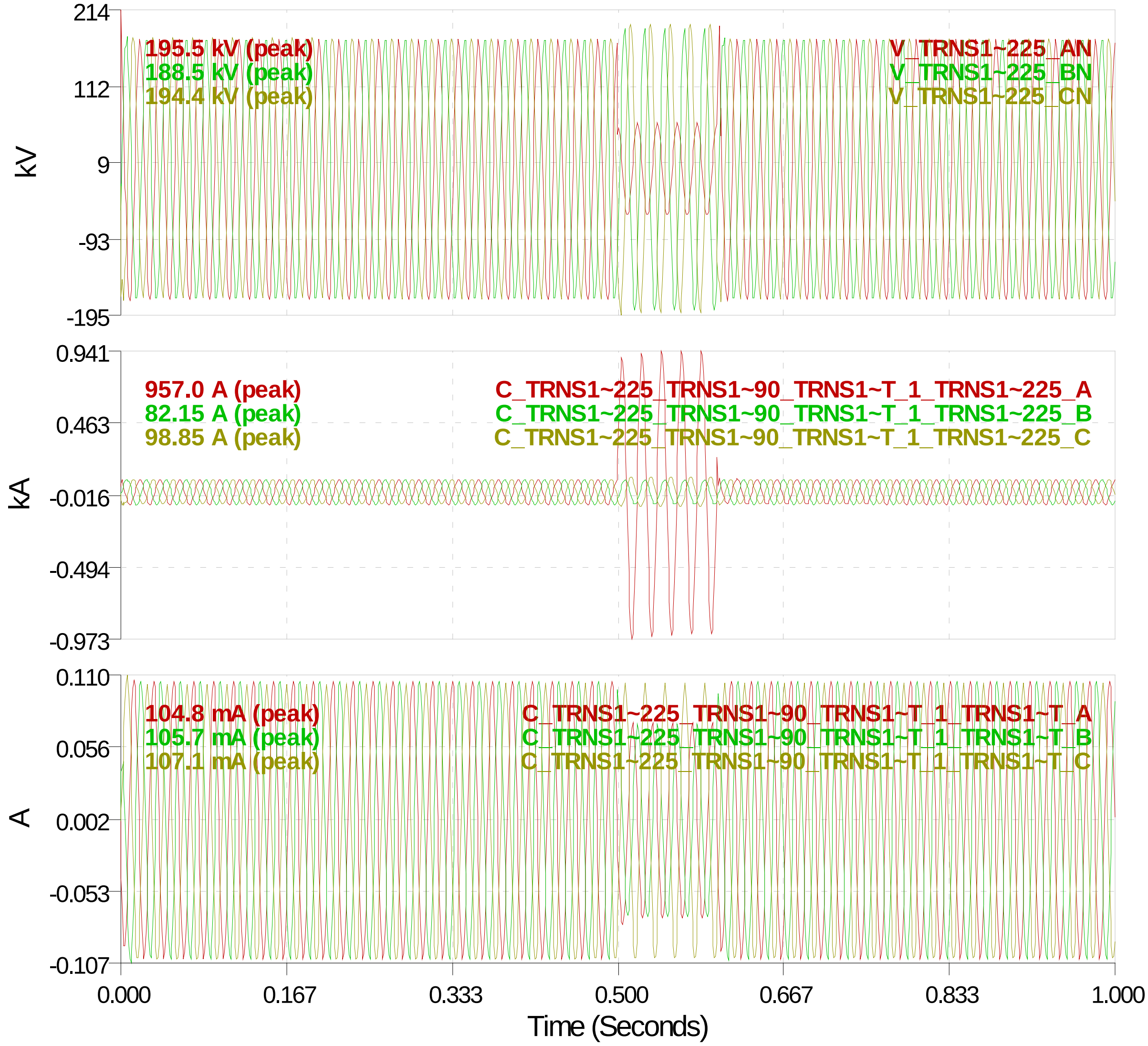


Figure 5-18: Voltage and Current Measurements Obtained from Merging Unit 1 in Event A

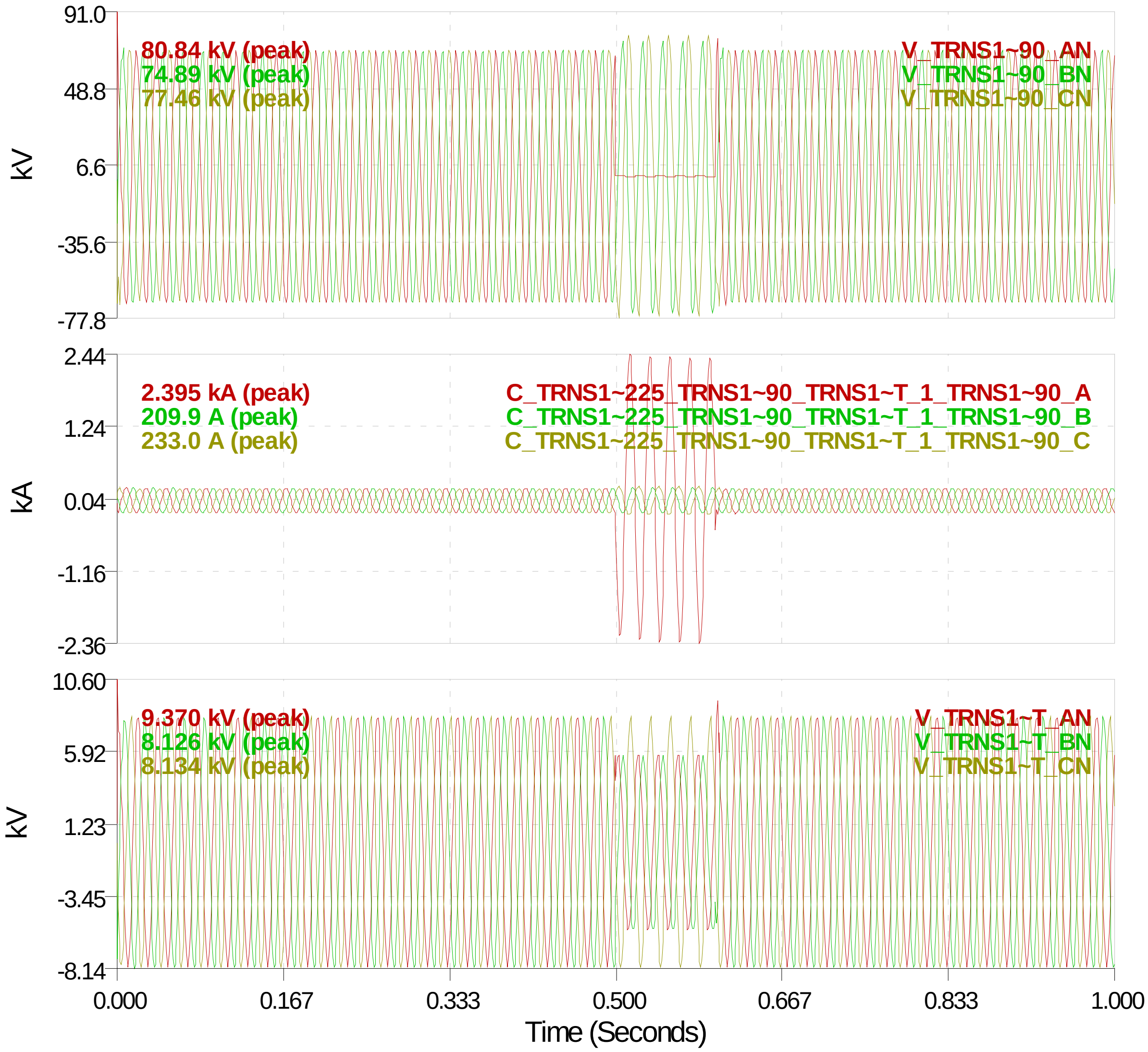


Figure 5-19: Voltage and Current Measurements Obtained from Merging Unit 2 in Event A

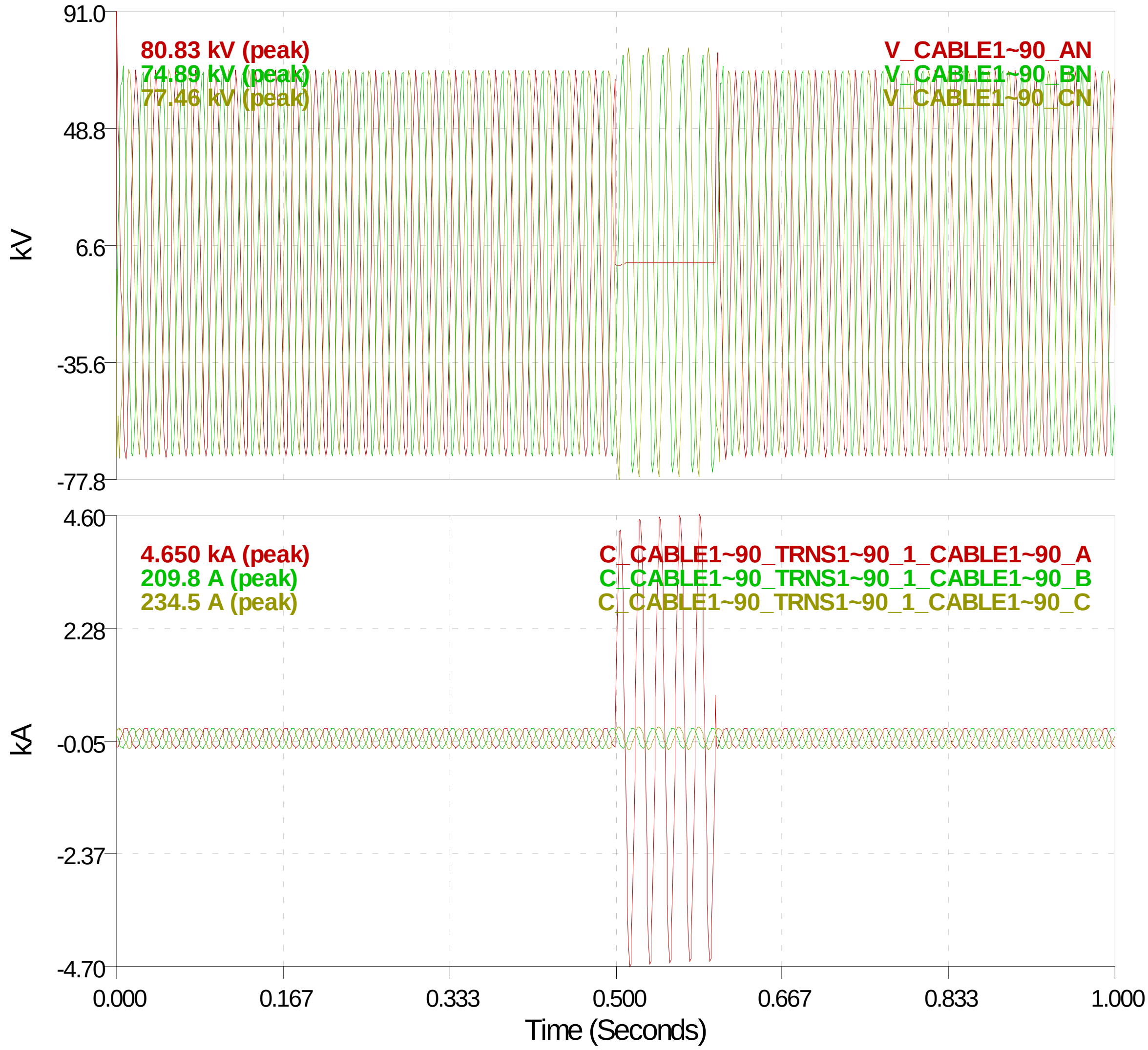


Figure 5-20: Voltage and Current Measurements Obtained from Merging Unit 3 in Event A

5.2.2 Event B: UseCase_01.B

Event B is defined as a phase A to neutral fault at bus **A225D2** (an external fault). Figure 5-21 shows the fault model and fault model parameters dialog. This is a fault occurring outside protection zone 1 and therefore the breakers of zone 1 should not operate. The fault is initiated at 0.5 seconds from the start of the simulation and lasts 0.1 second.

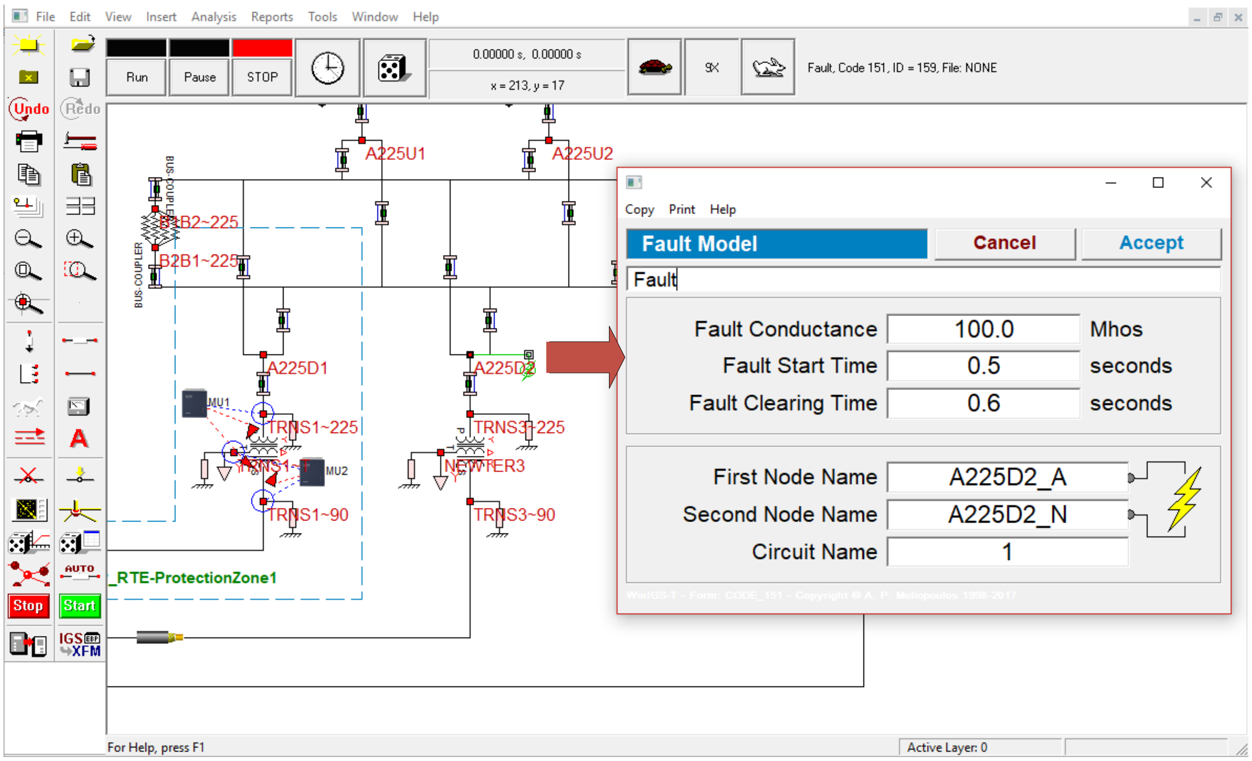


Figure 5-21: Network Model with Fault between Phase A and Neutral at Bus A225D2

The simulation is executed for a period of one second. The measurements generated during the simulation are stored in a COMTRADE file. The time step is selected to match the standard merging unit sampling rate at 80 samples per cycle, which for a 50 Hz system is 250 microseconds (i.e. same as for Event A).

The voltages and currents captured by the three merging units are plotted from Figure 5-22 to Figure 5-24.

The WinIGS-T case file is named as RTE_PZone1_EVENT_B.NMT and is provided with this report. The generated COMTRADE configuration and data files are named RTE_PZone1_EVENT_B_BLOCX.cfg and RTE_PZone1_EVENT_B_BLOCX.dat, respectively.

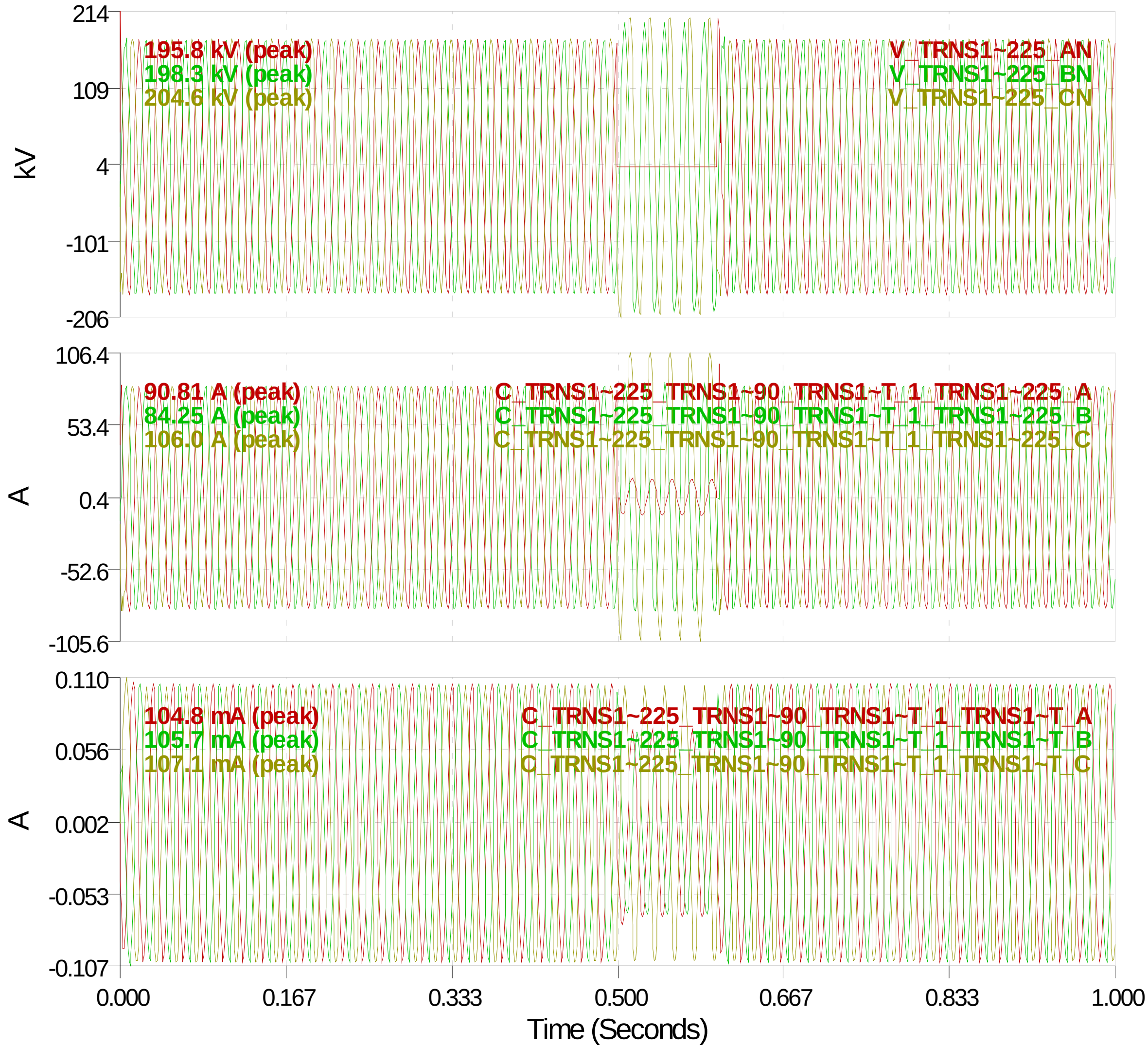


Figure 5-22: Voltage and Current Measurements Obtained from Merging Unit 1 in Event B

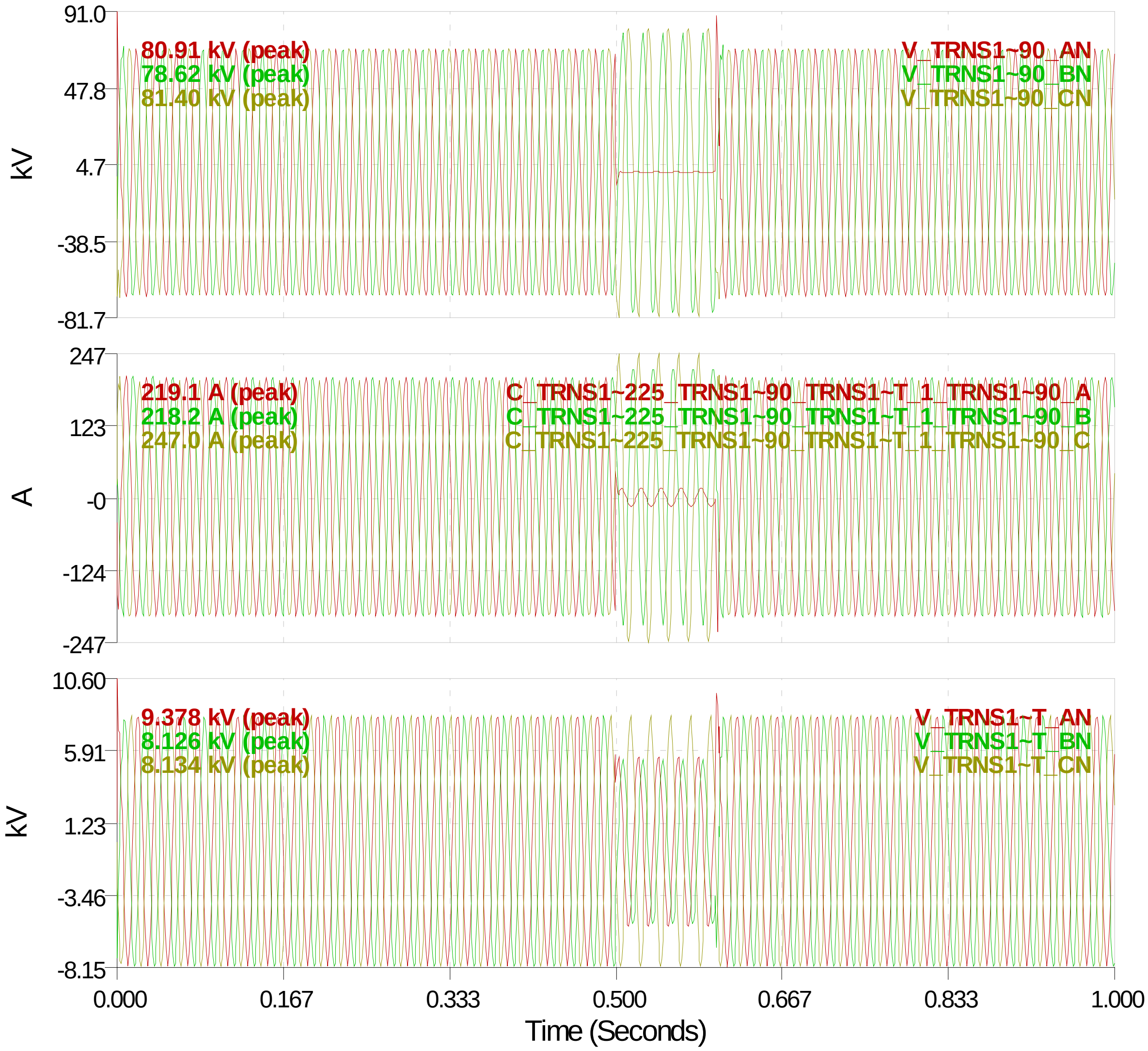


Figure 5-23: Voltage and Current Measurements Obtained from Merging Unit 2 in Event B

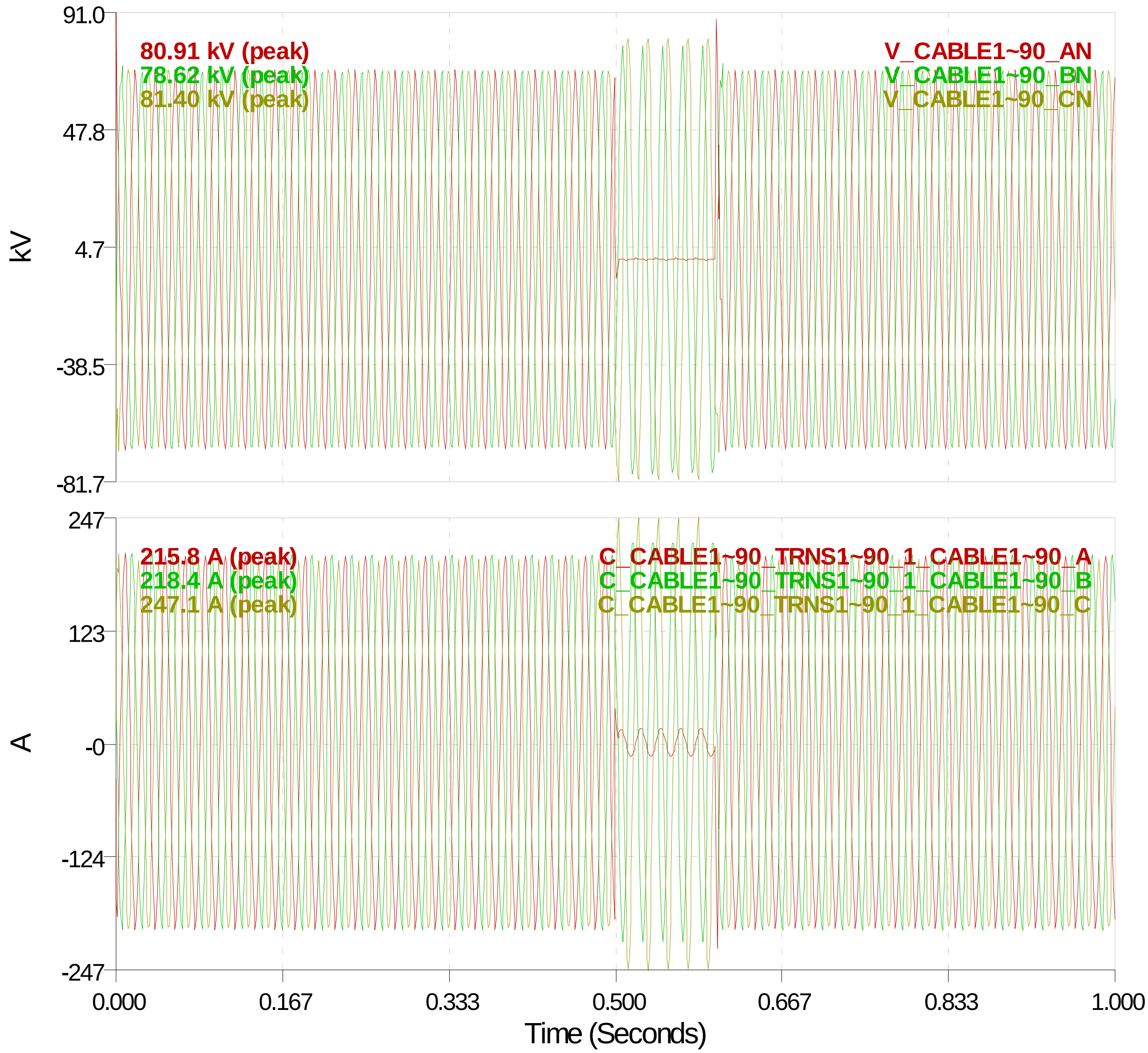


Figure 5-24: Voltage and Current Measurements Obtained from Merging Unit 3 in Event B

5.3 EBP Results

This section presents the results obtained from the EBP relay for the use case and events described in Section 5.2. The EBP relay has been implemented within the WinXFM Program. In order to setup the EBP relay and run the use cases, execute the WinXFM program, open one of the provided WinXFM files, and click on the EBP button as indicated in Figure 5-25.

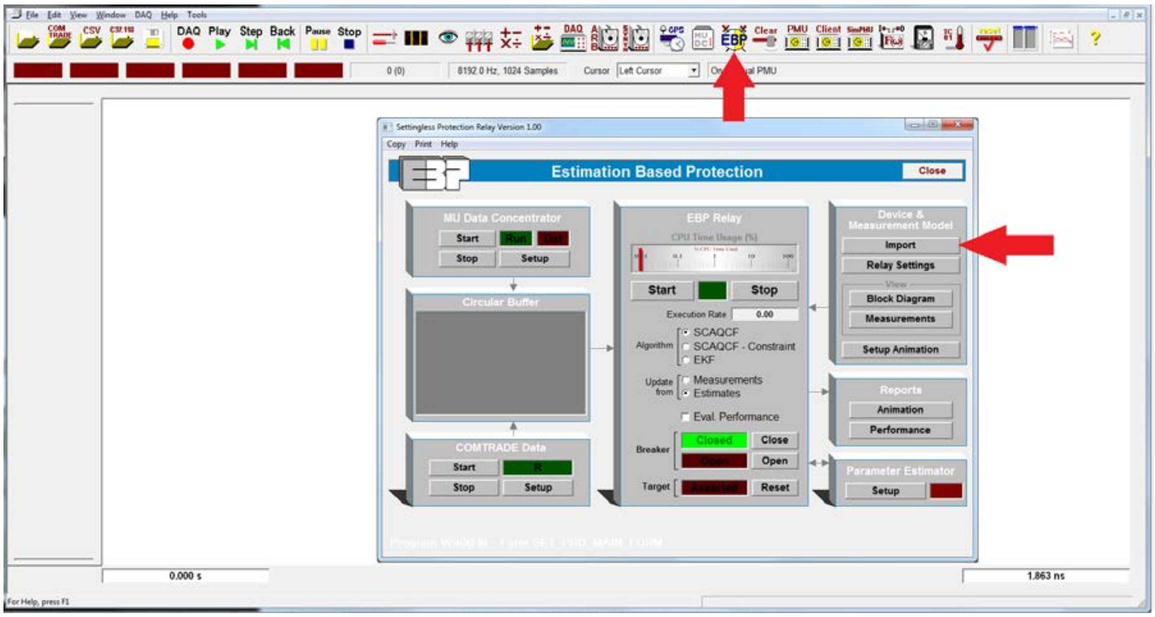


Figure 5-25: Opening the EBP Main Setup Form in the WinXFM Program

5.3.1 Event A: UseCase_01.A

As described in Section 5.2, Event A is defined as a phase A to neutral fault at bus TRNS1~90. To run the EBP relay using the Event A data, execute the WinXFM program and open the WinXFM file:

RTE-SYSTEM-B-EVENT-A

Note: this file is provided with this report under the file name RTE-SYSTEM-B-EVENT-A.xfm

Click on the Import button of the main EBP dialog window to open the "*Device and Measurement File*" dialog shown in Figure 5-25. Verify that the Zone_1 Device and Measurement files have been selected and that the model domain and model kind are selected as "**Time Domain**" and "**Algebraic Companion Form**". Click on the **Import** button, and verify that the selected protection zone devices are listed and the active column is checked as illustrated in Figure 5-26. Click on the **Accept** button to close the *Device and Measurement File* dialog. This procedure imports the measurement definition and device model data generated using the WinIGS-T program and stored in the data files:

- PZone1.TDMDEF (Measurement Definition File)

- PZone1.TDSCAQCF (Device Model File)

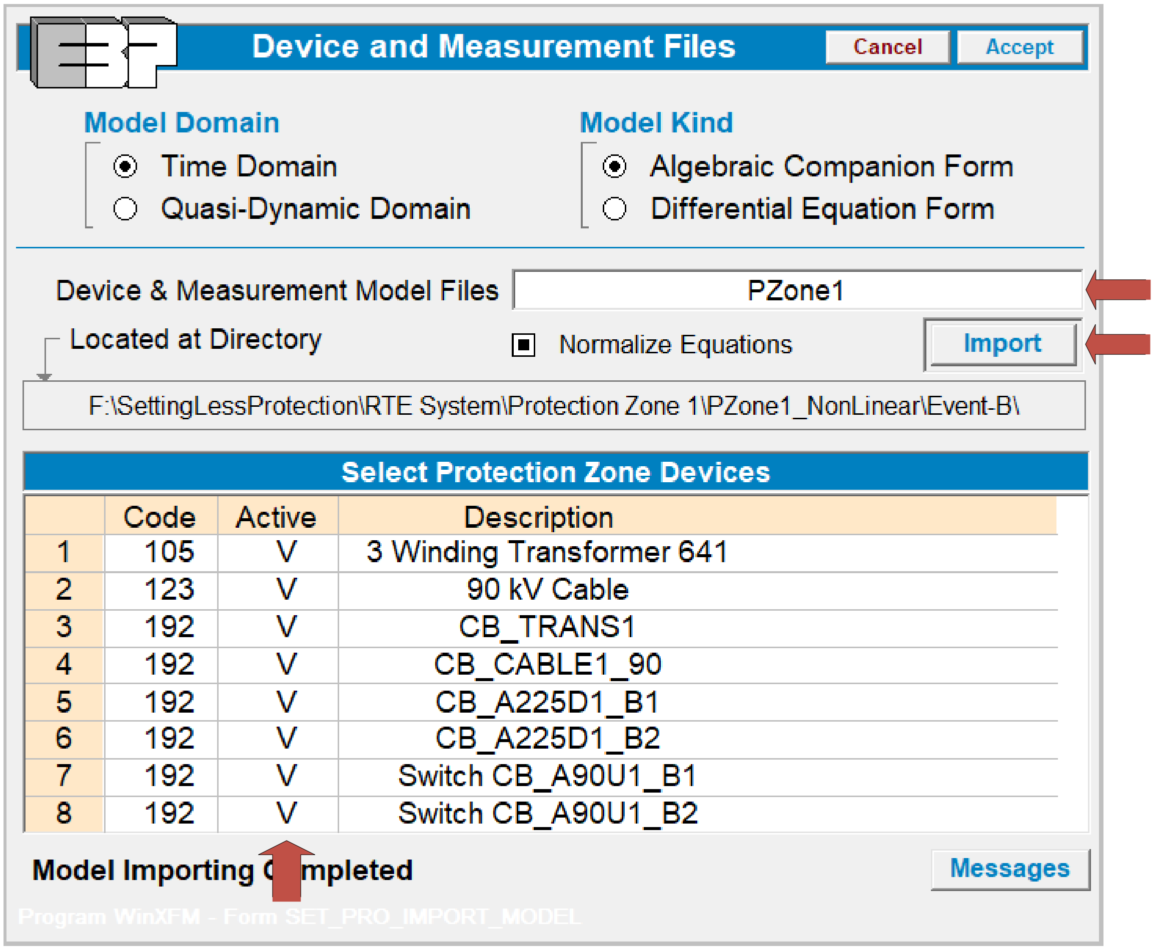


Figure 5-26: Importing Zone 1 Device and Measurement Definition Files

Next click on the Setup button of the COMTRADE Data block of the main EBP dialog (See Figure 5-27) to open the COMTRADE Data Playback dialog (shown in Figure 5-28). Verify that the **COMTRADE File Name** field indicating the Event A waveform data has been selected: (file name: RTE_PZone1_EVENT_A_BLOCX). Also verify the following:

- Playback rate is set at **4000** samples per second for 50 Hz systems.

- Speed Factor radio button is selected and the speed factor is set to 5.0.

The speed factor option allows the relay response to be observed in slow motion. Otherwise, if you select the real-time option, the playback will occur in real time and the whole process will be completed in one second, i.e., the duration of the waveform data stored in the COMTRADE file.

Click on the **Close** button to close the COMTRADE Data Playback dialog.

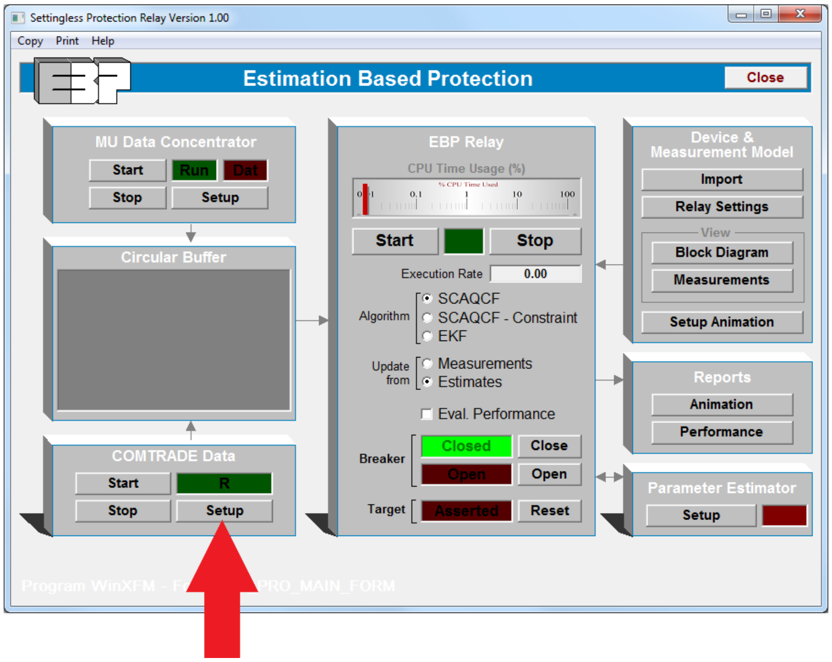


Figure 5-27: Opening the COMTRADE Setup Dialog

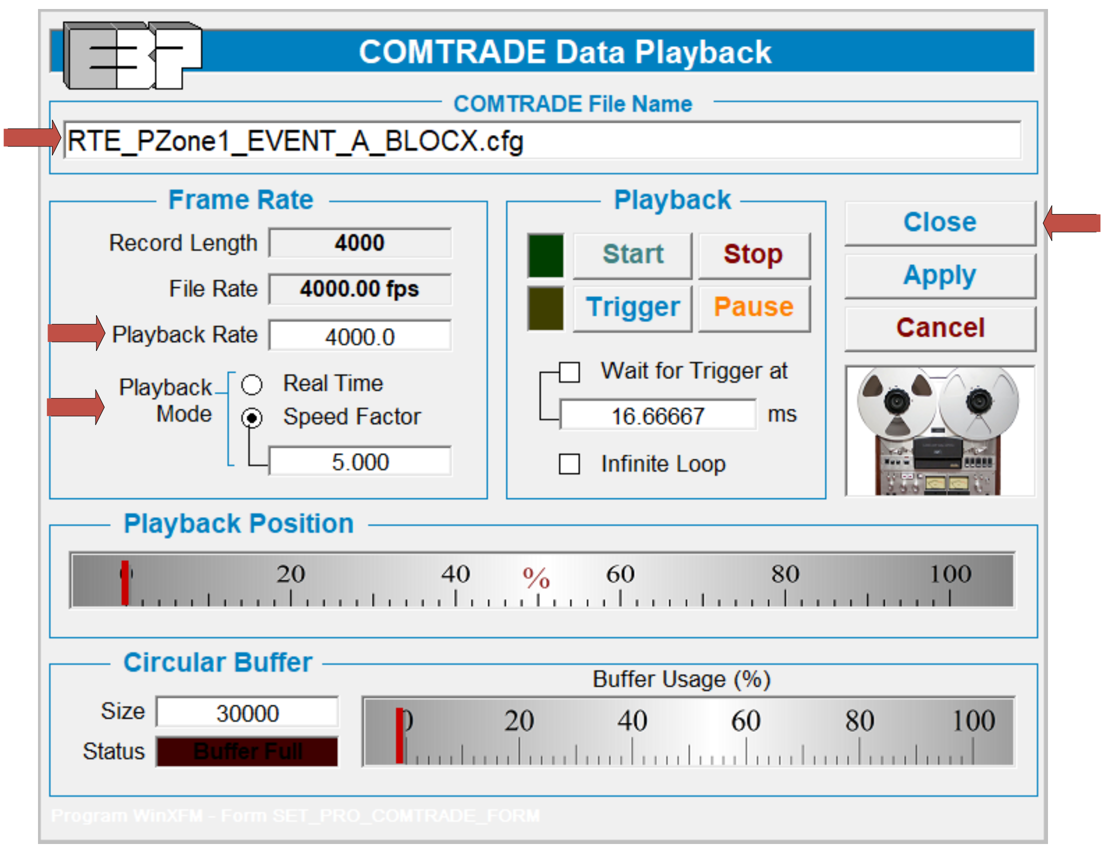


Figure 5-28: Selecting the COMTRADE Data Files for Playback

At this point, the system is ready to execute the EBP relay using the Event A data. It is recommended to click on the **Save** ( ) button of the main WinXFM user interface (Horizontal Tool-Bar) in order to save all entered setup parameters.

Click on the **Start** button of the EBP Relay block to start the EBP relay, then on the **Start** button of the COMTRADE Data block to start streaming the data to the relay.

The performance metrics of this event is illustrated in Figure 5-29. Note that the confidence level is 100% before the fault, and reaches to zero immediately upon the fault initiation. The trip decision is then made within a certain delay that can be determined by clicking the **Relay Setting**s button in Figure 5-27. In addition to the channels shown in Figure 5-29, a list of available channels for plotting is shown in Figure 5-30. This can be achieved by clicking on the **Select Channels to Display** ( ) button in the main WinXFM user interface (Horizontal Tool Bar).

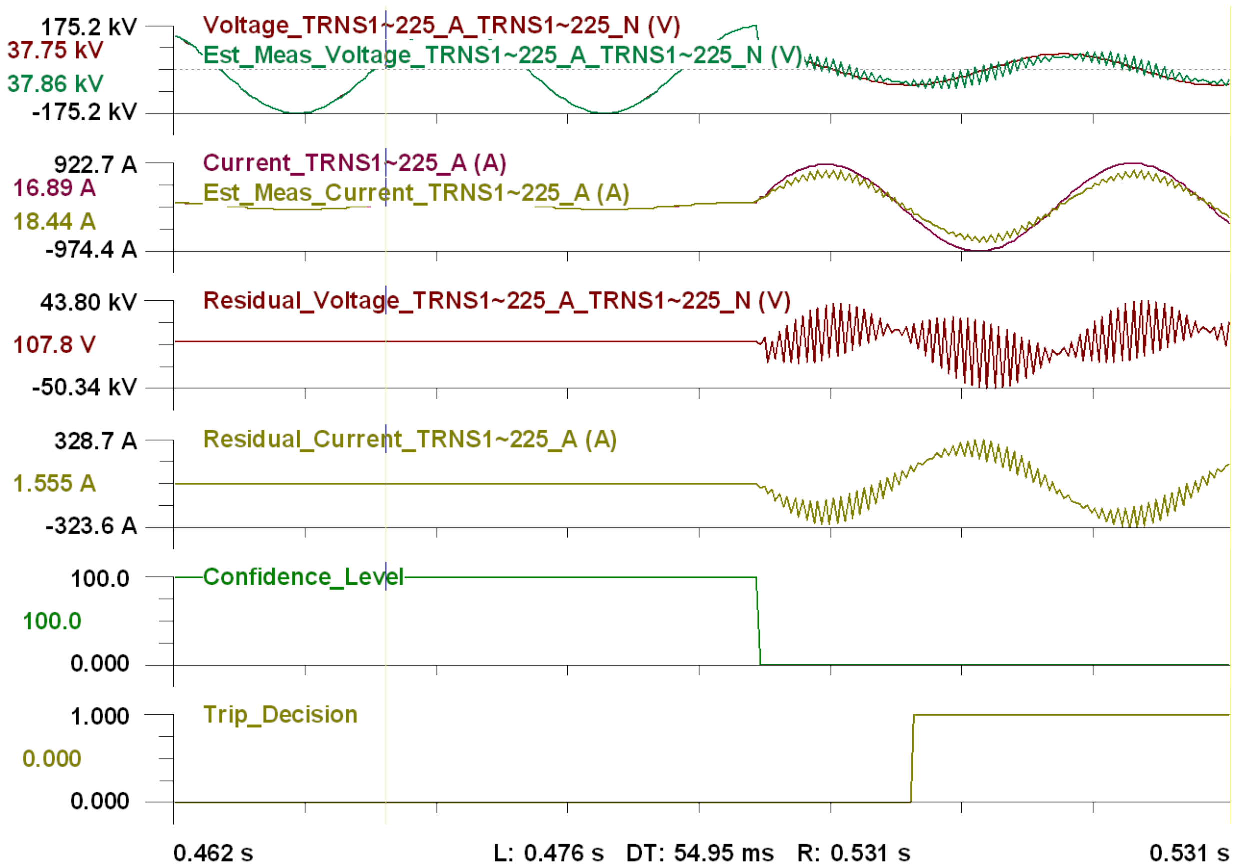


Figure 5-29: Plots of Some Actual/Estimated Measurements, Residuals, Confidence Level, and Trip Decision in Event A

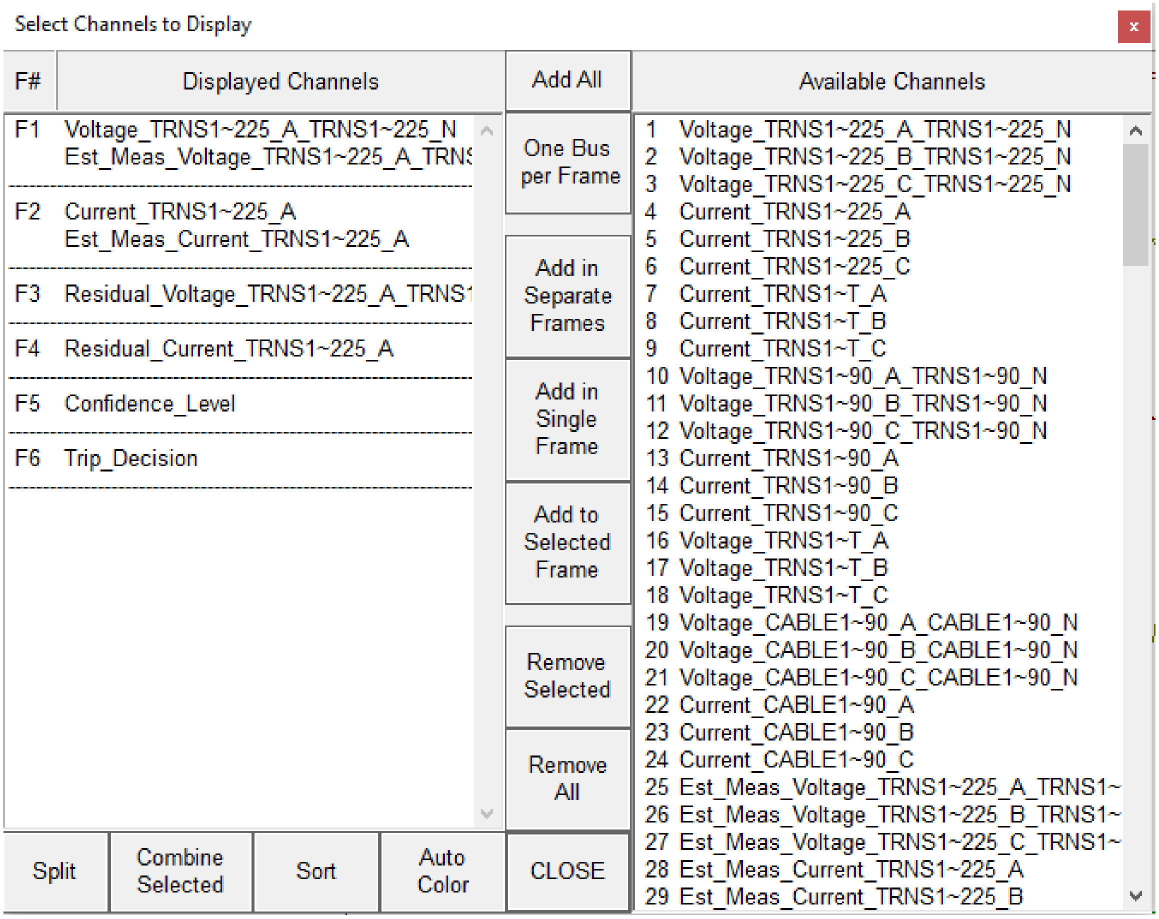


Figure 5-30: A List of Available Channels for Plotting

5.3.2 Event B: UseCase_01.B

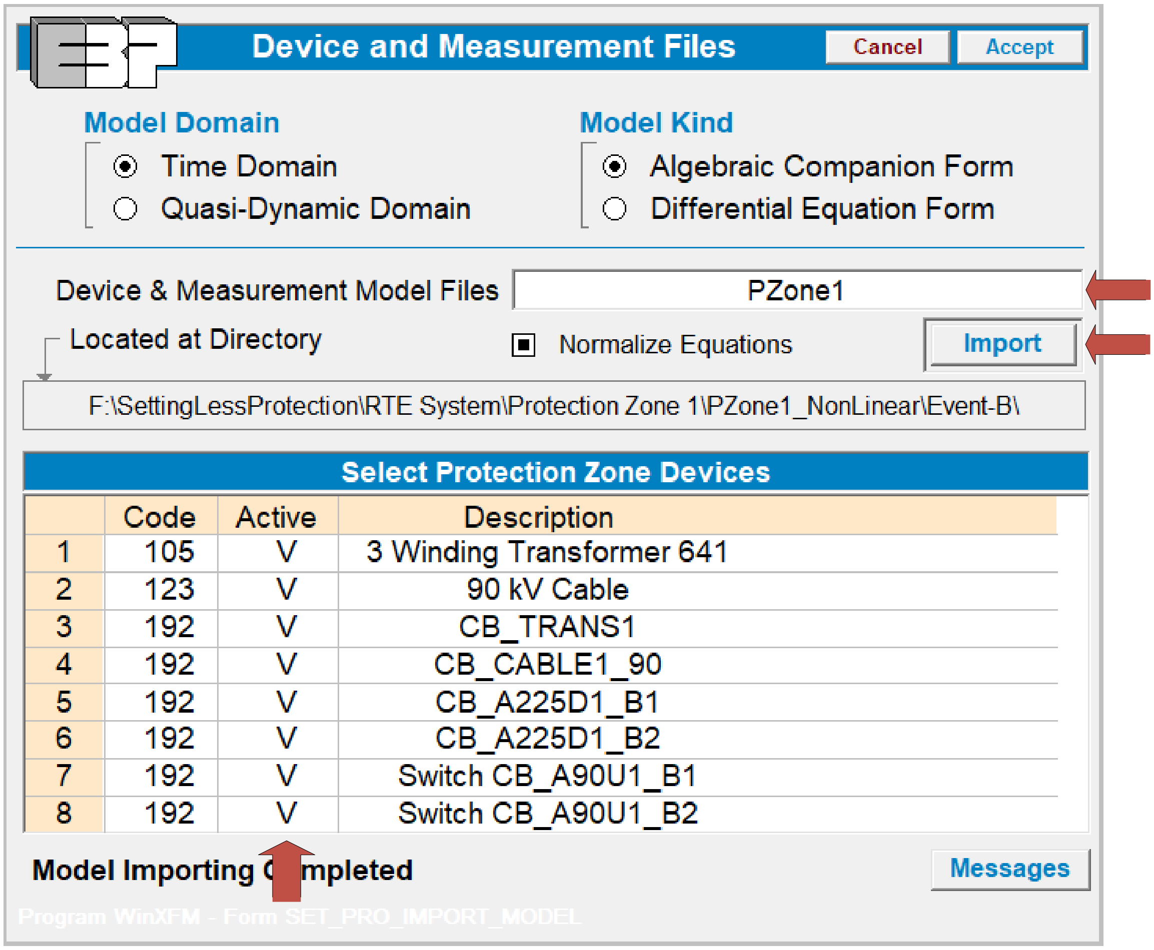
Event B is defined as a phase A to neutral fault at bus **A225D2** (an external fault). To run the EBP relay using the Event B simulated waveforms, execute the WinXFM program and open the WinXFM file:

RTE-SYSTEM-B-EVENT-B

Note: this file is provided with this report under the file name RTE-SYSTEM-B-EVENT-B.xfm

Click on the Import button of the main EBP dialog window to open the "*Device and Measurement Files*" dialog shown in Figure 5-31. Verify that the Zone_1 Device and Measurement files have been selected and that the model domain and model kind are selected as "Time Domain" and "Algebraic Companion Form". Click on the **Import** button, and verify that the selected protection zone devices are listed and the active column is checked as illustrated in Figure 5-31. Click on the Accept button to close the *Device and Measurement Files* dialog. This procedure imports the measurement definition and device model data generated using the WinIGS-T program and stored in the data files:

- PZone1.TDMDEF (Measurement Definition File)
- PZone1.TDSCAQCF (Device Model File)



	Code	Active	Description
1	105	V	3 Winding Transformer 641
2	123	V	90 kV Cable
3	192	V	CB_TRANS1
4	192	V	CB_CABLE1_90
5	192	V	CB_A225D1_B1
6	192	V	CB_A225D1_B2
7	192	V	Switch CB_A90U1_B1
8	192	V	Switch CB_A90U1_B2

Figure 5-31: Importing Zone 1 Device and Measurement Definition Files

Next click on the Setup button of the COMTRADE Data block of the main EBP dialog (See Figure 5-32) to open the COMTRADE Data Playback dialog (shown in Figure 5-33).

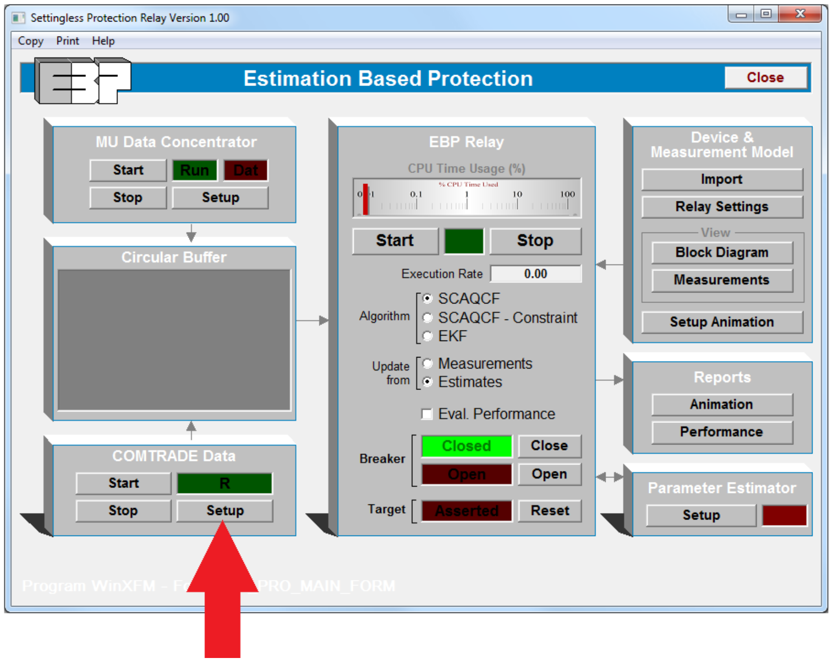


Figure 5-32: Opening the COMTRADE Setup Dialog

Verify that the **COMTRADE File Name** field indicates that the Event B waveform data has been selected: (file name: RTE_PZone1_EVENT_B_BLOCX). Also verify the following:

- Playback rate is set at **4000** samples per second for 50 Hz systems.

- Speed Factor radio button is selected and the speed factor is set to 5.0.

The speed factor option allows the relay response to be observed in slow motion. Otherwise, if you select the real-time option, the playback will occur in real time and the whole process will be completed in one second, i.e., the duration of the waveform data stored in the COMTRADE file.

Click on the **Close** button to close the COMTRADE Data Playback dialog.

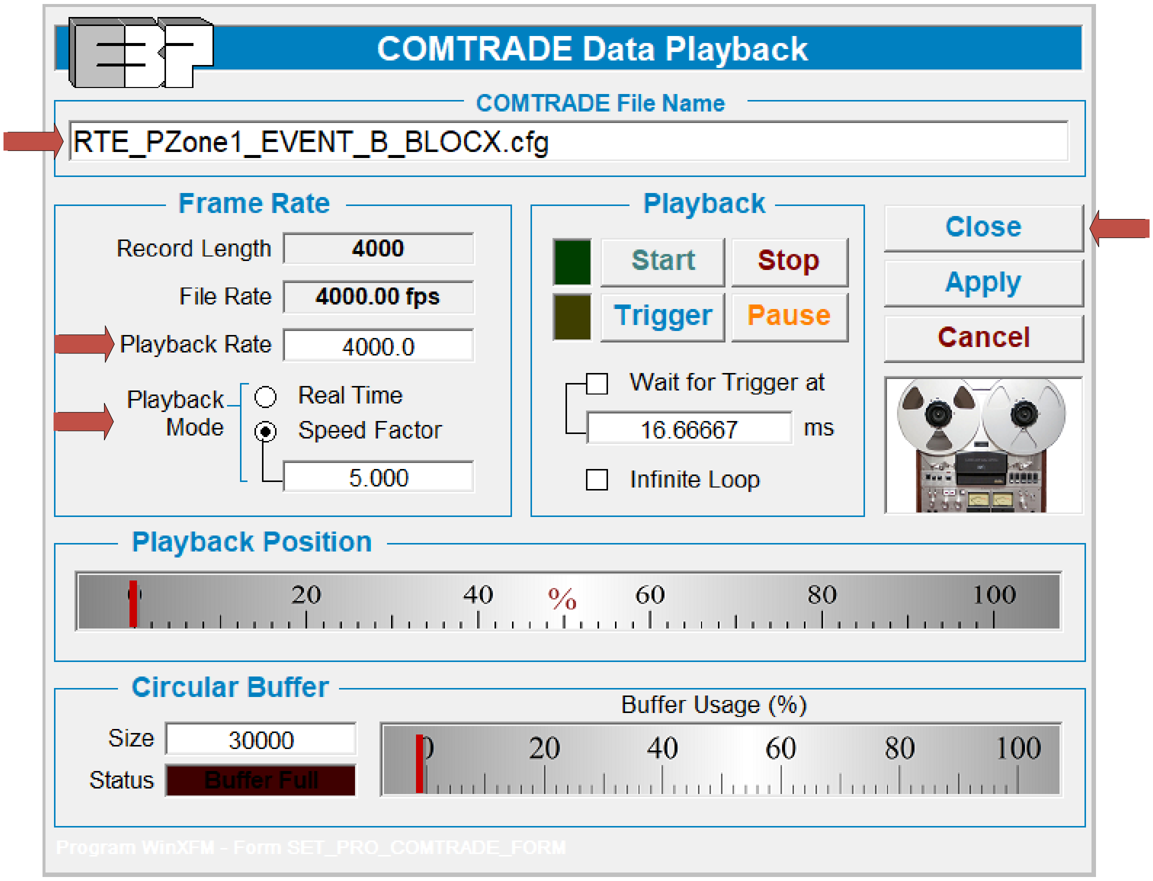


Figure 5-33: Selecting the COMTRADE Data files for Playback

At this point, the system is ready to execute the EBP relay using the Event B data. It is recommended to click on the **Save** ( ) button of the main WinXFM user interface (Horizontal Tool-Bar) in order to save any modified setup parameters.

Click on the **Start** button of the EBP Relay block to start the EBP relay, then on the **Start** button of the COMTRADE Data block to start streaming the data to the relay.

The performance metrics of this event is illustrated in Figure 5-34. Note that the confidence level is nearly 100% before the fault, as well as during the fault. Only small spikes occur when the fault is initiated and ended. Note that the breakers remain closed (as expected) during the whole event since the fault is outside the protection zone. In addition to the channels shown in Figure 5-34, a list of available channels for plotting is shown in Figure 5-35. This can be achieved by clicking on the **Select Channels to Display** ( ) button in the main WinXFM user interface (Horizontal Tool Bar).

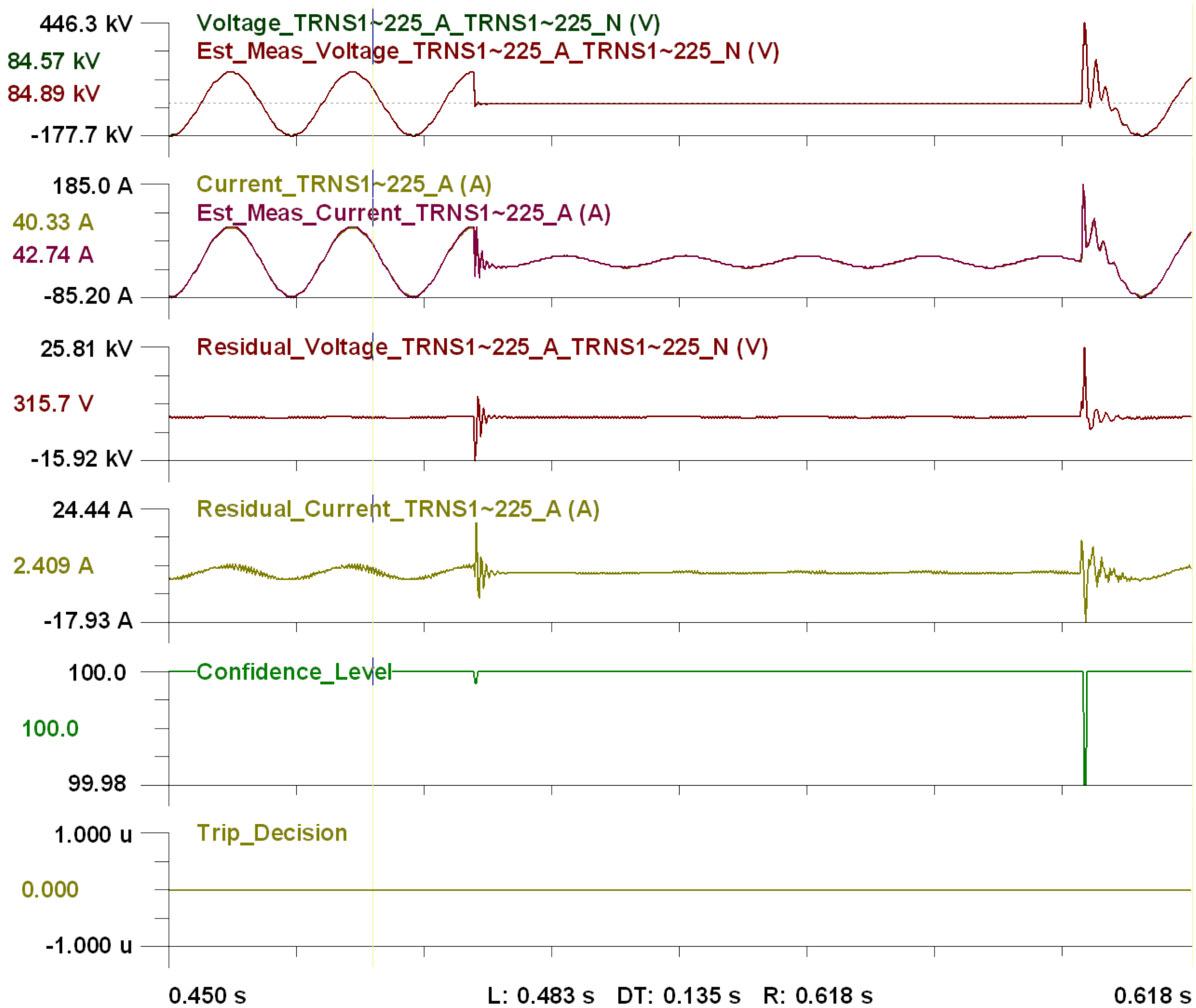


Figure 5-34: Plots of Some Actual/Estimated Measurements, Residuals, Confidence Level, and Trip Decision in Event B

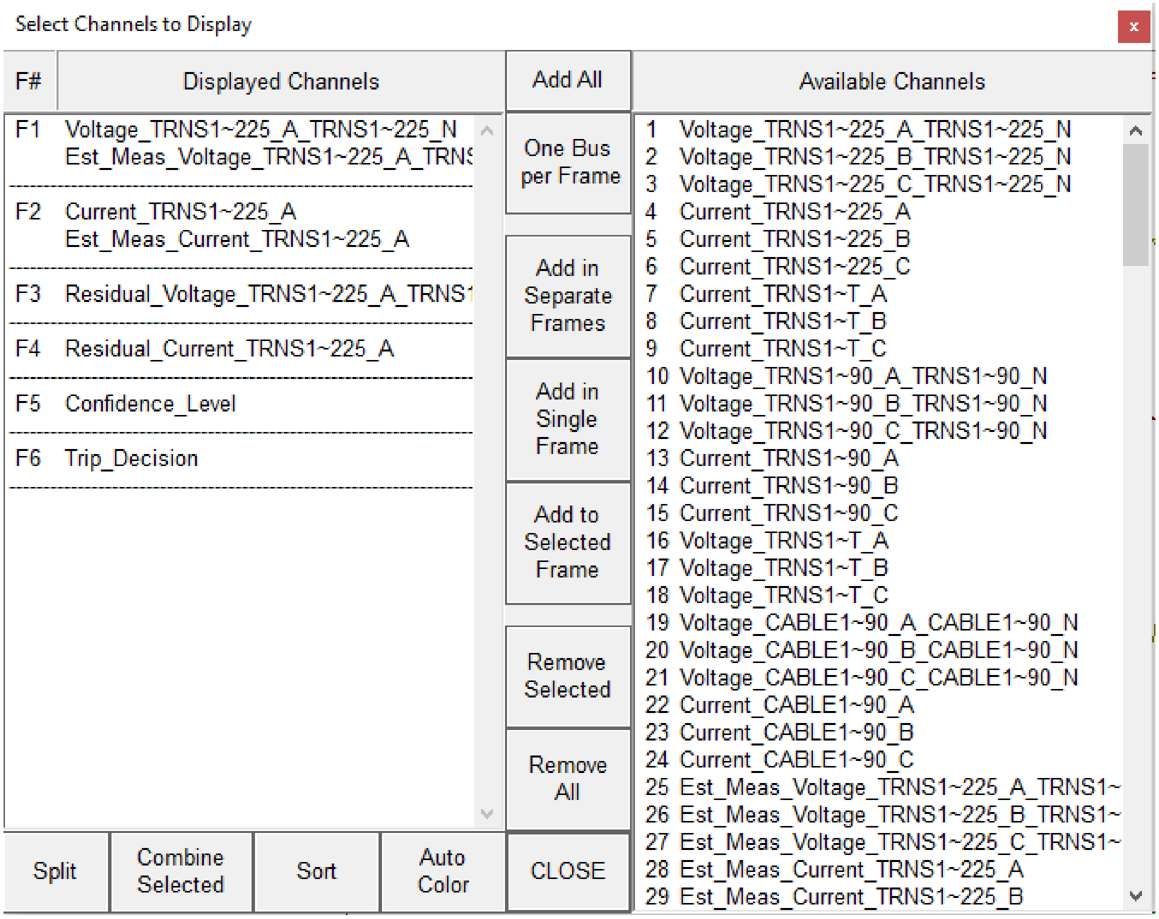


Figure 5-35: A List of Available Channels for Plotting

6. Example Test Results: RTE Protection Zone 04

This section describes a use case for preparing and running the setting-less relay for the specific protection zone 4 of the RTE substation BLOCX. Protection Zone 4 is a **shunt reactor bank** at the 225 kV section of the BLOCKX substation. The inductor bank is connected to breaker and a main/transfer bus arrangement.

First, the protection zone model is developed in the program WinIGS-T. Once the protection zone model has been defined, it is exported into two files that are readable by the Estimation Based Protection (EBP) program. The first file contains the model of the protection zone power components. Note that a protection zone may include one or more components, for example protection zone 4 contains a reactor and breakers. Each protection zone component model is represented in its SCPAQCF format (State, Control, and Parameter Algebraic Quadratic Companion Form). The second file contains the definition of the measurements. The measurements definition provides the IED (Merging unit providing the measurement, type of measurement, and where on the protection zone the measurement was taken. The measurement definition is key-word oriented.

A number of events have been simulated with the program WinIGS-T, using the RTE BLOCAUX substation model. The results of the simulation provided by the merging units of the Protection Zone 4 are stored in COMTRADE format. These files are used for playback through a series of conversions and amplifiers into merging units connected to the EBP relay in the laboratory.

The use case demonstrates the EBP procedure consisting of the following steps:

- Read model and measurement files
- Read event data (COMTRADE files)
- Run the setting-less relay.

This report includes several simulated events as well as the EBP results.

6.1 Creating Protection Zone Models for EBP Relays

WinIGS-T includes a tool which automatically generates the model of the user selected protection zone in the **SCPAQCF** syntax. The protection zone can be a single component protection zone or it may comprise several components and/or breakers. The estimation based protective relay (EBP, a.k.a. setting-less relay) requires the model of the protection zone in SCPAQCF standard. The user should select the components that constitute the protection zone and which must be exported in the **SCPAQCF** syntax into a file. In addition, the user must specify the merging units providing data to the EBP relay in order to generate a second file describing the measurement parameters. These two files are read by the WinXFM-EBP program which executes the estimation based protective relay algorithm.

6.1.1 Creating the Network Time Domain Model

The procedure to generate the EBP model file begins by building a system model in WinIGS-T. The WinIGS-T model could include the entire or part of the large system (for simulation studies and for generating events) and must also include the models of the protection zone under study. Specifically:

- The power devices comprising the EBP protection zone.
- The instrumentation channels available to the EBP relay via merging units.
- The breakers/switches that enable the protection of the zone.

The WinIGS-T model for the RTE system, including the necessary merging unit information is provided along with this document. The RTE network model is shown in Figure 6-1. Note that the RTE substation of interest is represented by the circular icon labelled **SUB BLOCKX**. Double click on this icon to open the substation single line diagram view, illustrated in Figure 6-2.

Next zoom in to view the protection zone if interest i.e. Protection Zone 4, containing a 3-Phase shunt reactor bank and a breaker. The diagram also includes a Merging Unit which captures the reactor voltages and currents.

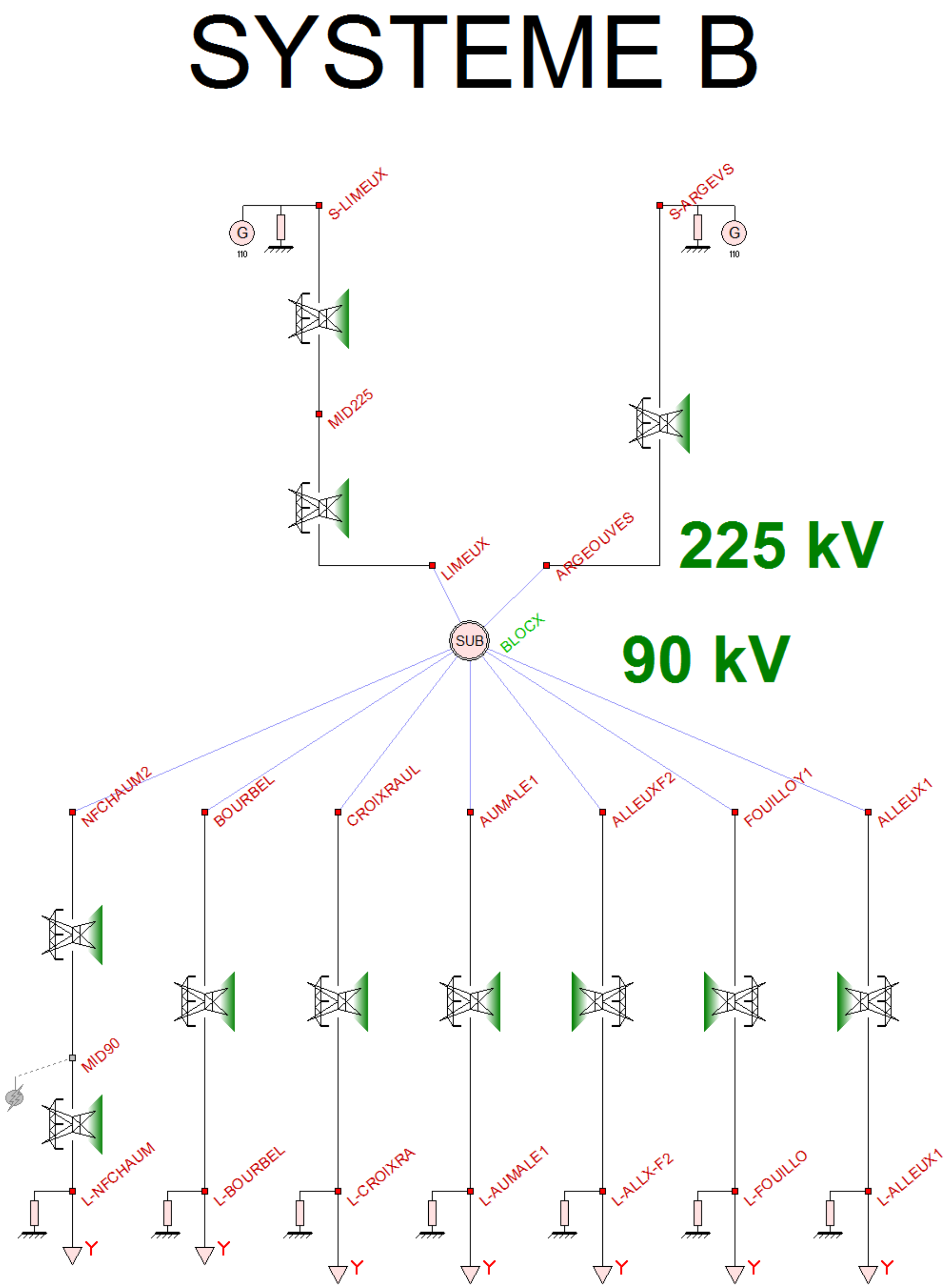


Figure 6-1: RTE System Network Model

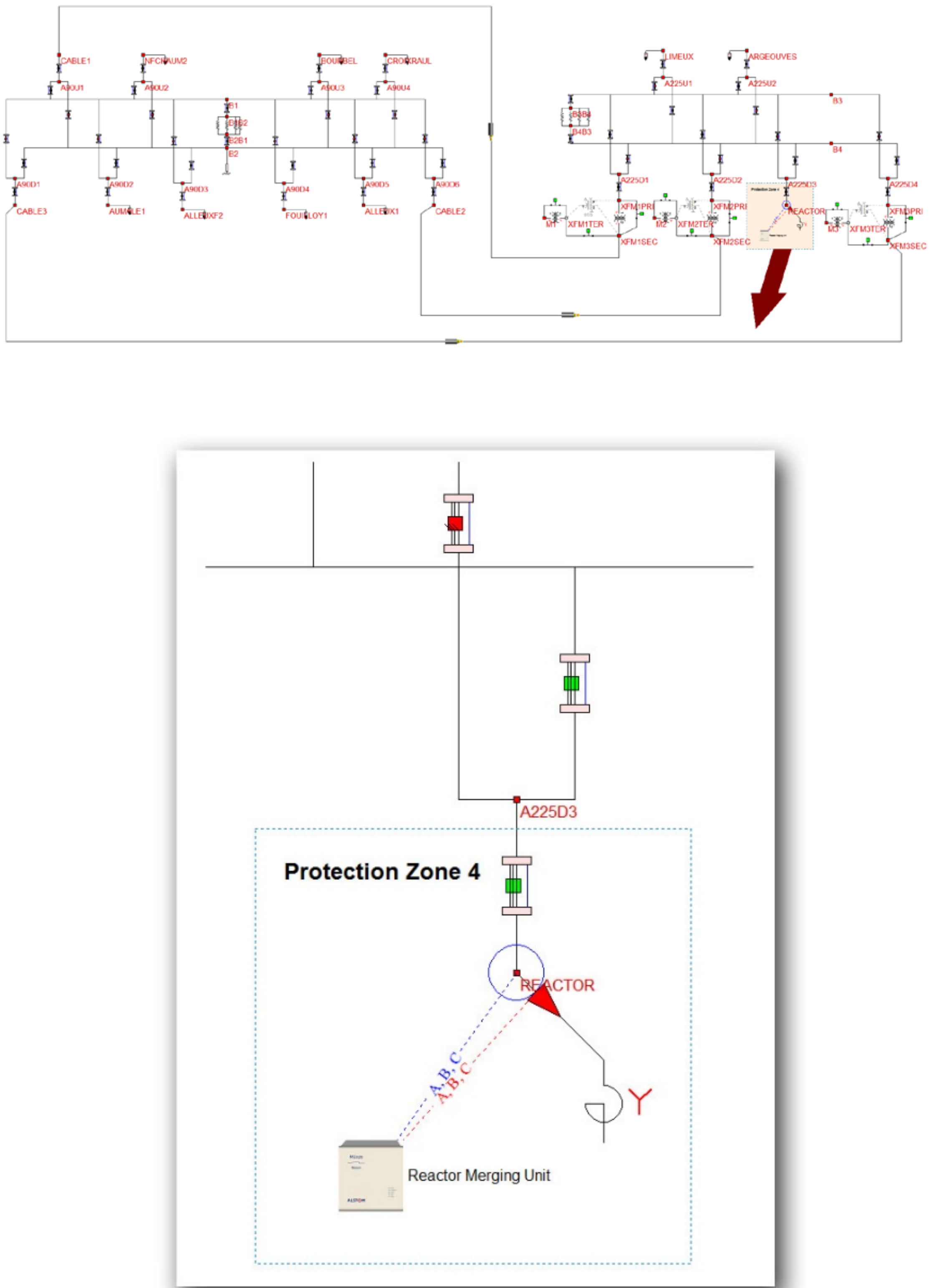


Figure 6-2: RTE Substation Single Line Diagram (top) and Protection Zone 04 (bottom)

The parameters dialog of the shunt inductor bank is illustrated in Figure 6-3. This dialog can be accessed via left button double clicking on the inductor icon. Note that the model parameters are typical nameplate information such as rated voltage and reactive power. Ensure that the reactor model parameters are correctly set. The magnetizing current of the inductor are calculated by a non-linear function in terms of the flux through the core.

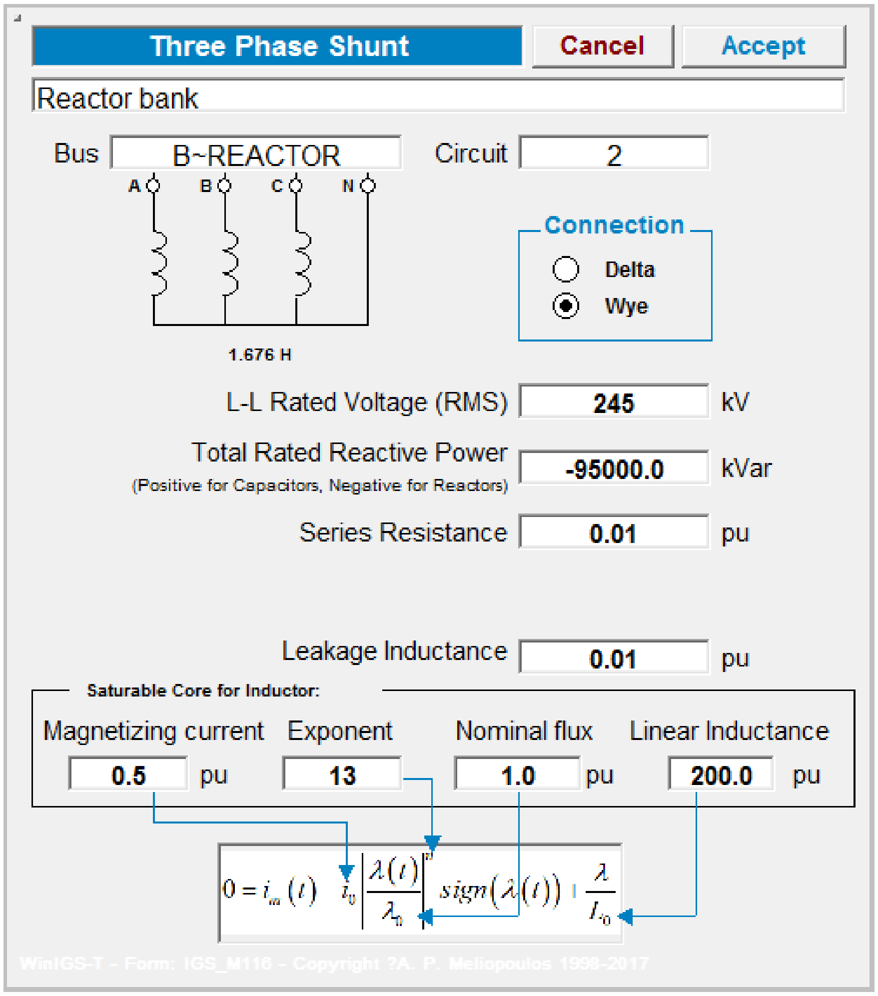


Figure 6-3: Protection Zone 4 Parameters

6.1.2 Creating Measurement Models for Merging Units

The instrumentation channel and measurement parameters to be used by the EBP relay for the Zone 4 Protection are modeled in the Merging Unit (see MU icon in Figure 6-2). In this example the EBP relay monitors the phase currents and voltages at the reactor bank terminals.

The merging unit model parameters and instrumentation channel list can be edited by clicking on the merging unit icon. This action will bring the user interface illustrated in Figure 6-4. Click on the Instrumentation button to open the instrumentation channel list dialog, illustrated in Figure 6-5.

Double-click on each list table entry to inspect the instrumentation channel parameters. Figures 6-6 and 6-7 illustrate examples of a voltage and a current channel respectively. Note that a WinIGS-T instrumentation channel model includes models of the instrument transformer, instrumentation cable, burdens, and data acquisition device (i.e. a merging unit in these example).

A short description of the instrumentation channel parameters is presented in TABLE 6-1.

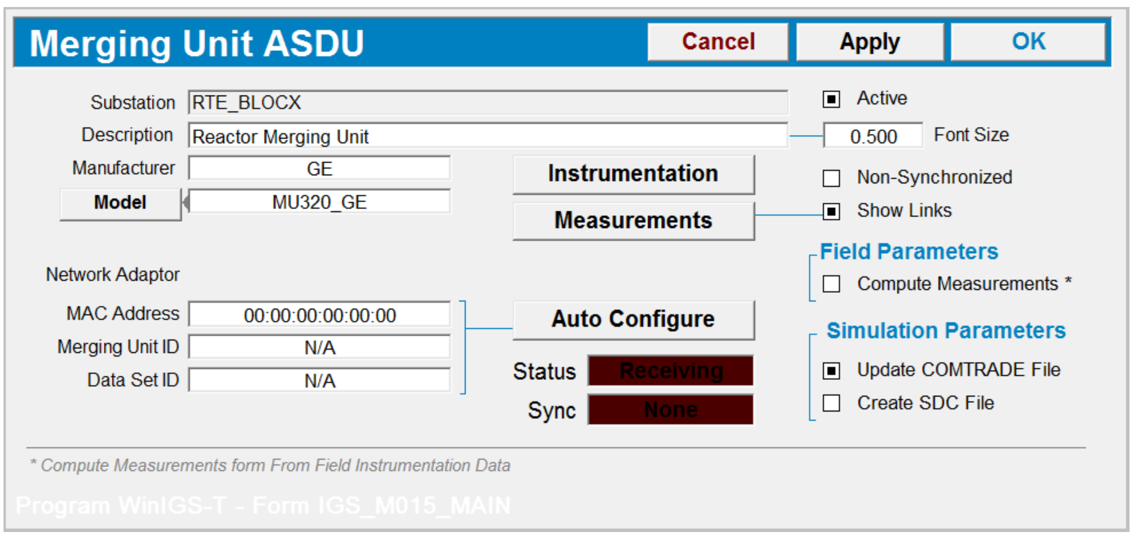


Figure 6-4: Merging Unit Main Parameter Dialog

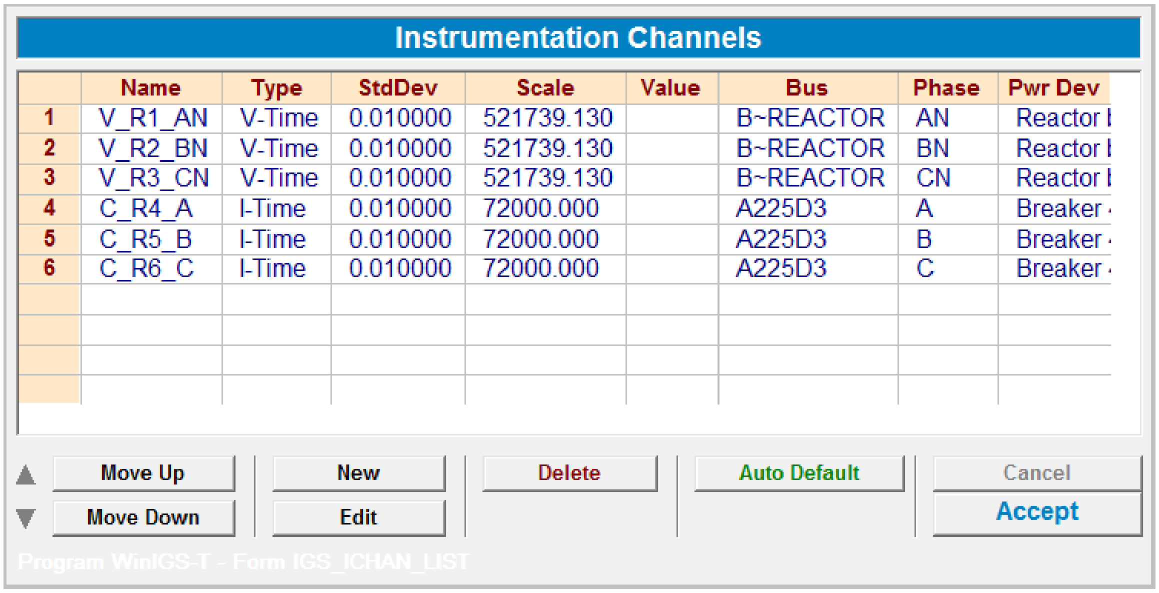


Figure 6-5: Merging Unit Instrumentation Channel List Dialog

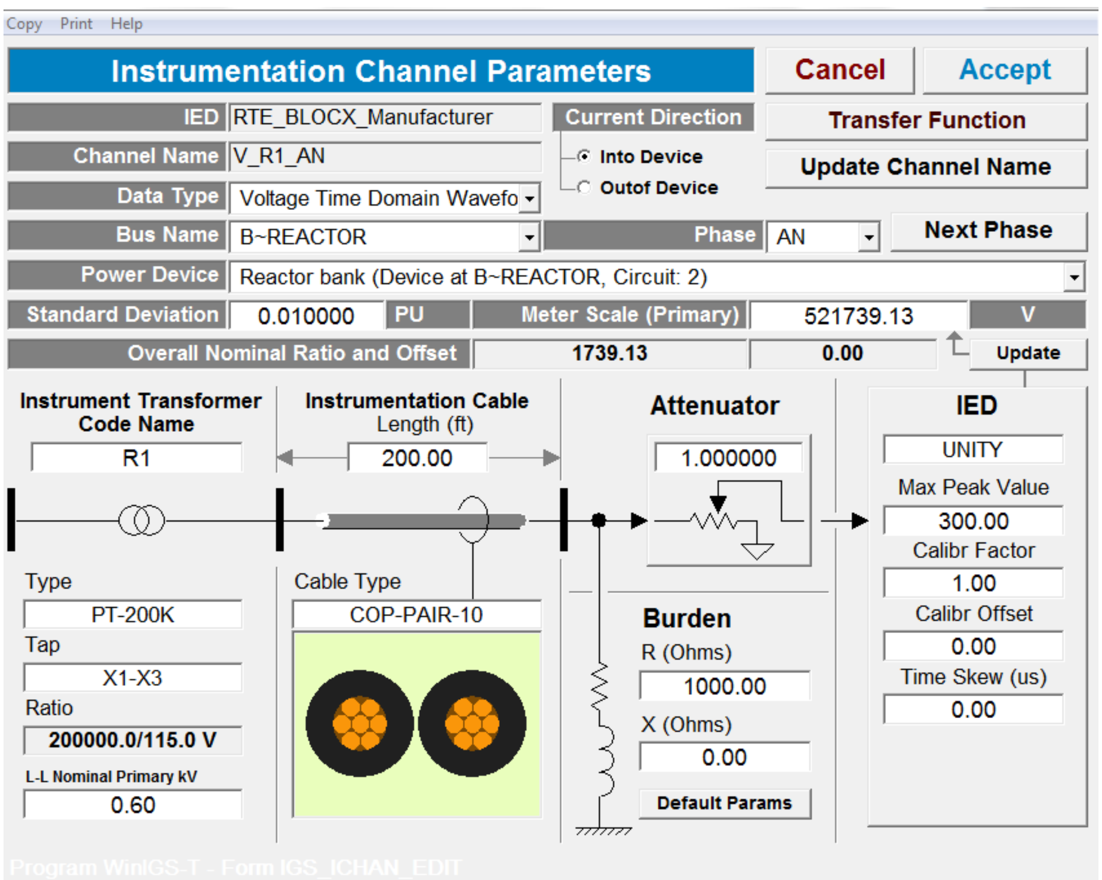


Figure 6-6: Example of a Voltage Instrumentation Channel Dialog

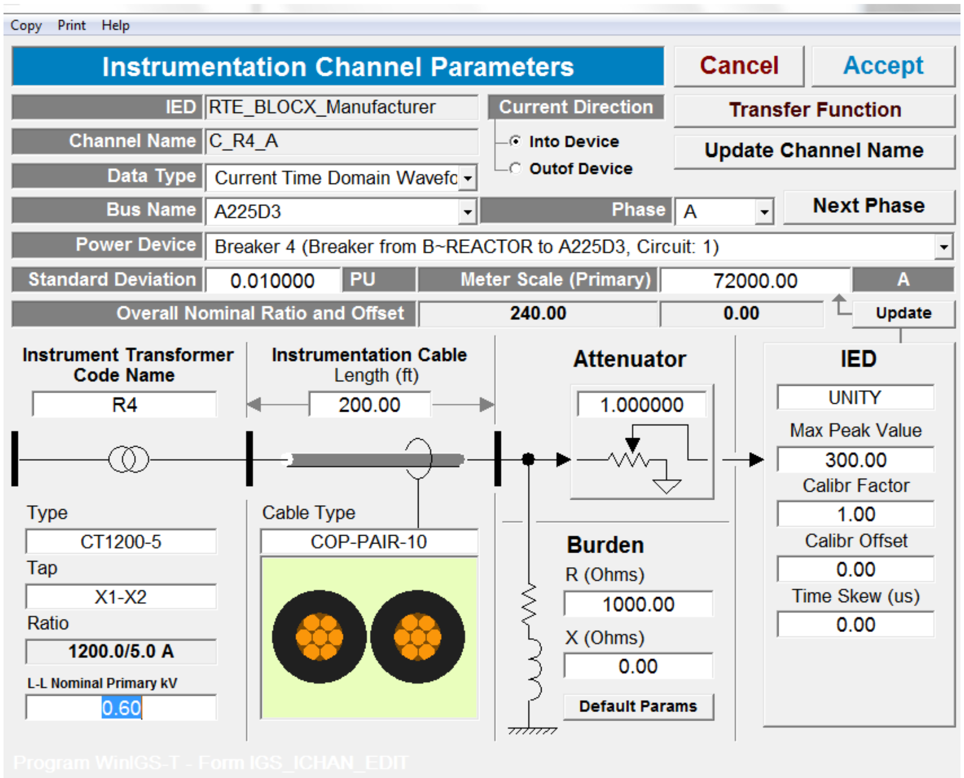


Figure 6-7: Example of a Current Instrumentation Channel Dialog

Table 6-1: Instrumentation Channel Parameters – User Entry Fields

Parameter	Description
Data Type	Specifies the type of the measured quantity. Valid options for merging units are Voltage Time Domain Waveform and Current Time Domain Waveform.
Bus Name	The bus name where the measurement is taken
Power Device	Identifies the power device into which the current is measured (not used for voltage measurements)
Phase	The phase of the measured quantity (A, B, C, N, etc.)
Current Direction	The direction of current flow which is considered positive. For example, checking into device indicates that the positive current flow is into the power device terminal (See also Power Device parameter above)
Standard Deviation	Quantifies the expected error of the instrumentation channel in per unit of the maximum value that the channel can measure (See also channel scale parameter).
Meter Scale	The maximum peak value that the channel can measure defined at the instrument transformer primary side. Note that this value can be directly entered by the user, or automatically computed from the instrument transformer and data acquisition device characteristics. In order to automatically compute the ,click on the **Update** button located below the Meter Scale field.
Instrument Transformer Code Name	An identifier of the instrument transformer associated with this channel. Note that WinIGS uses this identifier to generate the channel name. For example the phase A voltage channel is automatically named V_REACTOR_AN, if the instrument transformer name is set to REACTOR.
Instrument Transformer **Type** and **Tap**	Selects instrument transformer parameters from a data library. The library includes parameters needed to create instrument channel models such as turns ratio, frequency response, etc. To select an instrument transformer model, click on the **type** or **tap** field to open the instrument transformer data library dialog (See also Figure 6-8)
L-L Nominal Primary Voltage	The line to line voltage at the instrument transformer primary side.
Instrumentation Cable Length	The length of the instrumentation cable connecting the instrument transformer secondary with the data acquisition device.

Cable Type	The instrumentation cable type and size. Clicking on this field opens the cable library selection window. Note that if the desired cable is not found in the library, a cable library editor is available allowing adding and modifying cable parameters.(See WinIGS-T user's manual for details).
Attenuator	Attenuation value of any additional voltage or current reduction divider. Set to 1.0 if none.
Burden	The equivalent resistance of the burdens attached to the instrument transformer secondary.
IED	Selects data acquisition device from an IED library. This setting retrieved the data acquisition device frequency response for the purpose of applying error correction. Set to UNITY if this information is not available.
Maximum Peak Value	Set to the maximum instantaneous (peak) voltage or current value that will not saturate the data acquisition device input. This value can be found in data acquisition device specifications. For example, the GE Merging unit voltage and current max peak values can be derived from the voltage and current range specifications shown in Figure 6-9. Note that the range is specified in RMS so these Figures must be multiplied by $\sqrt{2}$ to obtain the peak values (i.e.: 325.3 Volts and 282.8 Amperes)
Calibration Factor	The channel output is multiplied by this value. Set to 1.0 if none required.
Calibration Offset	This value is added to the channel output. Set to 0.0 if none required.
Time Skew	Time delay in seconds of this channel with respect to time reference. Set to zero for no delay.

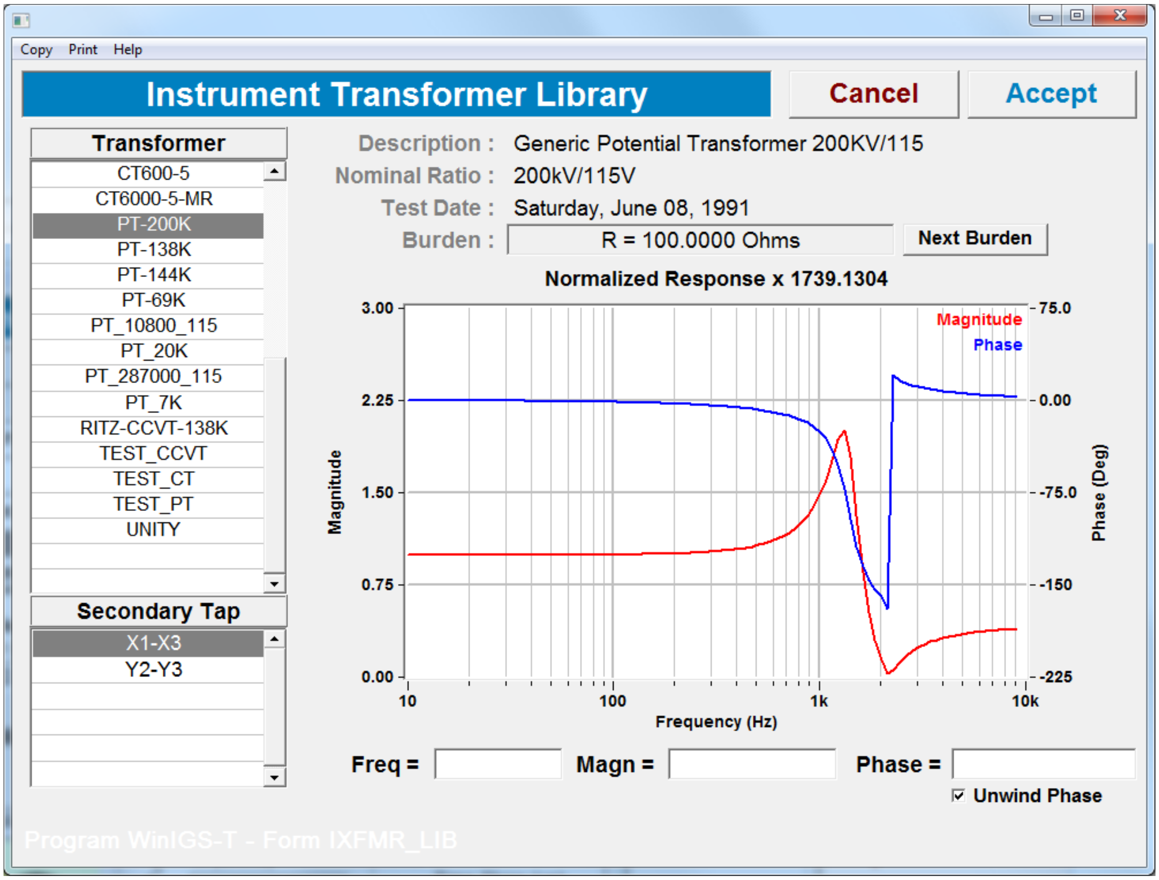


Figure 6-8: Instrument Transformer Library Dialog

CURRENT INPUTS

Nominal Current (In)	5 A	1 A
Nominal frequency	50/60Hz	50/60Hz
Current range (rms)	0.25 ... 200A	0.05 ... 40A
Accuracy	± 0.1 % F.S.	± 0.1 % F.S.
Impedance	3 m Ω	15 m Ω
Burden In	50 m VA	< 0.02 VA
Continuous overload	20A (4 x In)	4A (4 x In)
AC current thermal withstand 1 s (Ith rms)	320A (64 x In)	100A (100x In)
AC current thermal withstand 10 s (Ith rms)	100A (20 x In)	30A (30 x In)
Insulation	> 3.5 kV	> 3.5 kV
Bandwidth	3 k Hz	3 k Hz

VOLTAGE INPUTS

Nominal Voltage (Vn)	115 V
Nominal frequency	50/60Hz
Voltage range	0.02 ... 230 V
Accuracy	± 0.1 % F.S.
Impedance	> 210 k Ω
Burden Vn	< 0.1VA
Continuous overload	240 V
Maximum overload (1 s)	460 V (4 x Vn)
Bandwidth	3 k Hz

Figure 6-9: Example Input Specifications of A GE MU320 Merging Unit

Note that the order of the instrumentation channels can be modified using the **MoveUp** and **MoveDown** buttons of the instrumentation channel list dialog (Shown in Figure 6-5). Once the instrumentation channel parameter entry is completed, click on the Accept button of the instrumentation channel list dialog, to save the channel parameters. Note that the instrumentation channel parameters are saved in an ASCII file named:

CASENAME_Fnnnnn.ich

where CASENAME is the WinIGS-T network model file name root, and nnnnn is a 5-digit integer. These files are stored in the same directory as the WinIGS-T network model file.

The next step is to define the measurements to be used for the EBP relay, in terms of the defined instrumentation channels. This is accomplished by clicking on the **Measurement** button of the merging unit ASDU dialog (Shown in Figure 6-4). This action opens the Measurement List Dialog illustrated in Figure 6-10.

For most cases (including the protection zone 4 described in this document) the measurement parameters can be created automatically using the **Auto Create** button if the Measurement List Dialog.

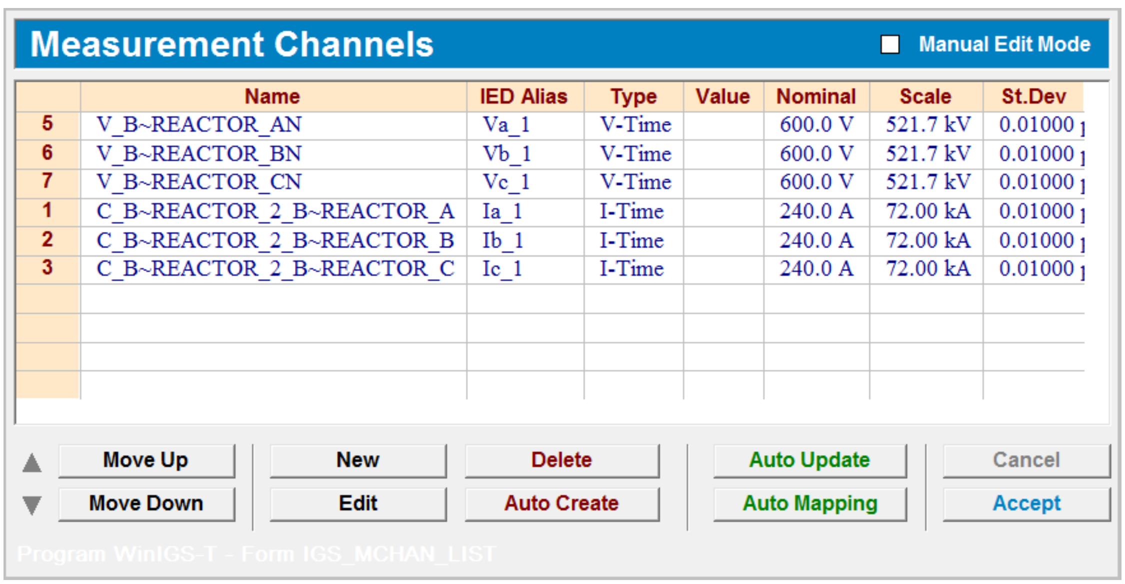


Figure 6-10: Measurement List Dialog

Measurement parameters can be manually created and edited using the **New** and **Edit** buttons of the Measurement List dialog (Figure 6-10), which open the measurement parameter dialog illustrated in Figures 6-11 and 6-12. The fields in this dialog are briefly described in Table 6-2.

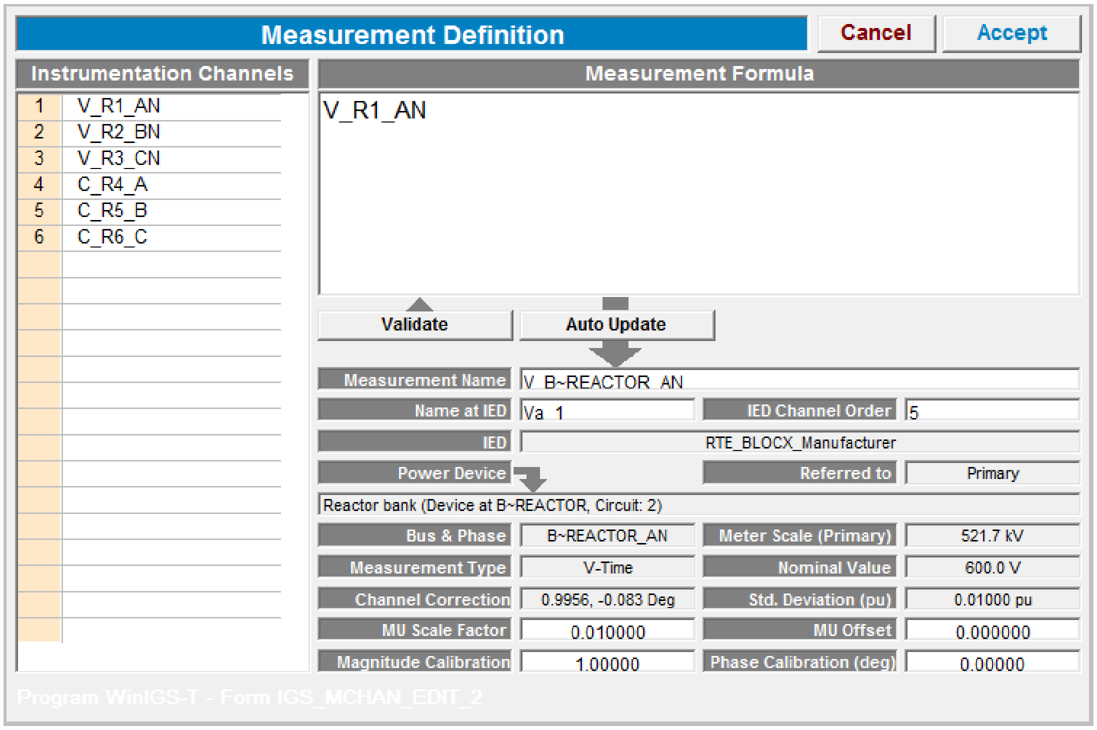


Figure 6-11: Voltage Measurement Parameters Dialog

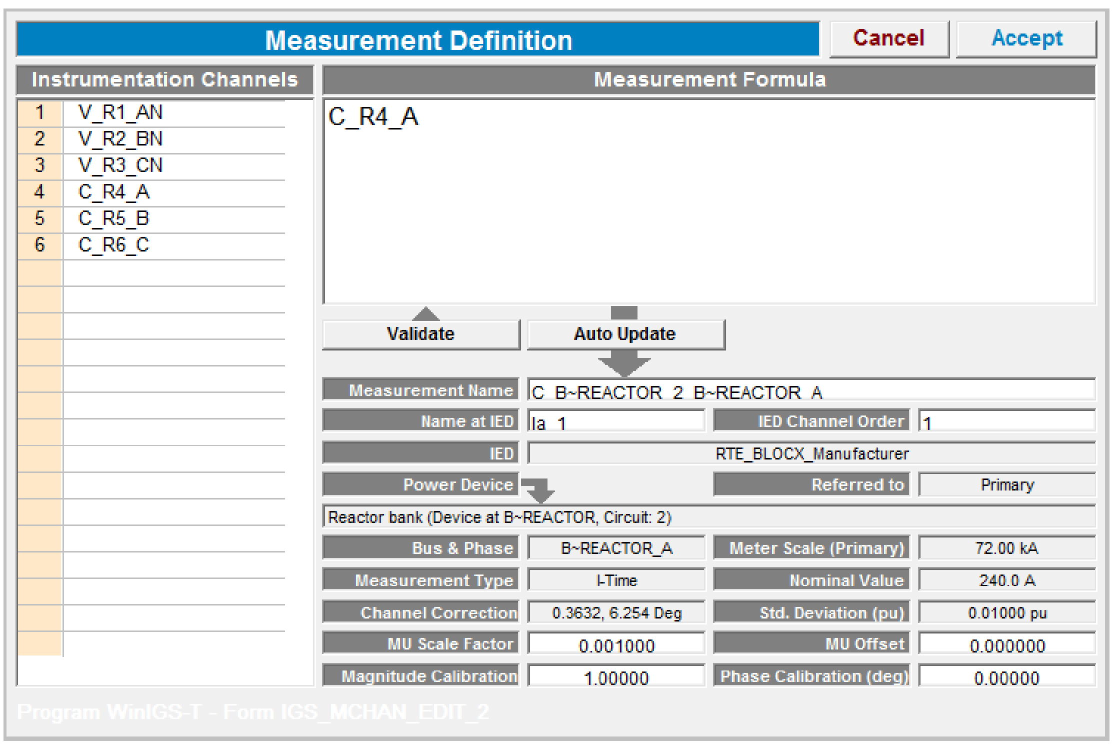


Figure 6-12: Current Measurement Parameters Dialog

Table 6-2: Measurement Parameters – User Entry Fields

Parameter	Description
Measurement Formula	Mathematical expression giving measurement value in terms of instrumentation channel values. Note that the measurement formula for automatically created measurements form instrument channels is simply the instrument channel name. However, a measurement can be manually defined as any expression involving all available instrument channels.
Measurement Name	***Voltage measurements*** names are automatically formed based on the bus name, phase and measurement type. For example, a phase A voltage measurement on Bus REACTOR is automatically named V_REACTOR_A. Similarly, ***current measurements*** are automatically formed by identifying a power device and a specific terminal into which the measured current is flowing. For example, the phase A current into the shunt reactor connected to bus reactor is named C_REACTOR_R1_REACTOR_A, where the part REACTOR_R1 identifies the power device as circuit the R1 connected to the bus REACTOR, and the last part _REACTOR_A identifies the terminal into which the measured current is flowing. Note that the name part R1 is the user specified Circuit Name of the reactor connected at bus REACTOR.
Name at IED	The measurement name as defined by the merging unit or other IED used. The default channel names vary with IED manufacturers and IED types. For example the GE MU320 merging units default channel names are Ia_1, Ib_1, Ic_1, ... for the current channels and Va_1, Vb_1, Vc_1, ... for voltage channels.
IED Channel Order	An order number (starting with 1) indicating the ordering of the channels in the Sample Value packets. For example GE MU320 merging units SV packets have four current channels followed by four voltage channels. Thus the current channel order numbers are 1, 2, 3, 4 for phase A, B, C N, and the voltage channel order numbers are 5, 6, 7, and 8 for phases A, B, C, and N.
Merging Unit Scale Factor and Merging Unit Offset	These values define the conversion from the 32 bit integer Sample Values to actual values in Volts and Amperes. Specifically: $V_k = a X_k + b$ where Vk is a voltage sample in volts, a is the Scale Factor, Xk is the sample value voltage sample (32 bit integer), and b is the Merging Unit Offset. The default merging unit scale factor for voltage channels is 0.01, while for current channels is 0.001. Default offsets are zero.

Magnitude Calibration and Phase Calibration	Measurement magnitude and a phase angle correction value. Default values are 1.0 and 0.0 respectively.

6.1.3 Exporting Measurement and Protection Zone Models

In order to generate the estimation based protective relay files (to be used in the XFM program EBP feature), perform the following steps:

6. Select the power devices belonging to the protection zone of interest. In this example select the shunt reactor bank connected to bus REACTOR and also the breaker connected in series with the shunt reactor bank. (NOTE: to select multiple objects, hold down the CTRL key, and ***left-click*** on the elements to be selected).

7. Select the merging units monitoring the voltages and currents to be used in the EBP relay. In this example select the merging unit named “Reactor Merging Unit” in Figure 6-2. (NOTE: to select multiple objects, hold down the CTRL key, and ***left-click*** on the elements to be selected).

8. Execute the SCAQCF Export command of the Tools menu, or click on the toolbar icon:

(See also Figure 6-13)

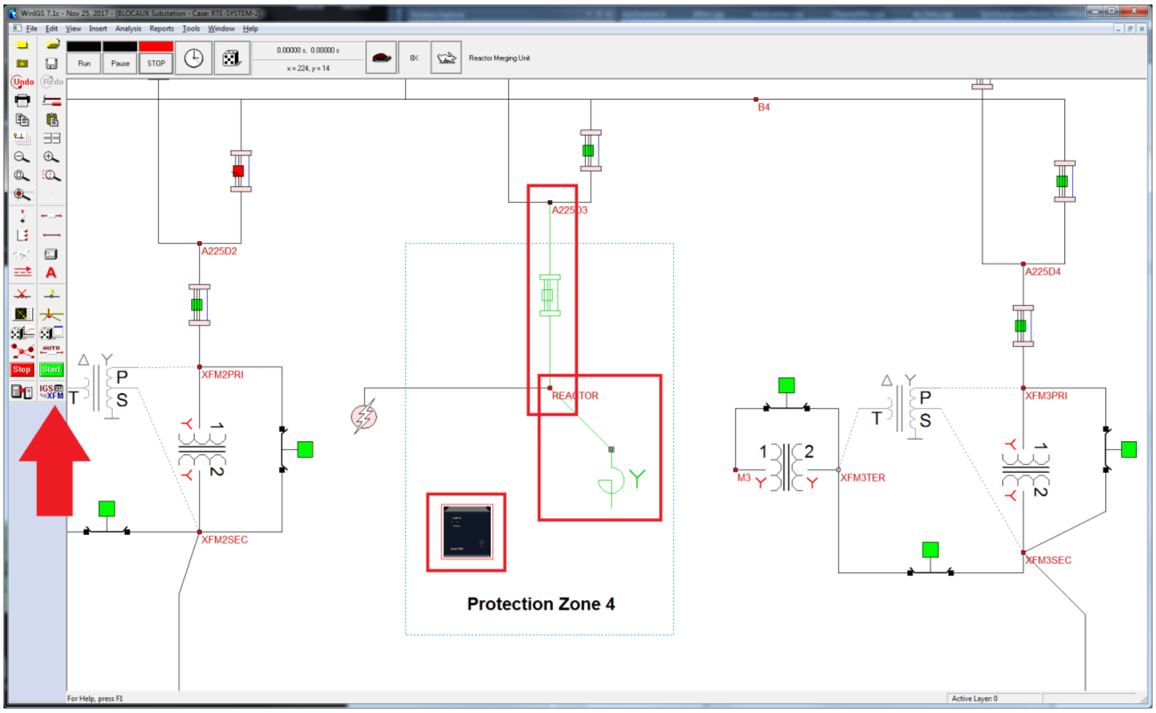


Figure 6-13: Selecting Zone Power Devices and Merging Units

This command/toolbar button opens the dialog window illustrated in Figure 6-14

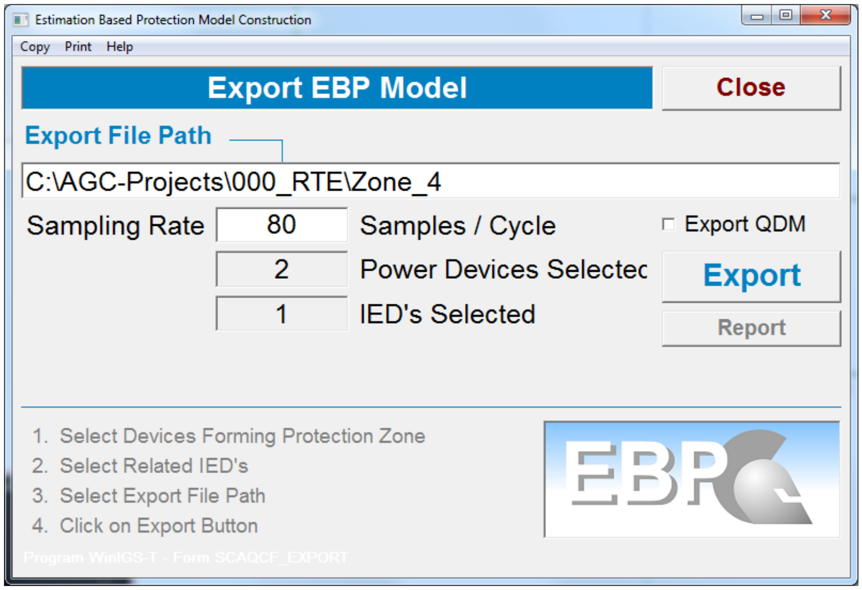


Figure 6-14: EBP Export Dialog

9. Click on the entry field under the Export File Path label in order to select the file path of the files to be generated.
10. Click on the **Export** button to generate the files. Optionally click on the Report button to verify that the process was completed successfully (See Figure 6-15)

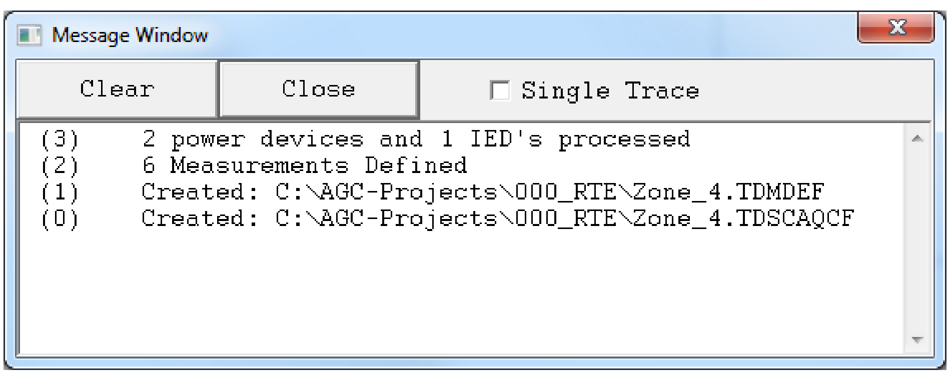


Figure 6-15: Message Window Indicating EBP File Creation Progress & File Paths

The generated files are next used to automatically setup the EBP relay in the XFM program.

6.2 Creating Events and Storing in COMTRADE

For the above stated purpose, we use WinIGS-T to define events, simulate the events and store the results in COMTRADE format. Two such events are described below.

6.2.1 Event A: UseCase_01.A

Event A is defined with a Phase A to neutral fault on the REACTOR bus within the protection zone. Figure 6-16 shows the fault model and fault model parameters dialog. This is a fault occurring inside Zone 4 which should be cleared by opening the reactor breaker. The fault is initiated at 0.5 seconds from the start of the simulation.

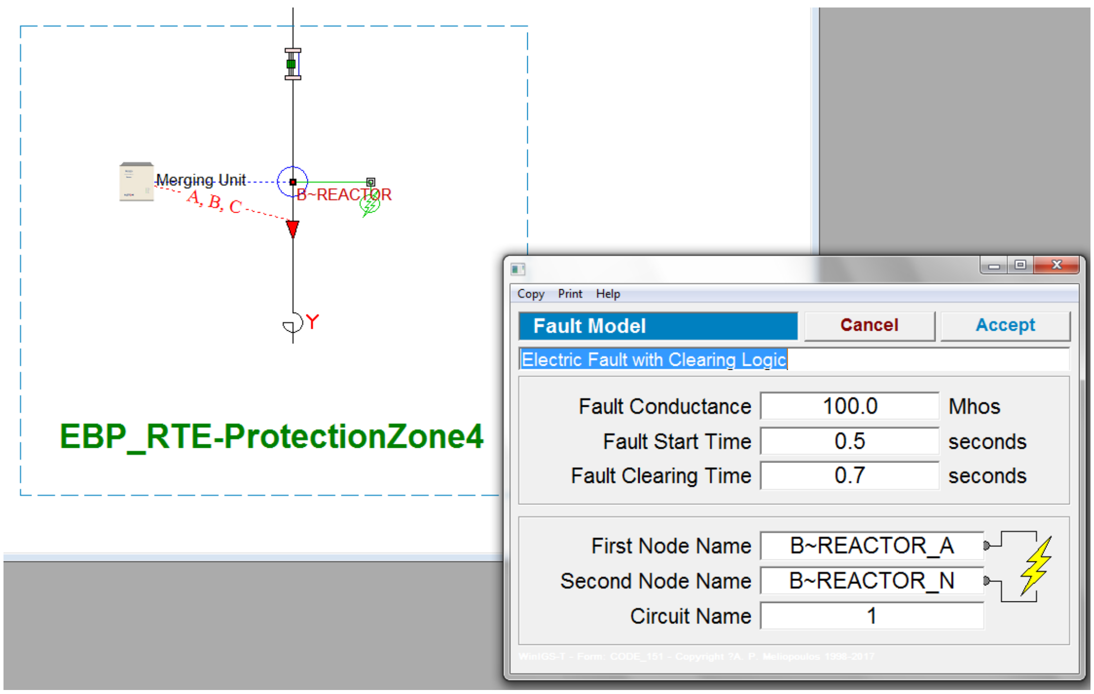


Figure 6-16: Network Model with Fault between Phase A and Neutral of REACTOR Bus

The simulation is executed for a period of one second. The measurements generated during the simulation are stored in a COMTRADE file. Figure 6-17 shows the time domain simulation parameters dialog where the simulation time step, duration, as well as the COMTRADE output is specified. Note that the time step is selected to match the standard merging unit sampling rate at 80 samples per cycle. For 50 Hz system this is achieved by selecting the time step at:

$$\Delta t = 1.000.000 / (50 \times 80) = 250 \text{ microseconds.}$$

The voltages and currents captured by the reactor bank merging unit are plotted in Figure 6-18.

The WinIGS-T case files is named RTE-SYSTEM-B-EVENT-A.nmt and is provided with this report. The generated COMTRADE configuration and data files are named RTE-SYSTEM-B-EVENT-A_BLOCX.cfg and RTE-SYSTEM-B-EVENT-A_BLOCX.dat respectively.

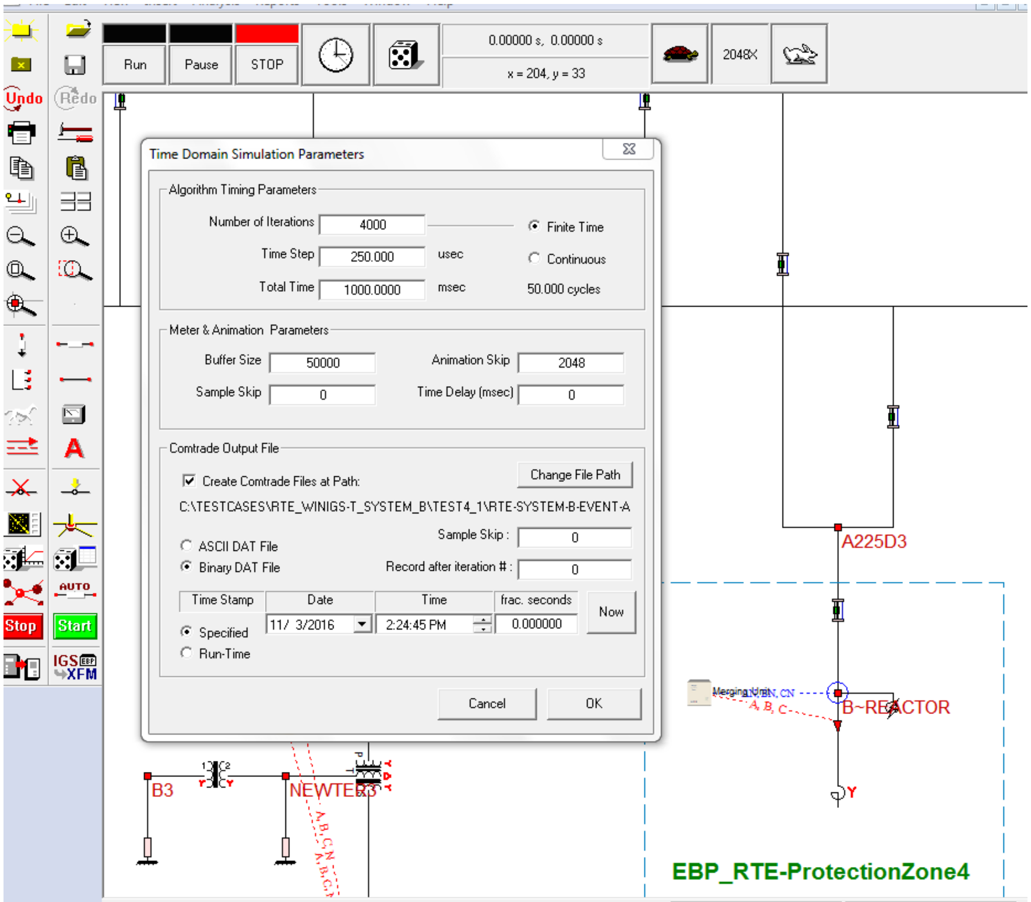


Figure 6-17: Time Domain Simulation Parameters Dialog.

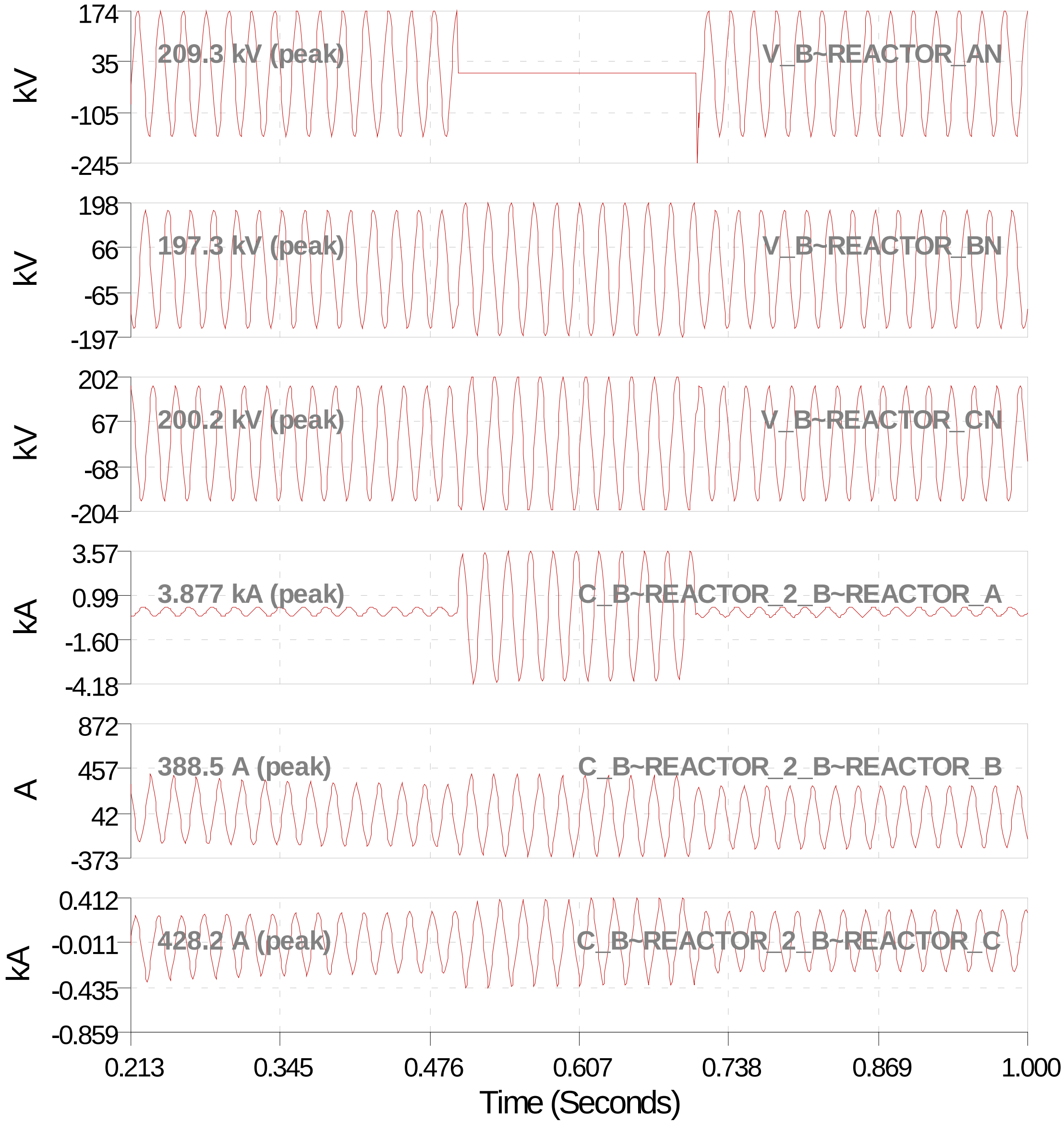


Figure 6-18: Time Domain Simulation Output Plot for Event A

6.2.2 Event B: UseCase_01.B

Event B is defined a Phase A to neutral fault on the bus **A225D2**. Figure 6-19 shows the fault model and fault model parameters dialog. This is a fault occurring outside Zone 4 and therefore the reactor breaker should not operate. The fault is initiated at 0.5 seconds from the start of the simulation and lasts 0.2 seconds.

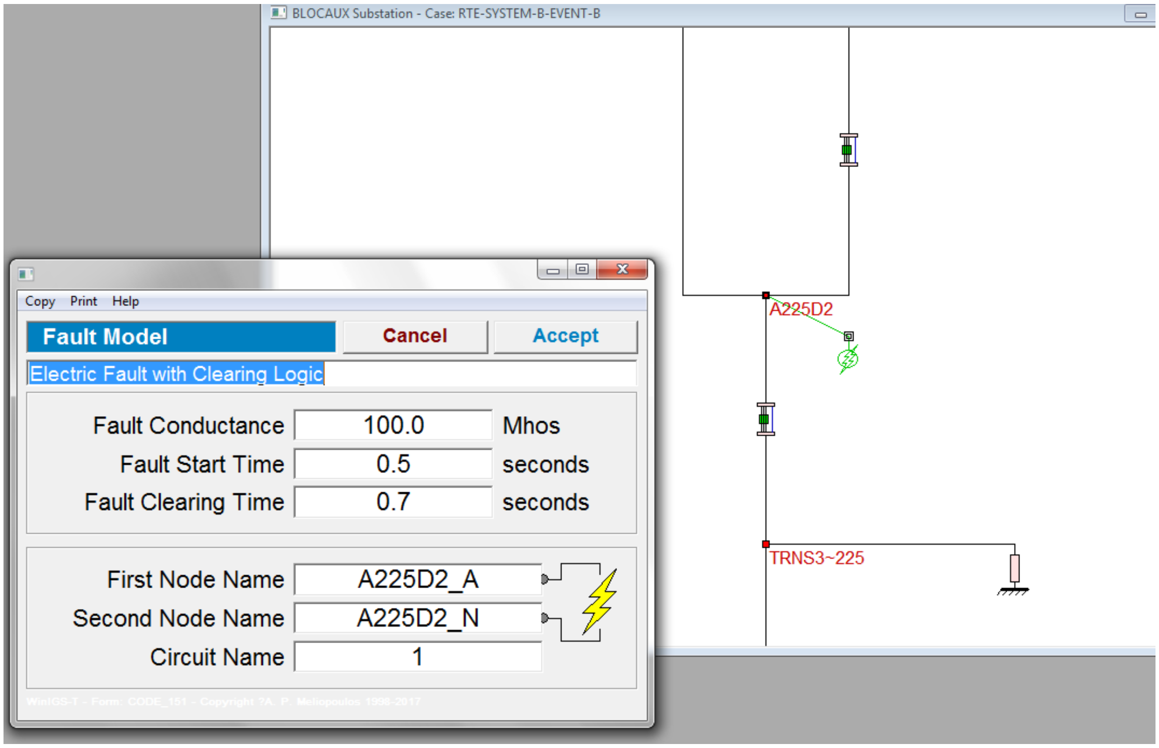


Figure 6-19: Network Model with Fault between Phase A and Neutral of Bus A225D2.

The simulation is executed for a period of one second. The measurements generated during the simulation are stored in a COMTRADE file. The time step is selected to match the standard merging unit sampling rate at 80 samples per cycle, which for a 50 Hz system is 250 microseconds (i.e. same as for Event A).

The voltages and currents captured by the reactor bank merging unit are plotted in Figure 6-20

The WinIGS-T case files is named RTE-SYSTEM-B-EVENT-B.nmt and is provided with this report. The generated COMTRADE configuration and data files are named RTE-SYSTEM-B-EVENT-B_BLOCX.cfg and RTE-SYSTEM-B-EVENT-B_BLOCX.dat respectively.

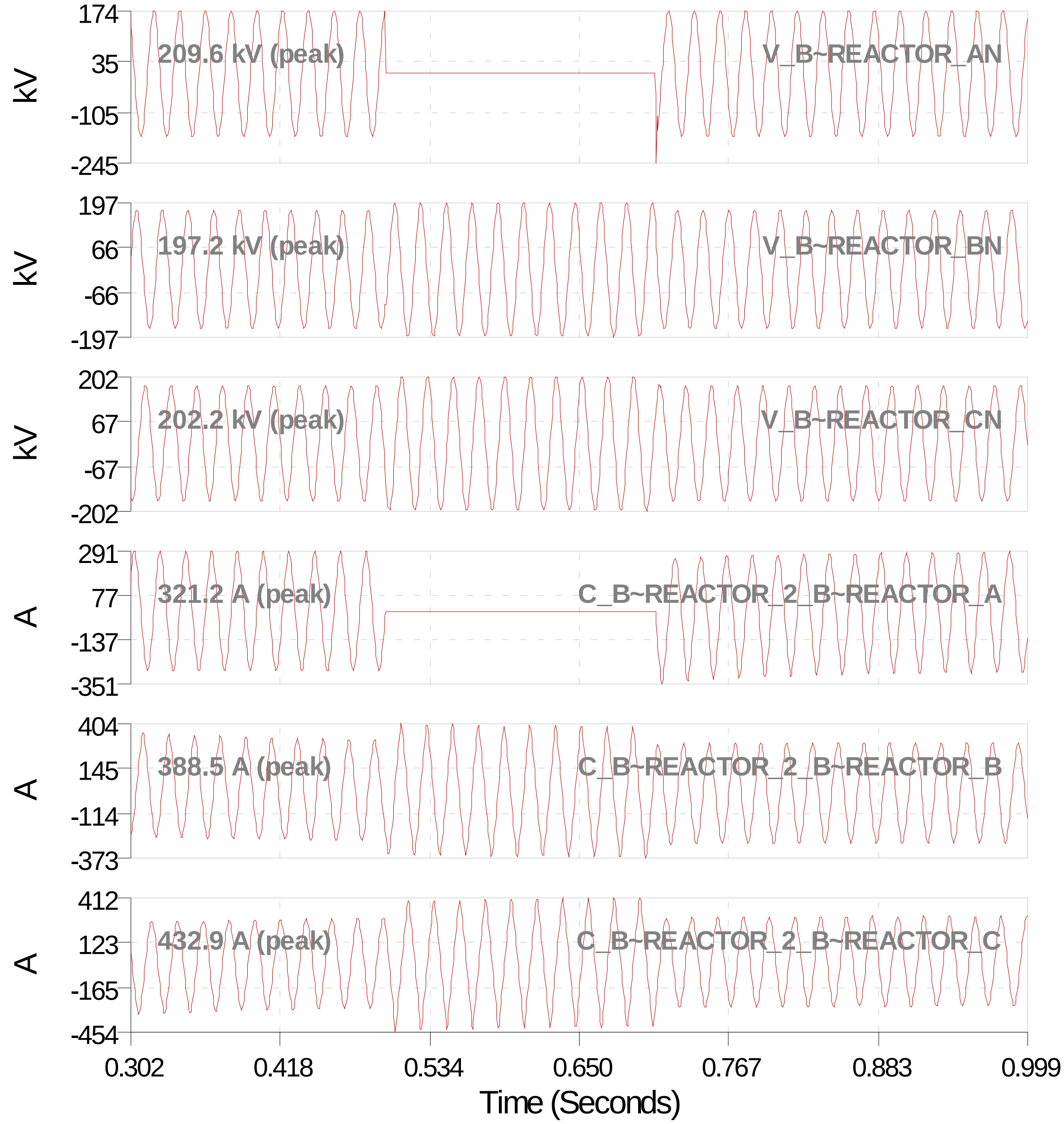


Figure 6-20: Time Domain Simulation Output Plot for Event B

6.3 EBP Results

This section presents the results obtained with the EBP relay for the use case and events described in Section 6.2. The EBP relay has been implemented within the WinXFM Program. In order to setup the EBP relay to run the use cases, execute the WinXFM program, open one of the provided WinXFM files, and click on the EBP button as indicated in Figure 6-21.

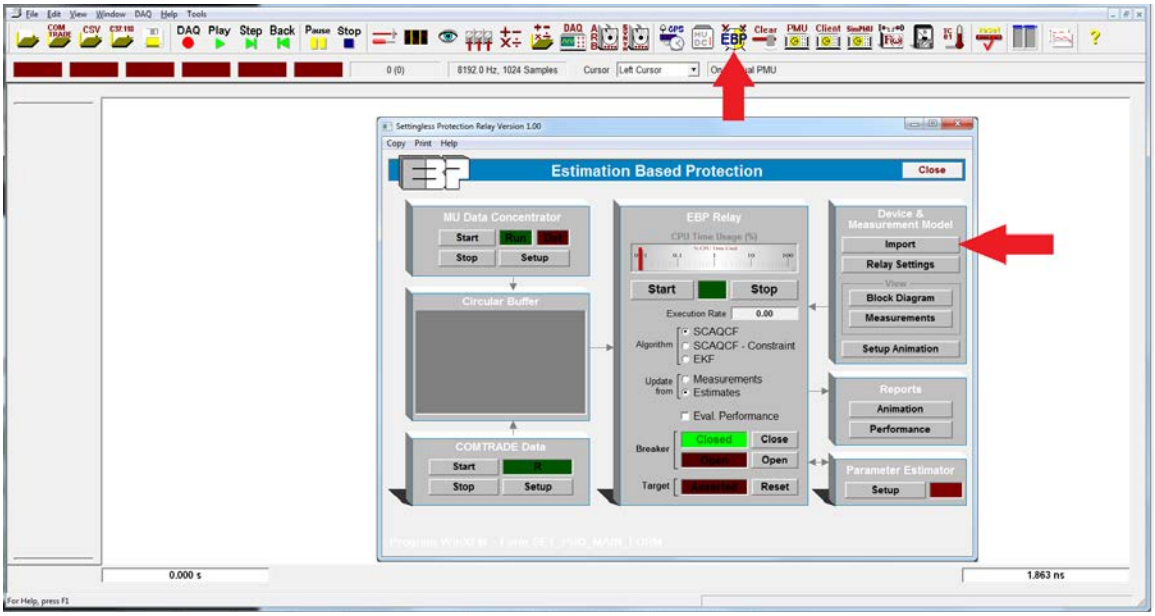


Figure 6-21: Opening the EBP Main Setup Form in the WinXFM Program

6.3.1 Event a: UseCase_01.A

As described in Section 6.2, event A is defined as a Phase A to neutral fault on the REACTOR bus. To run the EBP relay using the Event A data, execute the WinXFM program and open the WinXFM file:

RTE-SYSTEM-B-EVENT-A

Note: this file is provided with this report under the file name RTE-SYSTEM-B-EVENT-A.xfm

Click on the Import button of the main EBP dialog window to open the "*Device and Measurement File*" dialog shown in Figure 6-22. Verify that the Zone_4 Device and Measurement files have been selected and that the two checkboxes titled Time Domain and Algebraic Companion Form are checked. Click on the **Import** button, and verify that the selected protection zone devices are listed and the active column is checked as illustrated in Figure 6-22. Click on the **Accept** button to close the *Device and Measurement File* dialog. This procedure imports the measurement definition and device model data generated using the WinIGS-T program and stored in the data files:

- Zone_4.TDMDEF (Measurement Definition File)
- Zone_4.TDSCAQCF (Device Model File)

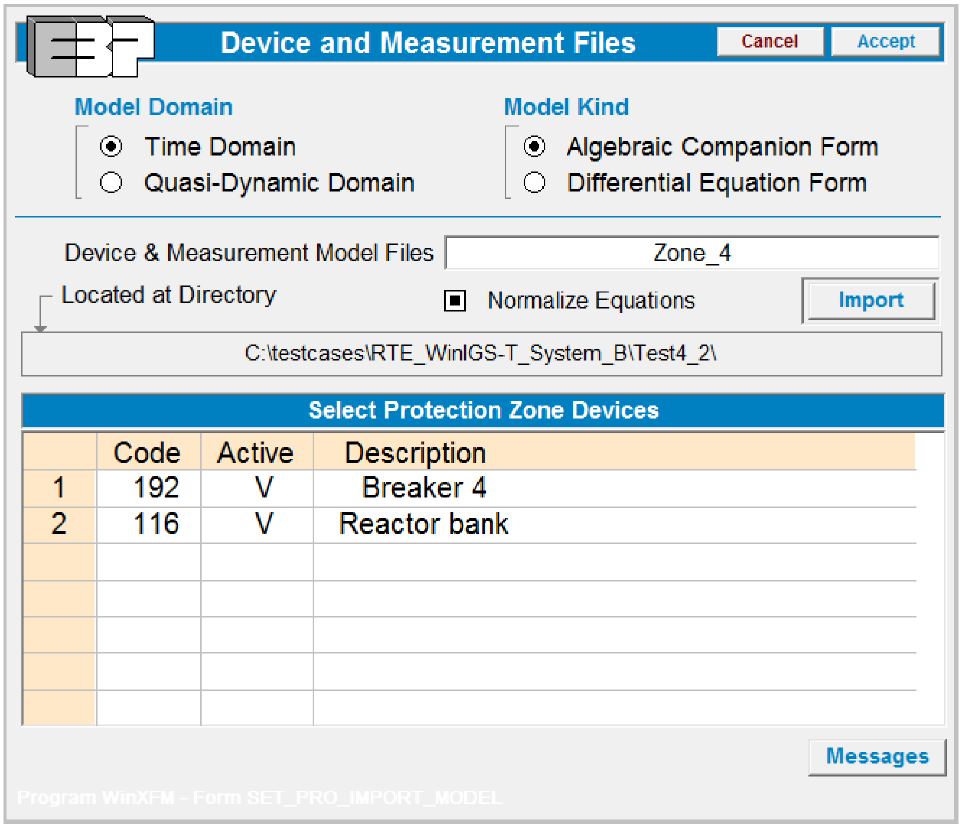


Figure 6-22: Importing Zone 4 Device and Measurement Definition Files

Next click on the Setup button of the COMTRADE Data block of the main EBP dialog (See Figure 6-23) to open the COMTRADE Data Playback dialog (shown in Figure 6-24). Verify that the **COMTRADE File Name** field indicates that the Event A waveform data has been selected: (file name: RTE-SYSTEM-B-EVENT-A_BLOCX). Also verify the following:

- Playback rate is set at **4000** samples per second for 50 Hz systems.
- Speed Factor radio button is selected and the speed factor is set to 20.0.

The speed factor option allows the relay response to be observed in slow motion. Otherwise, if you select the real time option, the playback will occur in real time and the whole process will be completed in one second i.e. the duration of the waveform data stored in the COMTRADE file.

Click on the **Close** button to close the COMTRADE Data Playback dialog.

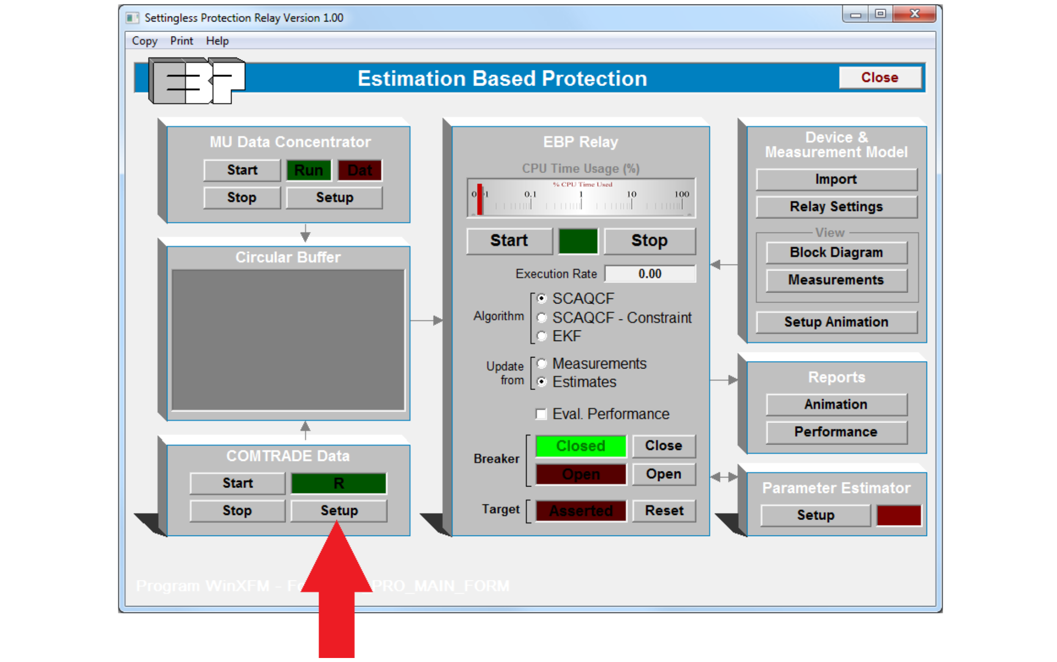


Figure 6-23: Opening the COMTRADE Setup Dialog

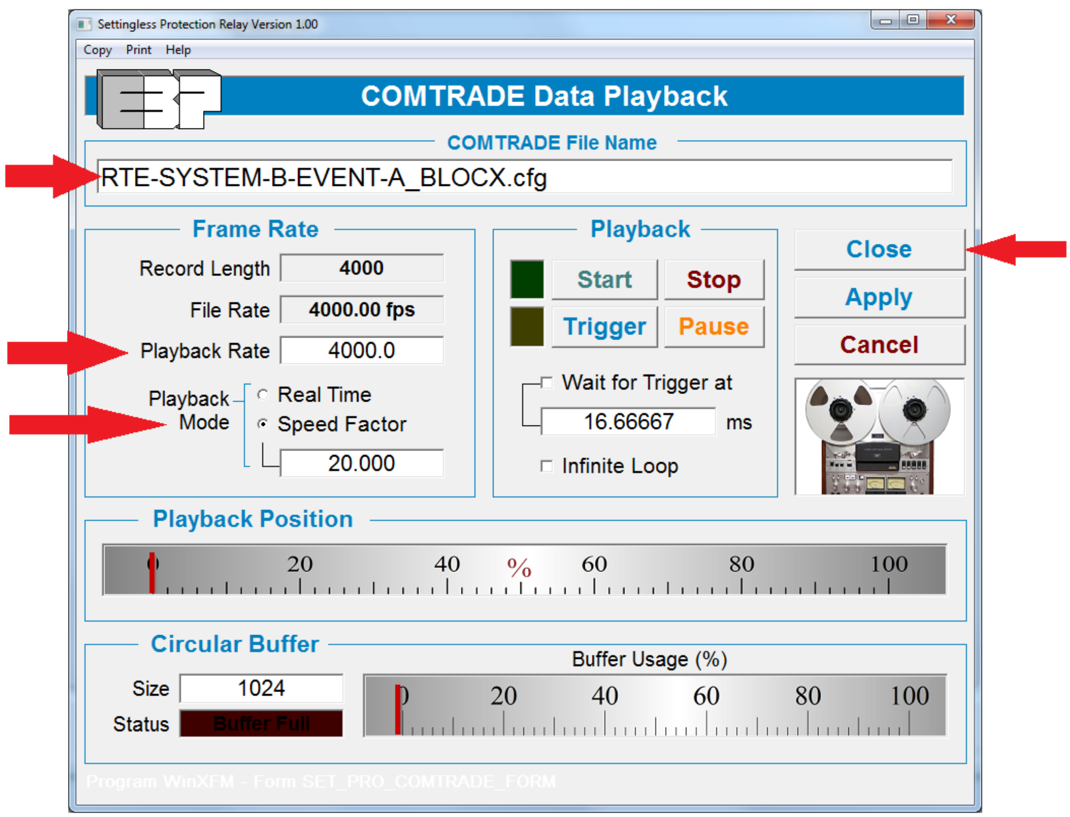
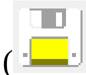


Figure 6-24: Selecting the COMTRADE Data files for Playback

At this point, the system is ready to execute the EBP relay using the Event A data. It is recommended to click on the **Save** () button of the main WinXFM user interface (Horizontal Tool-Bar) in order to save all entered setup parameters.

Click on the **Start** button of the EBP Relay block to start the EBP relay, then Click on the **Start** button of the COMTRADE Data block. (See Figure 6-25 for the location of these buttons).

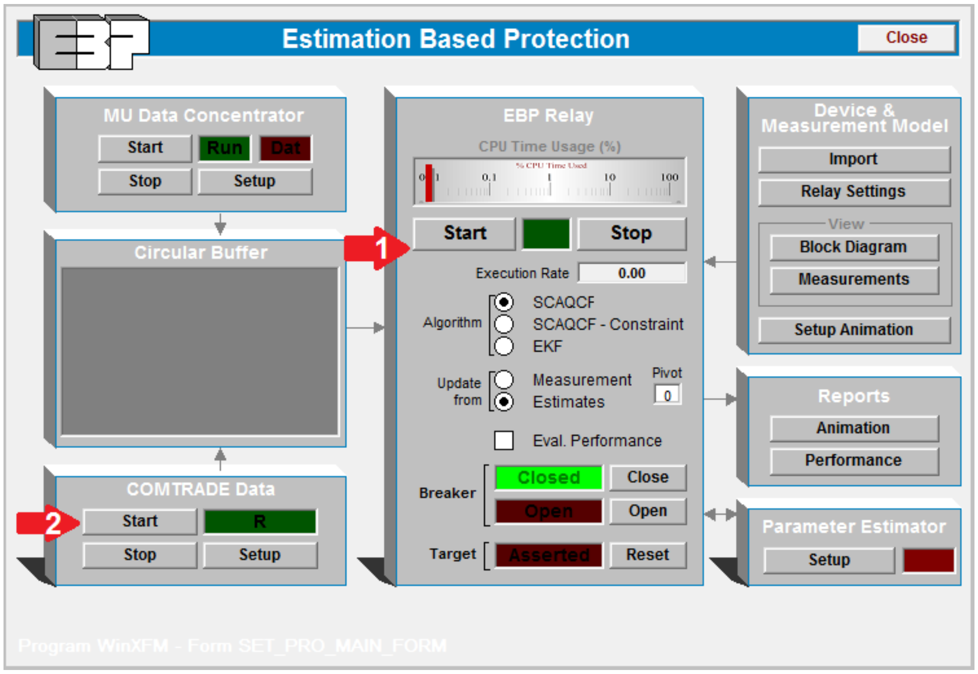


Figure 6-25: Starting the EBP Relay Using Playback Data (COMTRADE)

A number of plots can be viewed on the main WinXFM user interface such as measured and estimated values trip decision etc. An example of such plots is given in Figure 6-26. A list of the available channels for plotting is shown in Figure 6-27. Note that the confidence level is nearly 100% before the fault, and reaches to almost zero immediately upon the fault initiation.

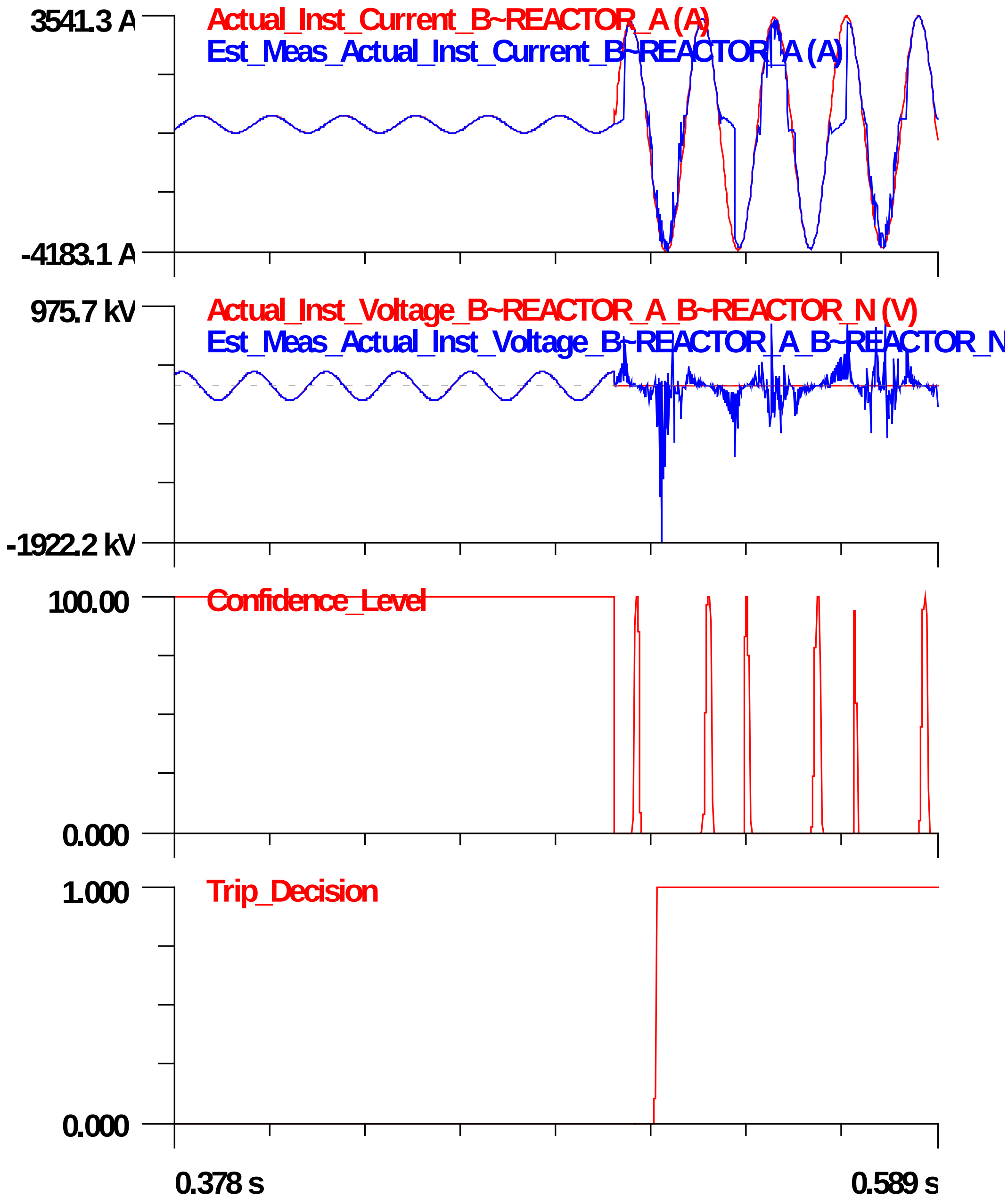


Figure 6-26: Plots of Measurement and Estimated Values, Confidence Level and Trip Decision during Event A

Available Channels

1 Actual_Inst_Voltage_B~REACTOR_A_B~REACTOR_N
2 Actual_Inst_Voltage_B~REACTOR_B_B~REACTOR_N
3 Actual_Inst_Voltage_B~REACTOR_C_B~REACTOR_N
4 Actual_Inst_Current_B~REACTOR_A
5 Actual_Inst_Current_B~REACTOR_B
6 Actual_Inst_Current_B~REACTOR_C
7 Est_Meas_Actual_Inst_Voltage_B~REACTOR_A_B~REACTOR_N
8 Est_Meas_Actual_Inst_Voltage_B~REACTOR_B_B~REACTOR_N
9 Est_Meas_Actual_Inst_Voltage_B~REACTOR_C_B~REACTOR_N
10 Est_Meas_Actual_Inst_Current_B~REACTOR_A
11 Est_Meas_Actual_Inst_Current_B~REACTOR_B
12 Est_Meas_Actual_Inst_Current_B~REACTOR_C
13 Est_State_B~REACTOR_A
14 Est_State_B~REACTOR_B
15 Est_State_B~REACTOR_C
16 Est_State_B~REACTOR_N
17 Est_State_Internal_State_5
18 Est_State_Internal_State_6
19 Est_State_Internal_State_7
20 Est_State_Internal_State_8
21 Est_State_Internal_State_9
22 Est_State_Internal_State_10
23 Est_State_Internal_State_11
24 Est_State_Internal_State_12
25 Est_State_Internal_State_13
26 Est_State_Internal_State_14
27 Est_State_Internal_State_15
28 Est_State_Internal_State_16
29 Est_State_Internal_State_17
30 Est_State_Internal_State_18
31 Est_State_Internal_State_19
32 Est_State_Internal_State_20
33 Est_State_Internal_State_21
34 Est_State_Internal_State_22
35 Est_State_Internal_State_23
36 Est_State_Internal_State_24
37 Est_State_Internal_State_25
38 Residual_Actual_Inst_Voltage_B~REACTOR_A_B~REACTOR_N
39 Residual_Actual_Inst_Voltage_B~REACTOR_B_B~REACTOR_N
40 Residual_Actual_Inst_Voltage_B~REACTOR_C_B~REACTOR_N
41 Residual_Actual_Inst_Current_B~REACTOR_A
42 Residual_Actual_Inst_Current_B~REACTOR_B
43 Residual_Actual_Inst_Current_B~REACTOR_C
44 Norm_Res_Actual_Inst_Voltage_B~REACTOR_A_B~REACTOR_N
45 Norm_Res_Actual_Inst_Voltage_B~REACTOR_B_B~REACTOR_N
46 Norm_Res_Actual_Inst_Voltage_B~REACTOR_C_B~REACTOR_N
47 Norm_Res_Actual_Inst_Current_B~REACTOR_A
48 Norm_Res_Actual_Inst_Current_B~REACTOR_B
49 Norm_Res_Actual_Inst_Current_B~REACTOR_C
50 Chi_Square
51 Confidence_Level
52 Execution_time
53 Trip_Decision
54 Avg_covariance
55 Min_covariance
56 Max_covariance

Figure 6-27: Available Data for Plotting on the Main WinXFM Window

6.3.2 Event b: UseCase_01.B

Event B is defined as a Phase A to neutral fault on bus **A225D2**. To run the EBP relay using the Event B simulated waveforms, execute the WinXFM program and open the WinXFM file:

RTE-SYSTEM-B-EVENT-B

Note: this file is provided with this report under the file name RTE-SYSTEM-B-EVENT-B.xfm

Click on the Import button of the main EBP dialog window to open the "*Device and Measurement File*" dialog shown in Figure 6-28. Verify that the Zone_4 Device and Measurement files have been selected and that the two checkboxes titled TDSCAQCF and TDMDEF are checked. Click on the **Import** button, and verify that the selected protection zone devices are listed and the active column is checked as illustrated in Figure 6-28. Click on the Accept button to close the *Device and Measurement File* dialog. This procedure imports the measurement definition and device model data generated using the WinIGS-T program and stored in the data files:

- Zone_4.TDMDEF (Measurement Definition File)
- Zone_4.TDSCAQCF (Device Model File)

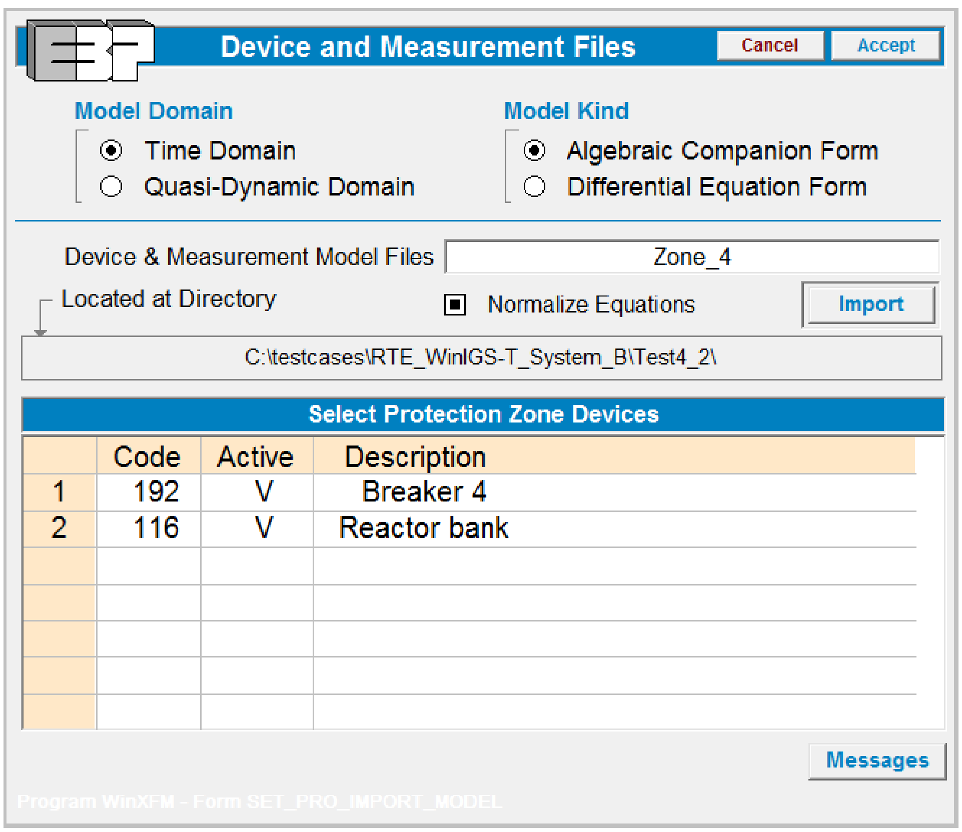


Figure 6-28: Importing Zone 4 Device and Measurement Definition Files

Next click on the Setup button of the COMTRADE Data block of the main EBP dialog (See Figure 6-29) to open the COMTRADE Data Playback dialog (shown in Figure 6-30).

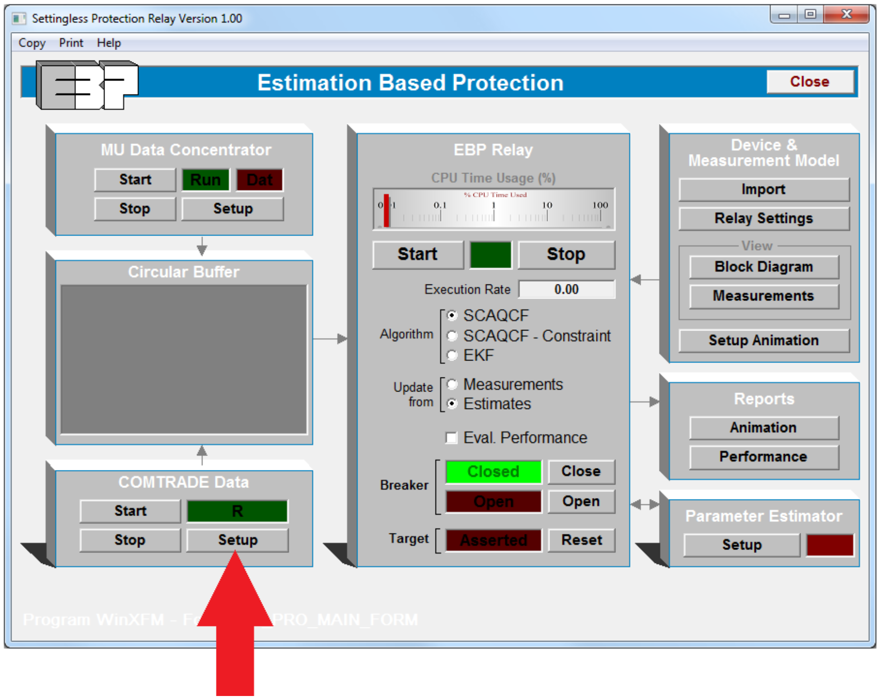


Figure 6-29: Opening the COMTRADE Setup Dialog

Verify that the **COMTRADE File Name** field indicates that the Event B waveform data has been selected: (file name: RTE-SYSTEM-B-EVENT-B_BLOCX). Also verify the following:

- Playback rate is set at **4000** samples per second for 50 Hz systems.
- Speed Factor radio button is selected and the speed factor is set to 20.0.

The speed factor option allows the relay response to be observed in slow motion. Otherwise, if you select the real time option, the playback will occur in real time and the whole process will be completed in one second i.e. the duration of the waveform data stored in the COMTRADE file.

Click on the **Close** button to close the COMTRADE Data Playback dialog.

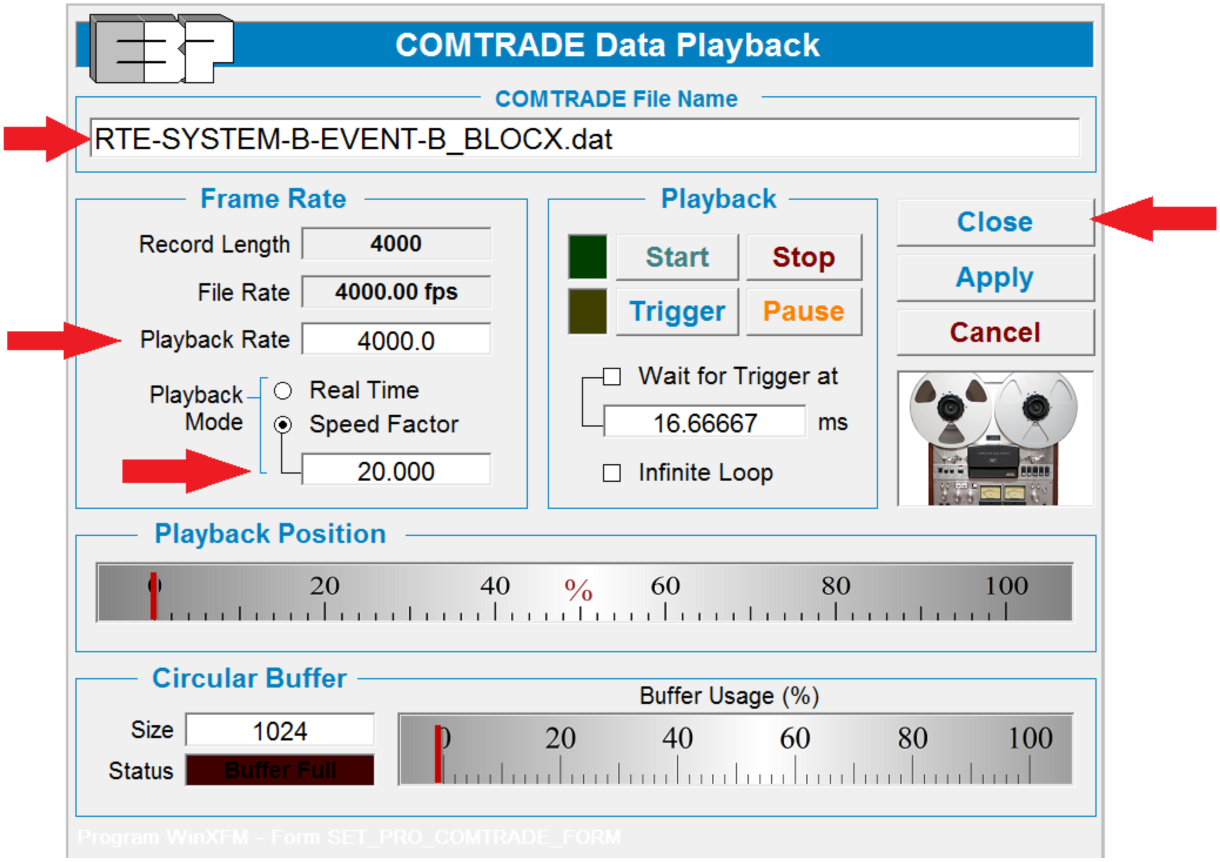


Figure 6-30: Selecting the COMTRADE Data Files for Playback

At this point, the system is ready to execute the EBP relay using the Event B data. It is recommended to click on the **Save** ( ) button of the main WinXFM user interface (Horizontal Tool-Bar) in order to save any modified setup parameters.

Click on the **Start** button of the EBP Relay block to start the EBP relay, then Click on the **Start** button of the COMTRADE Data block. (See Figure 6-31 for the location of these buttons).

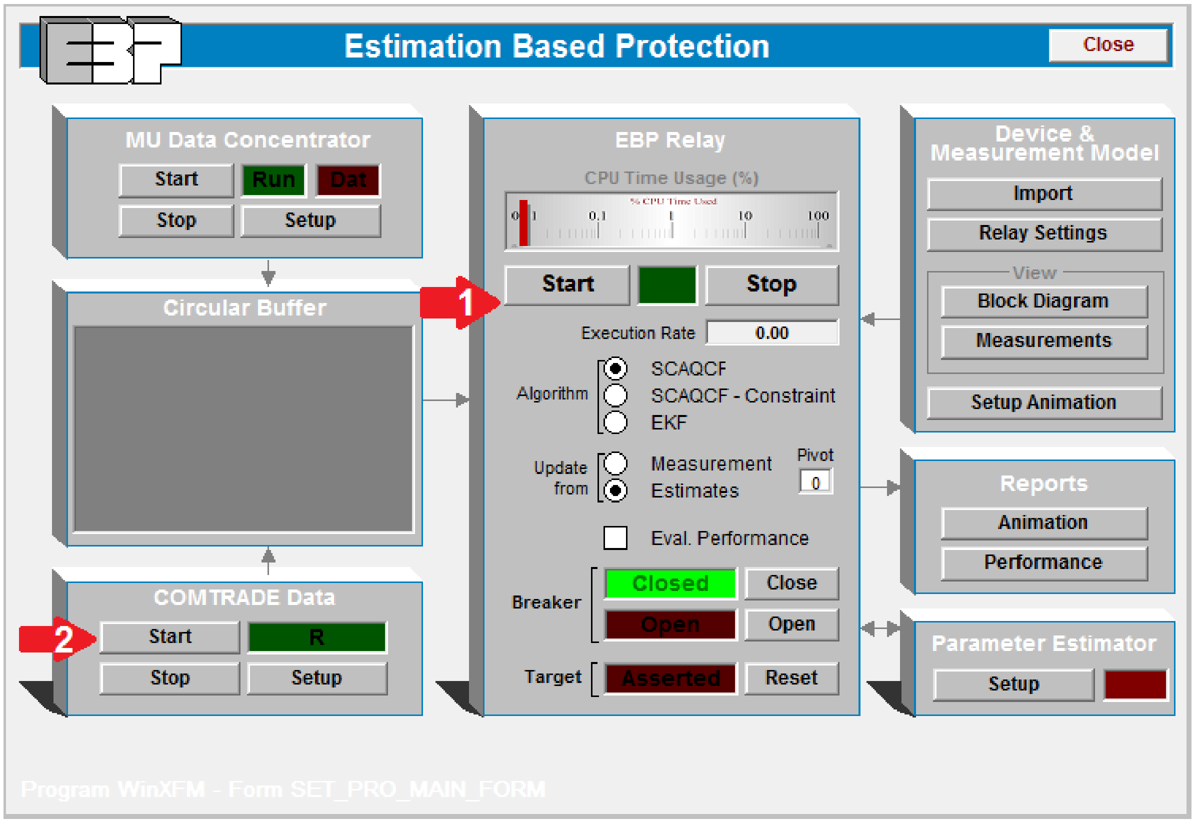


Figure 6-31: Starting the EBP Relay Using Playback Data (COMTRADE)

A number of plots can be viewed on the main WinXFM user interface such as measured and estimated values trip decision etc. An example of such plots is given in Figure 6-32. Note that the confidence level is nearly 100% before the fault, as well as during the fault. Note that the breaker remains closed (as expected) since the fault is outside the protection zone.

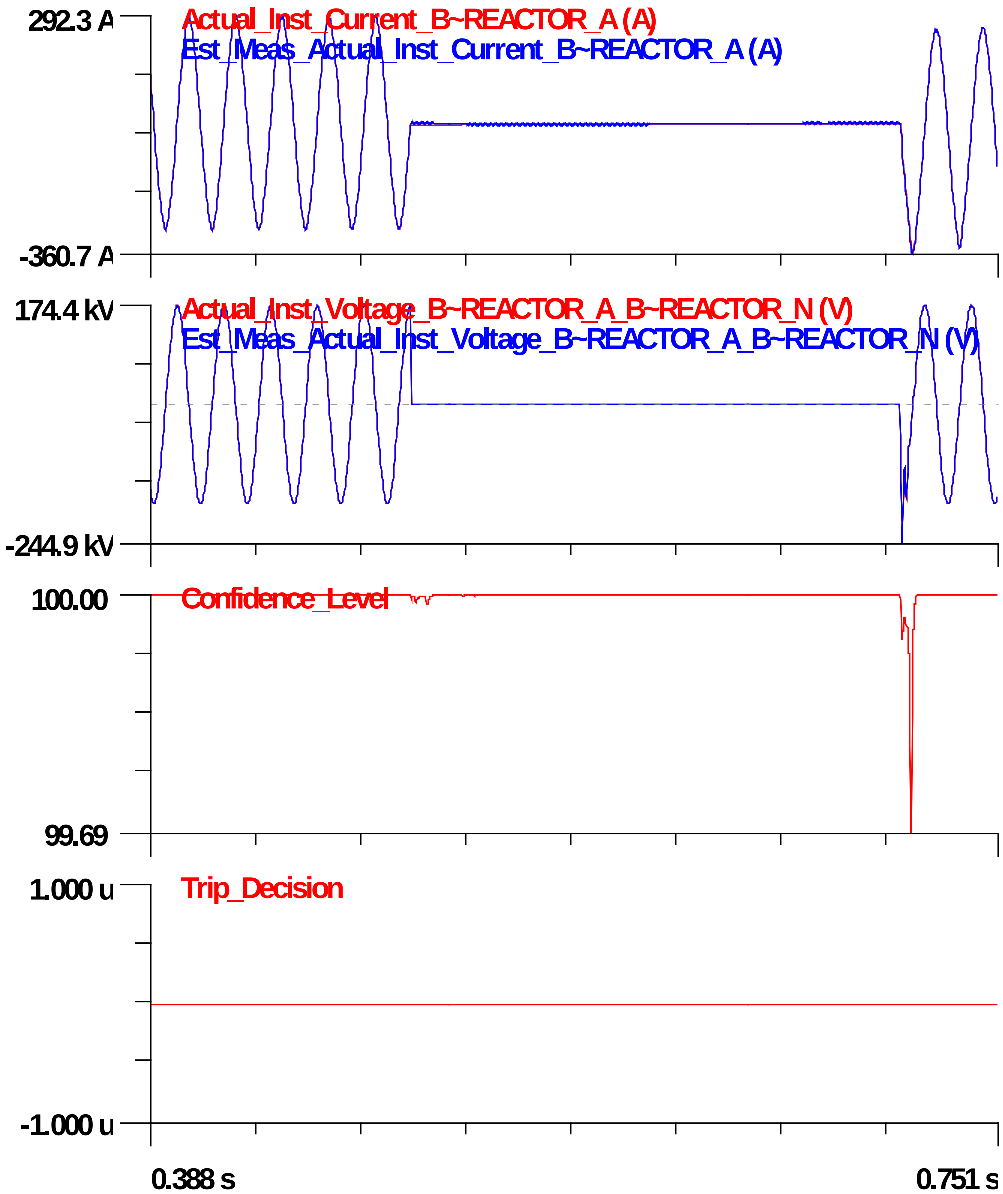


Figure 6-32: Plots of Measurement and Estimated Values, Confidence Level and Trip Decision during Event B

7. Summary, Conclusions and Future Work

The application of setting-less protection on the RTE substation BLOCAUX has been demonstrated on selected protection zones of the substation. The application was testing with numerical experiments and at the laboratory with hardware in the loop. The application was focused on four protection zones of the BLOCAUX substation. Three of the protection zones represent a unit protection. Specifically the protection zone consists of a 90 kV three phase cable and a three winding transformer protected as a single unit. The forth protection zone consists of a three phase reactor bank. The results demonstrate the feasibility of the approach.

The report also describes a new development, the ability to correct for instrumentation channel errors within a merging unit. The method has been demonstrated with numerical examples. The method performs remarkably well correcting the instrumentation channel error even in cases when the instrument transformer experiences high saturation.

The future plan is to install the setting-less relays in the field. The timetable will depend on the utility.

Appendix A: RTE Model: Device List and Parameters

The list of devices that have been modeled is provided in Table A-1. The columns provide information about the device location, type (transmission line, transformer, etc.) and name. The device name consists of its operating voltage, device type and the bus/buses that the device is connected to.

Table A-1: Tabulation of Major Devices Included in the Model

Location	Device Type	Name
Outside of Substation	3 phase Voltage Source	225 kV SOURCE LIMEUX
		225 kV SOURCE ARGOEUVES
	Transmission Line	225 kV Transmission Line From S-LIMEUX To LIMEUX
		225 kV Transmission Line From ARGEOUVES To S-ARGEVS
		90 kV Transmission Line From L-NFCHAUM To NFCH~AUM2
		90 kV Transmission Line From L-BOURBEL To BOURBEL
		90 kV Transmission Line From L-CROIXRA To CROIXRAUL
		90 kV Transmission Line From L-AUMALE1 To AUMALE1
		90 kV Transmission Line From ALLEUX~F2 To L-ALLX-F2
		90 kV Transmission Line From FOUILLOY1 To L-FOUILLO

		90 kV Transmission Line From ALLEUX1 To L-ALLEUX1
	Load	90 kV Load NEUFCHATEL-AUMALE 2
		90 kV Load BOURBEL
		90 kV Load CROIXRAULT
		90 kV Load AUMALE1
		90 kV Load ALLEUX FOUILLOY2
		90 kV Load FOUILLOY 1
		90 kV Load ALLEUX1
Inside the Substation	Underground Cable	90 kV cable 1
		90 kV cable 2
		90 kV cable 3
	3-Winding Transformer	225/93/10.5 kV Transformer 641
		225/93/9.9 kV Transformer 642
		225/93/10 kV Transformer 643
	2- Winding Transformer	10.5/0.23 kV Transformer 1
		9.9/0.23 kV Transformer 2

		10.0/0.23 kV Transformer 3
	3-Phase Reactor	245 kV 3 phase shunt reactor

The parameters of the major devices of the model are provided in this section. Most of the parameters are taken from the documents provided by RTE. **The objective of this part of the report is to provide a working document on which RTE personnel will mark the correct parameters of the various components**.

The single line diagram of the modeled power system including the BLOCAUX substation and its external links are shown in Figure A-1. The substation is connected to the power grid via two 225 kV transmission lines terminated to two substations. The remaining system past these two substations is represented as two equivalent sources. On the 90 kV level, seven 90 kV transmission lines connect the substation to several substations of the power grid. Because of lack of information, the rest of the 90 kV power grid is represented with loads – this may change, most likely we need an equivalent.

The parameters of the major components of the system are provided in several Appendices.

Appendix B provides the parameters of all components in the 225 kV section of the substation BLOCAUX.

Appendix C provides the parameters of all components in the 90 kV section of the substation BLOCAUX.

Appendix D provides the parameters of all components connecting the 90 kV and 225 kV sections of the substation BLOCAUX.

Appendix E provides the parameters of all components in the external 225 kV system.

Appendix F provides the parameters of all components in the external 90 kV system.

Appendix G provides the protection zones of the BLOCAUX substation which were considered for protection using the setting-less relay.

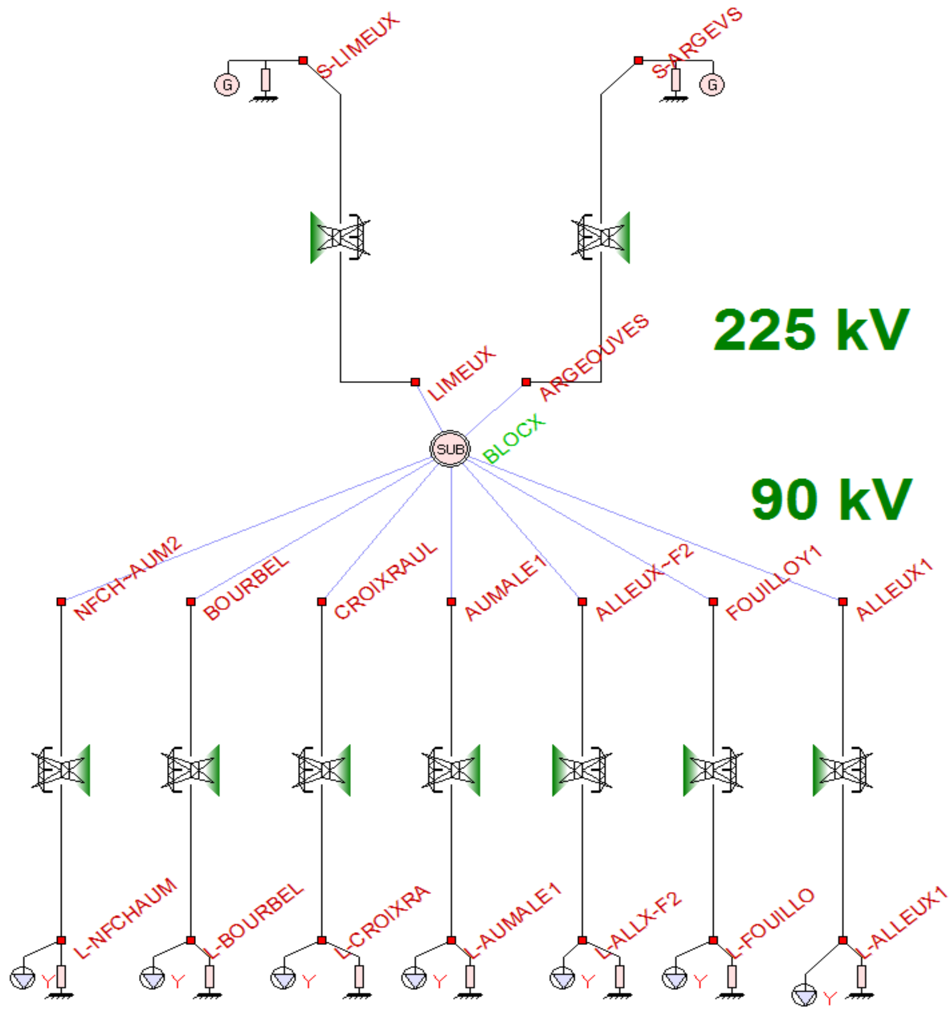


Figure A-1: Single Line Diagram of the RTE System including the BLOCAUX Substation and Its External Links

Appendix B: BLOCAUX Substation 225 kV Section

The parameters of all components in the 225 kV section of the substation BLOCAUX are provided here. The 225-kV bus configuration of the substation is shown in the figure below. We provide the parameters for all components appearing in the single line diagram of Figure B-1.

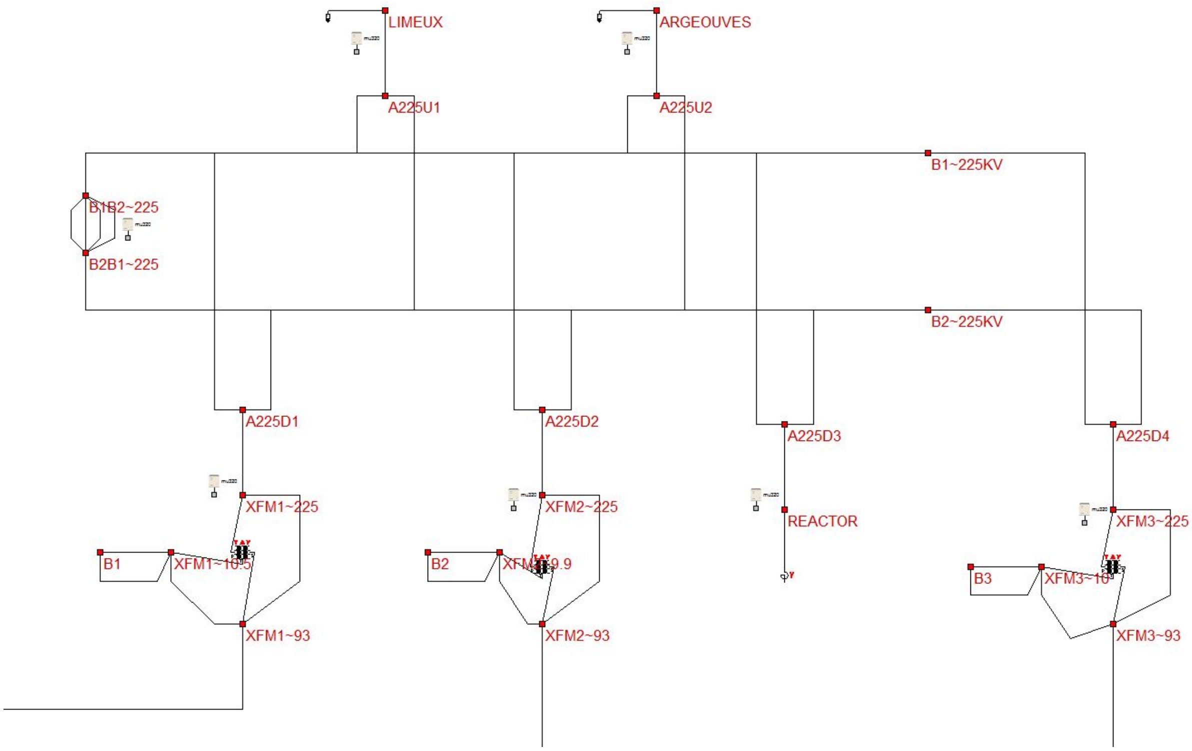


Figure B-1: Single Line Diagram of 225 kV Section

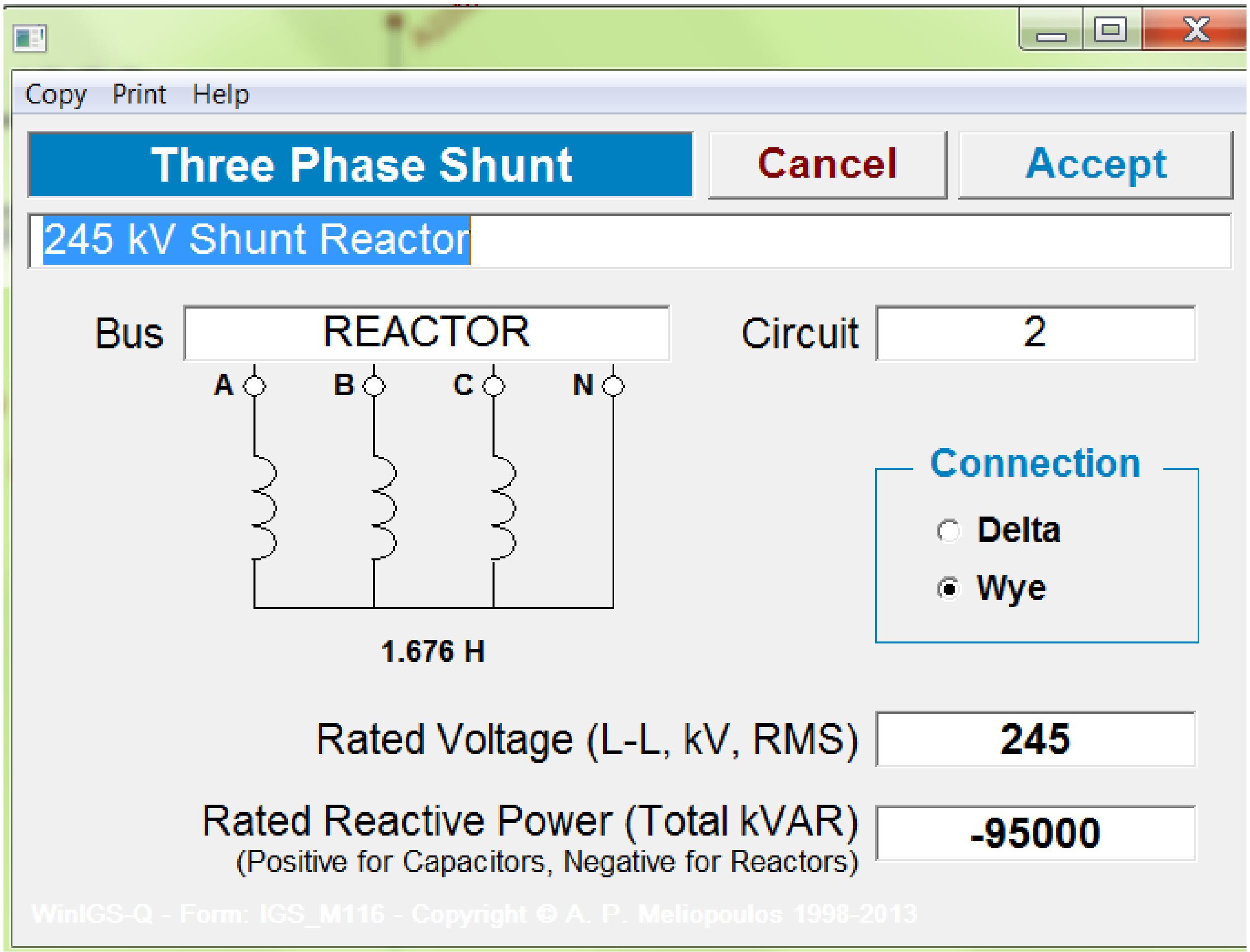


Figure B-2: 245 kV Shunt Reactor Parameters

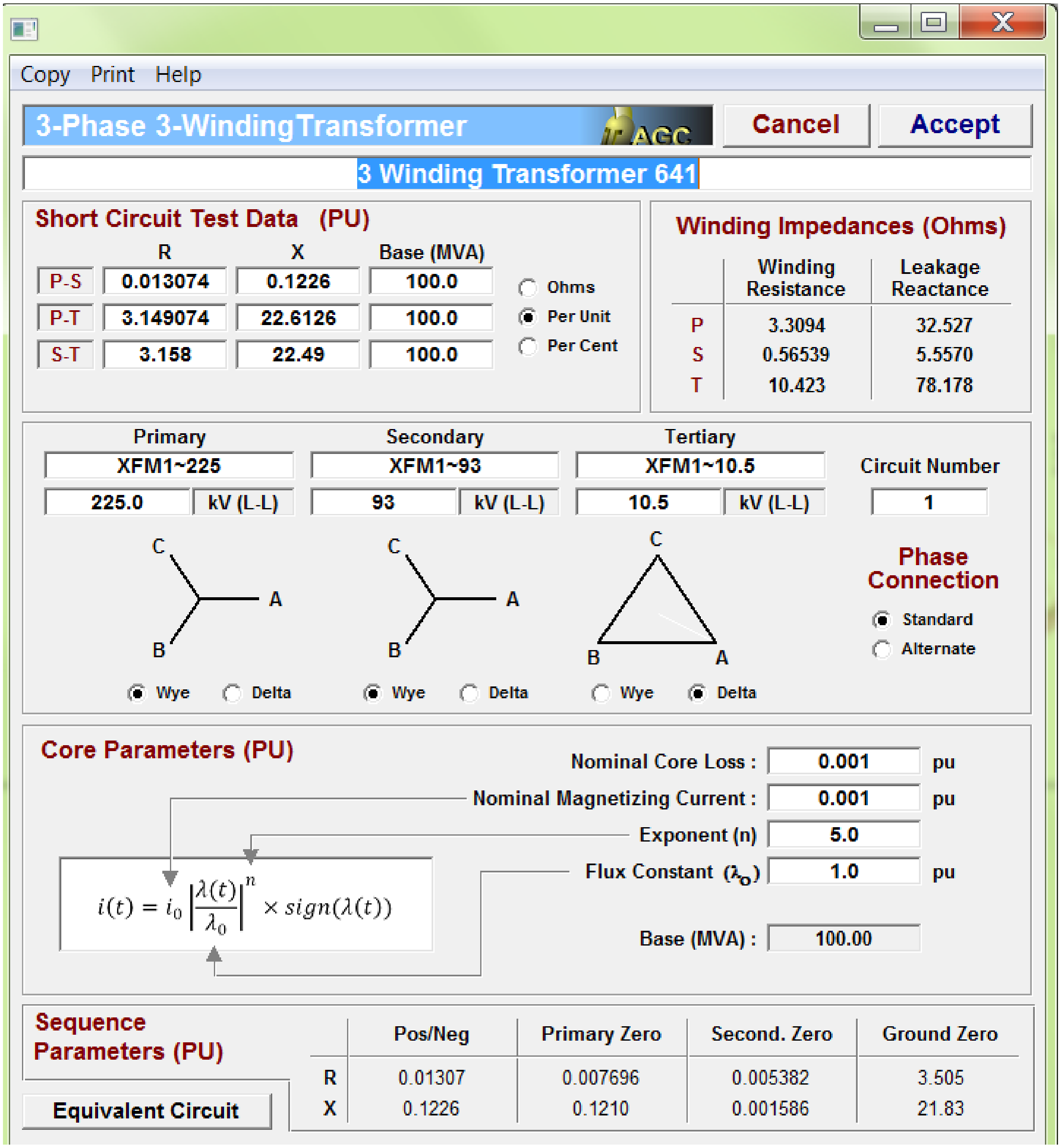


Figure B-3: 225/93/10.5 kV Transformer 641 Parameters

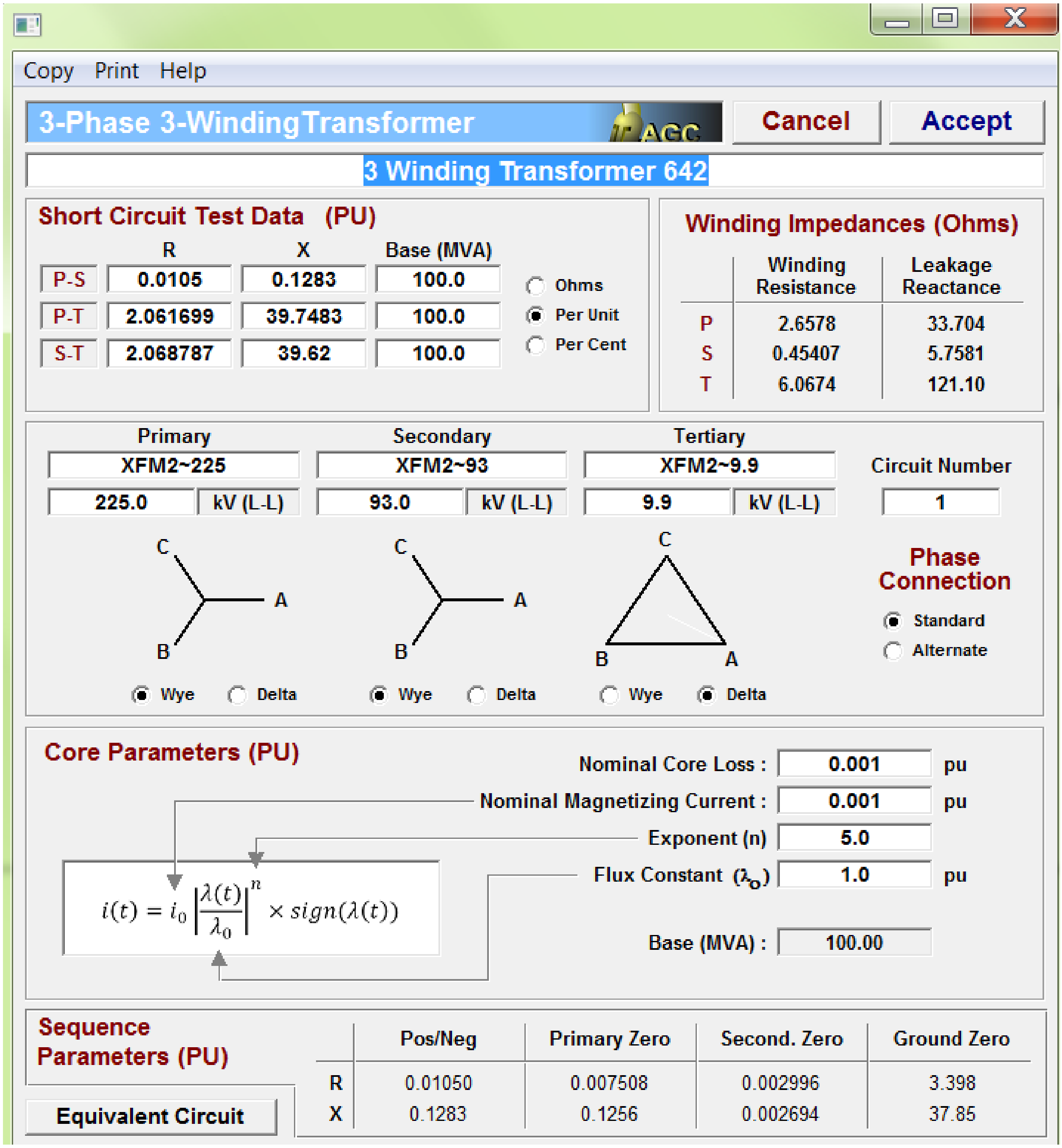


Figure B-4: 225/93/9.9 kV Transformer 642 Parameters

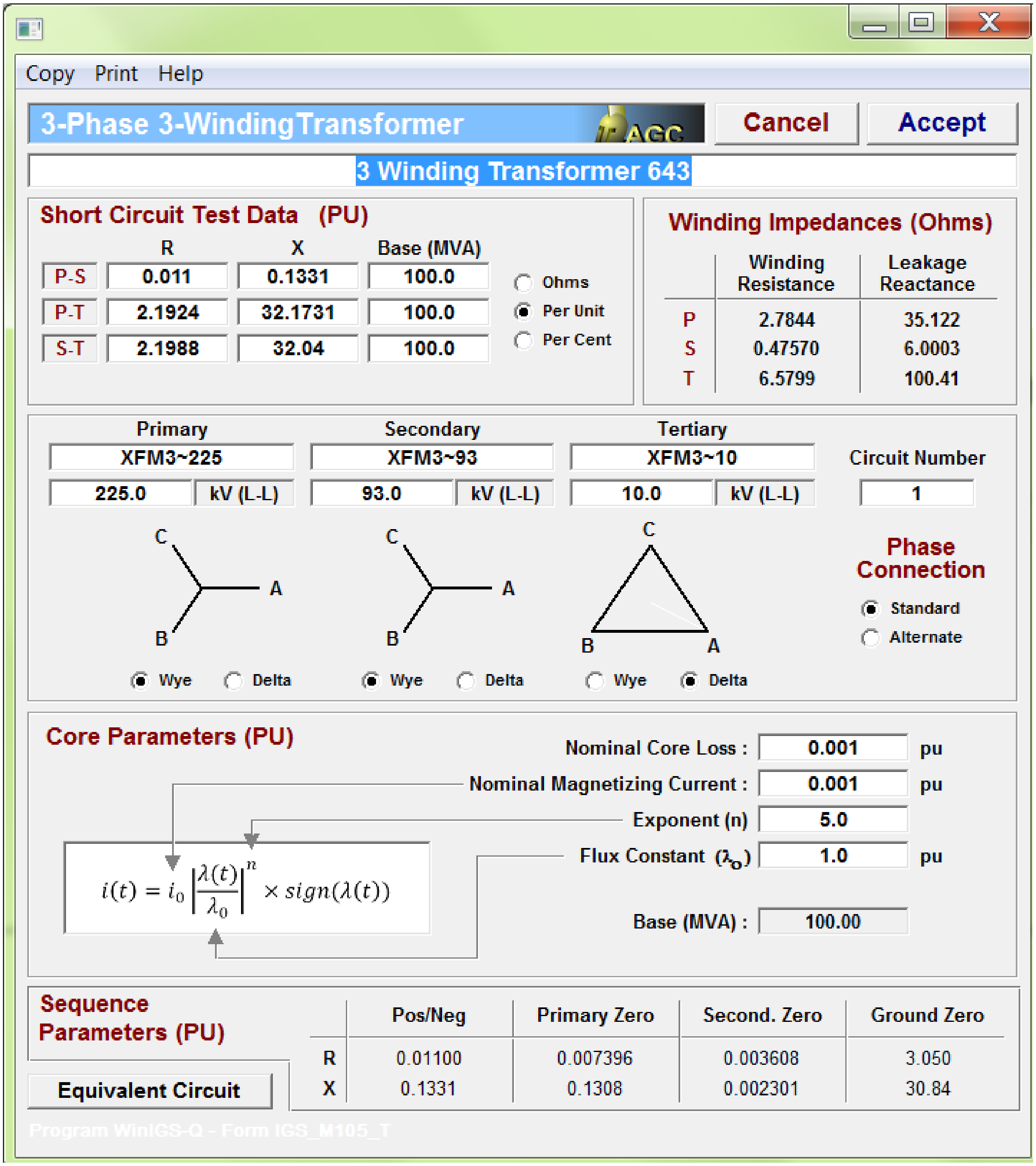


Figure B-5: 225/93/10.0 kV Transformer 643 Parameters

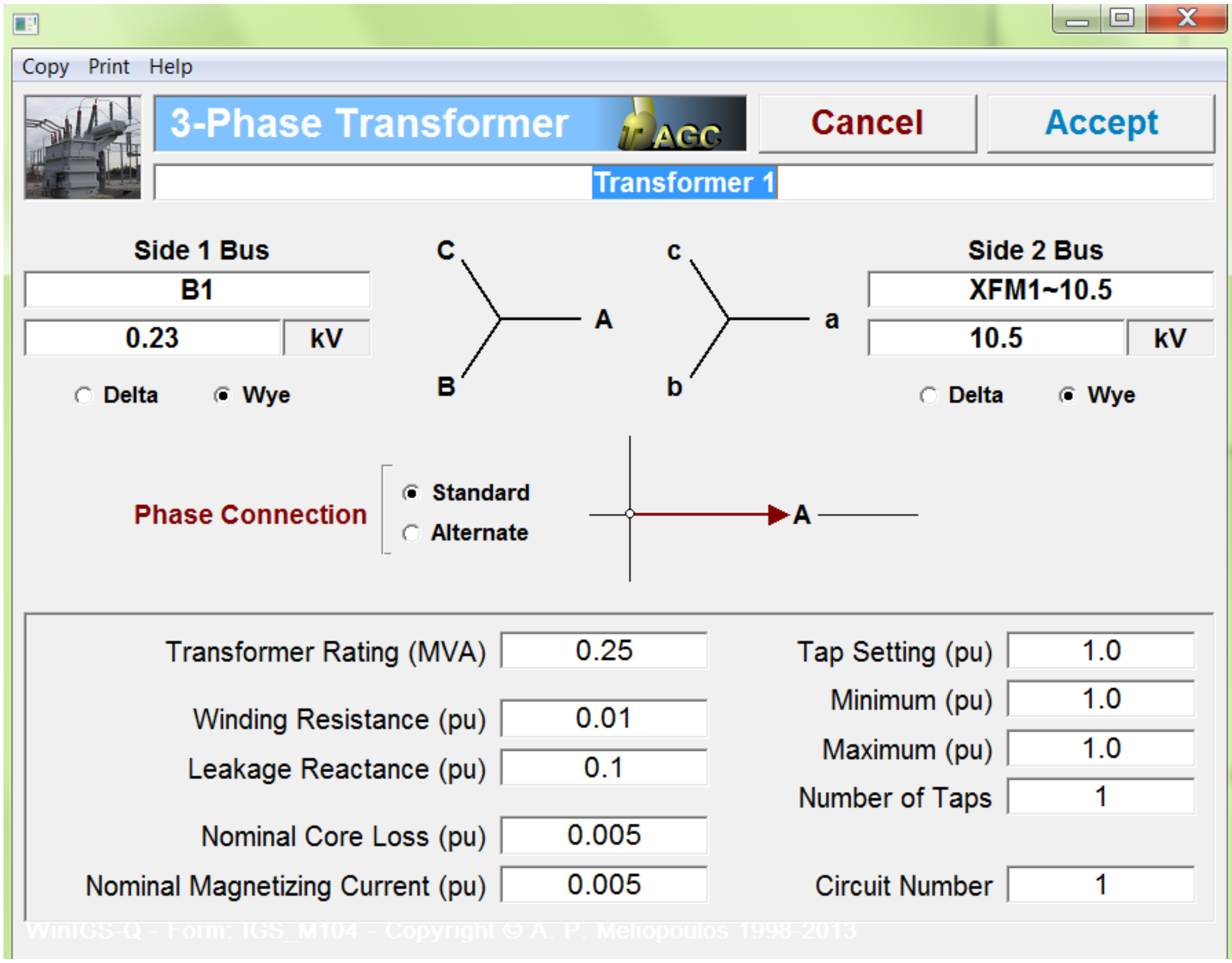


Figure B-6: 2 Winding Transformer 1 Parameters

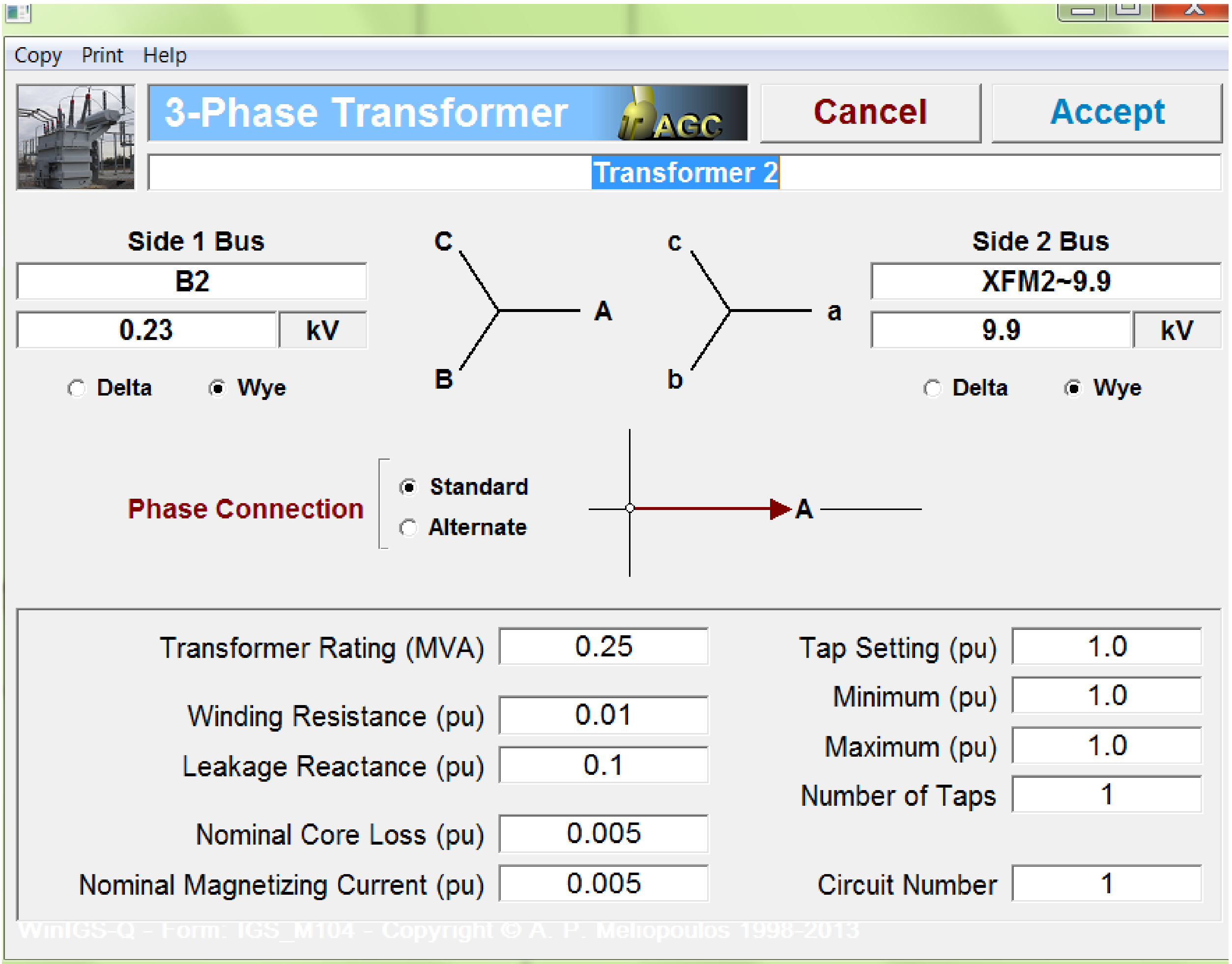


Figure B-7: 2 Winding Transformer 2 Parameters

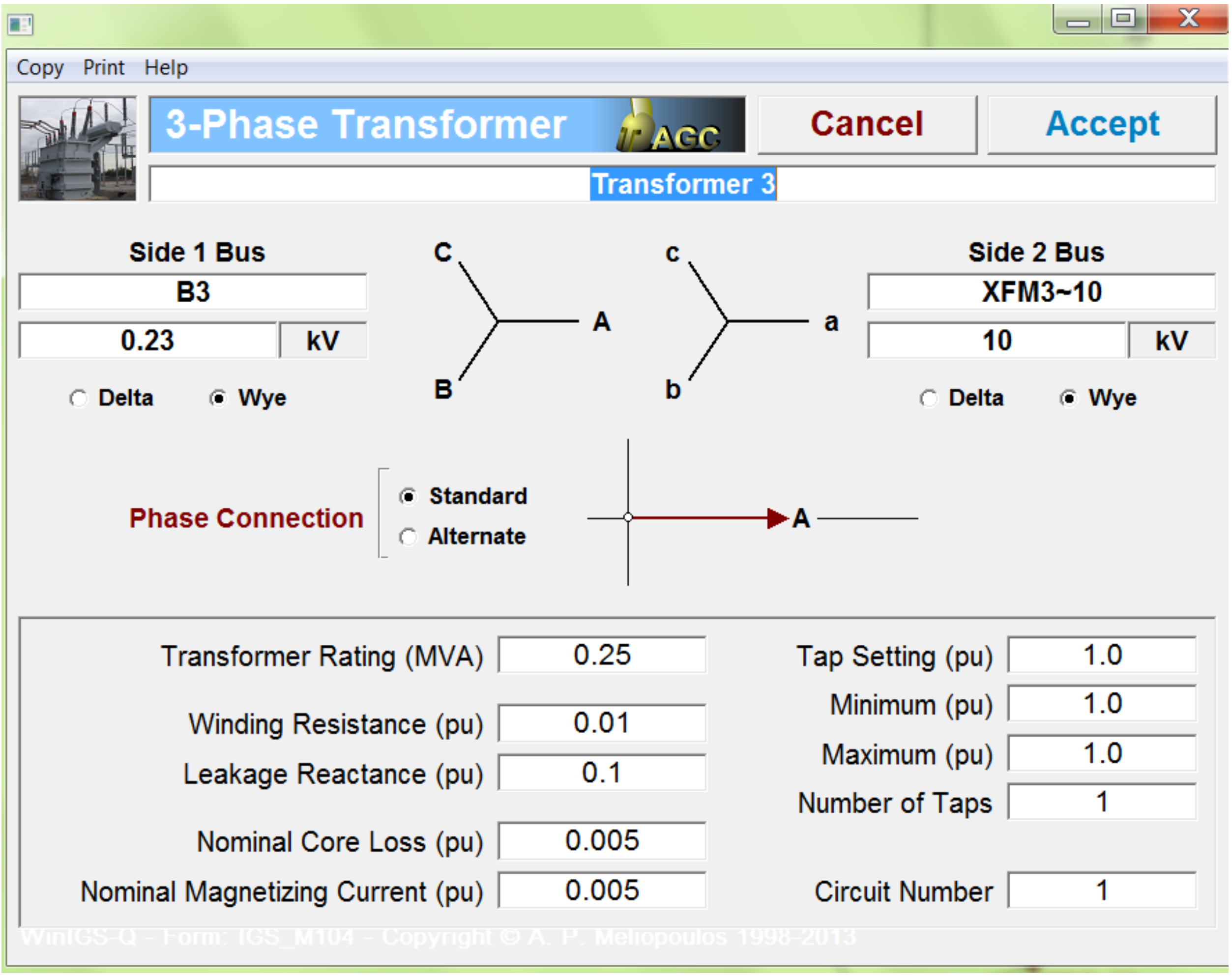


Figure B-8: 2 Winding Transformer 3 Parameters

Appendix C: BLOCAUX Substation 90 kV Section

The parameters of all components in the 90 kV section of the substation BLOCAUX are provided here. The 90-kV bus configuration of the substation is shown in Figure C-1. We provide the parameters for all components appearing in the single line diagram of Figure C-1.

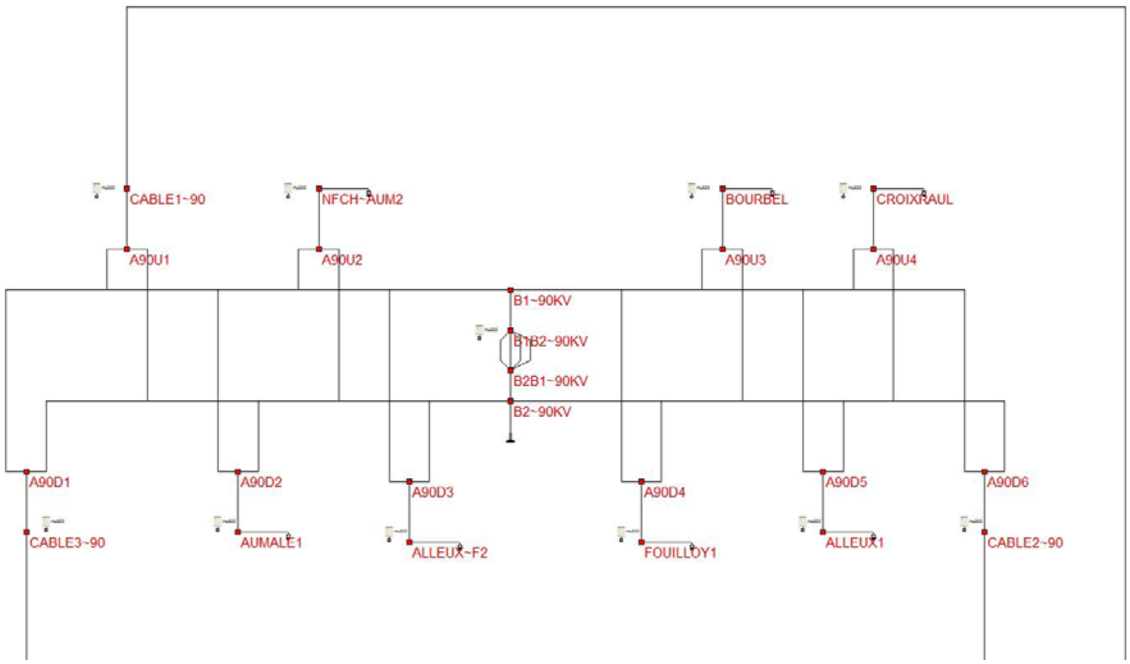


Figure C-1: Single Line Diagram of 90 kV Section

Appendix D: Cables Between 225 kV and 90 kV Section

The parameters of the three cables connecting the 225 kV and 90 kV sections of the substation BLOCAUX are provided here. The three 90 kV cables connect the 90 kV section to the 90 kV side of the transformers in the 225 kV section.

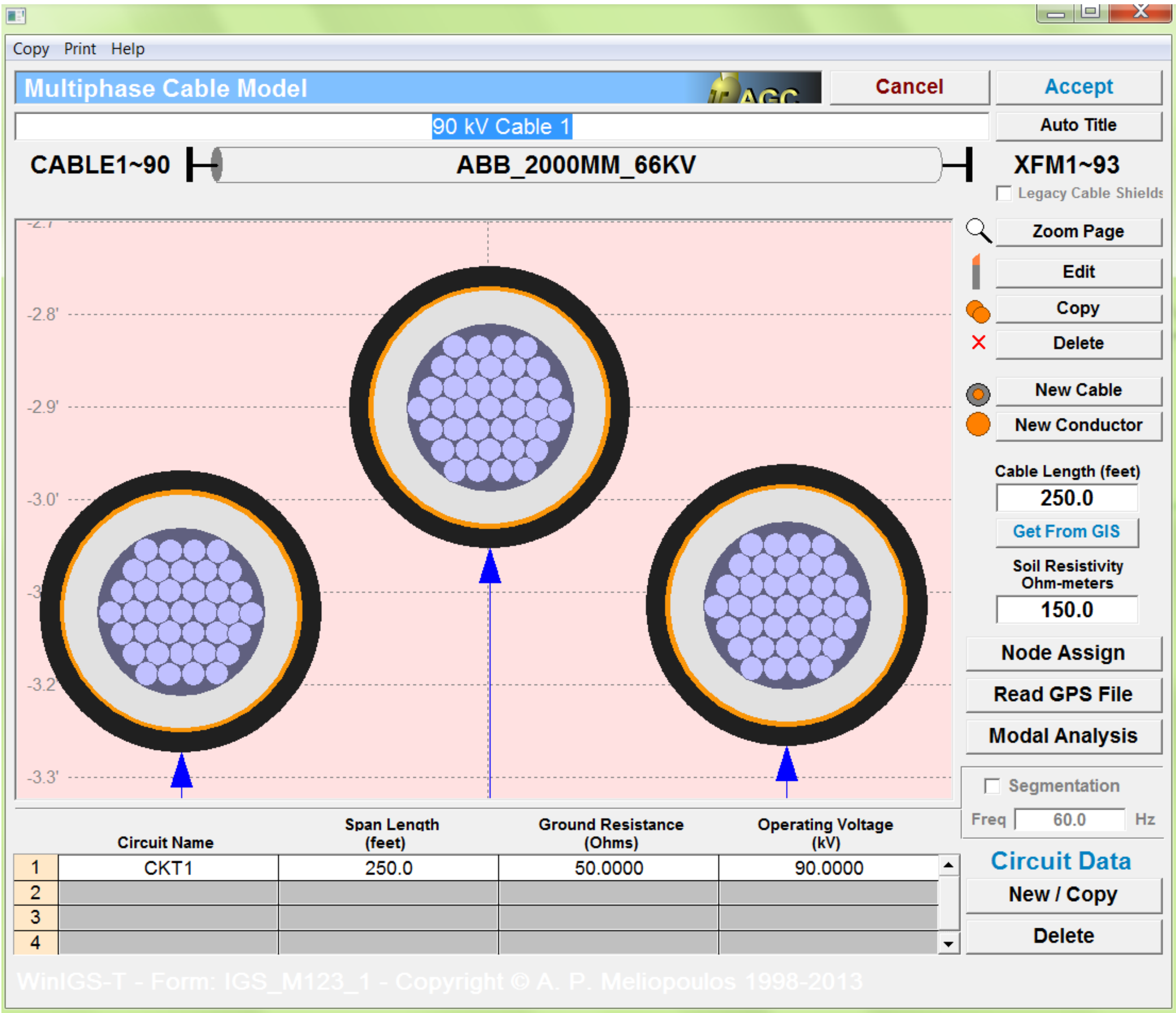


Figure D-1: 90 kV cable 1 Parameters, Inside Substation

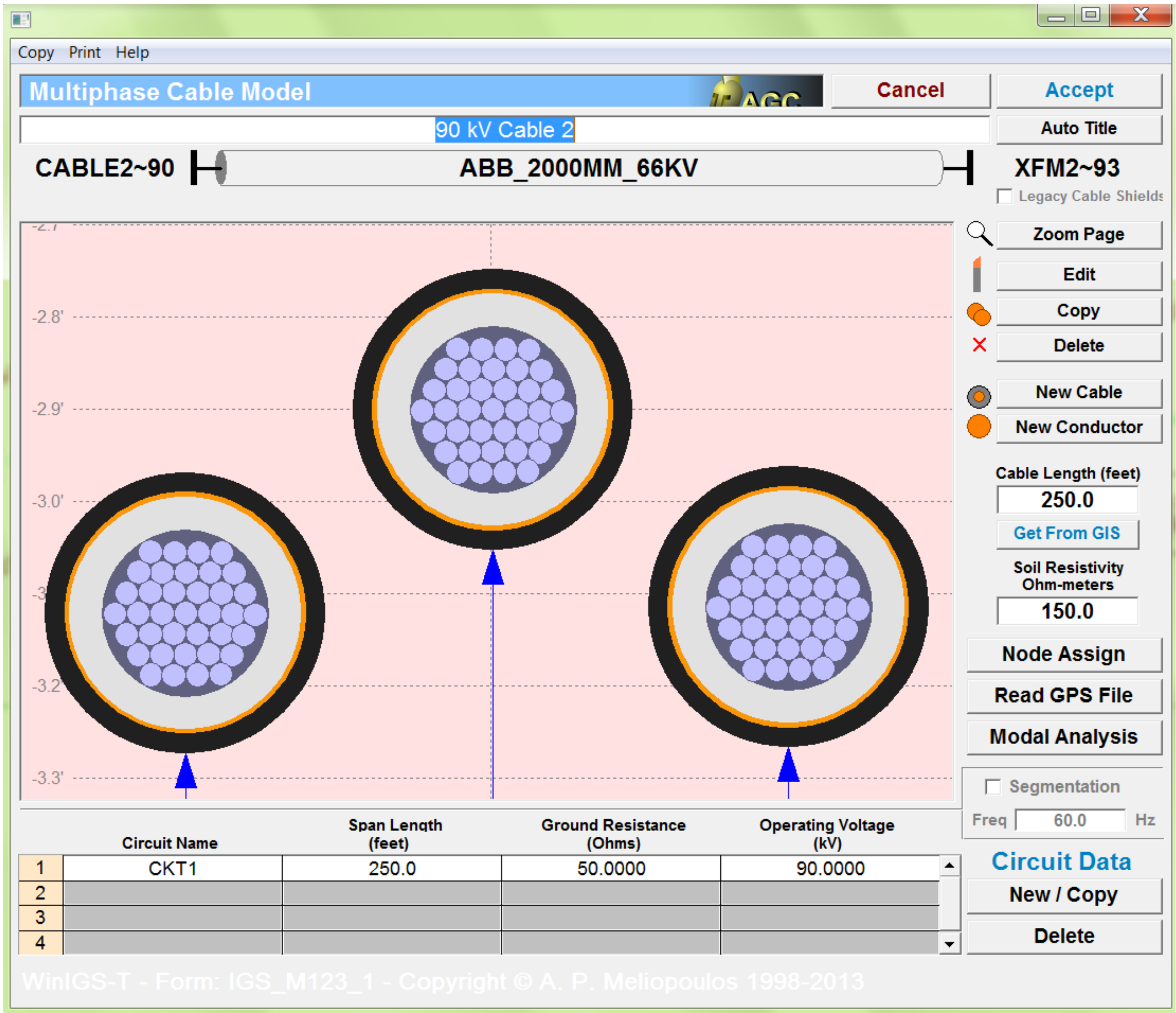


Figure D-2: 90 kV cable 2 Parameters, Inside Substation

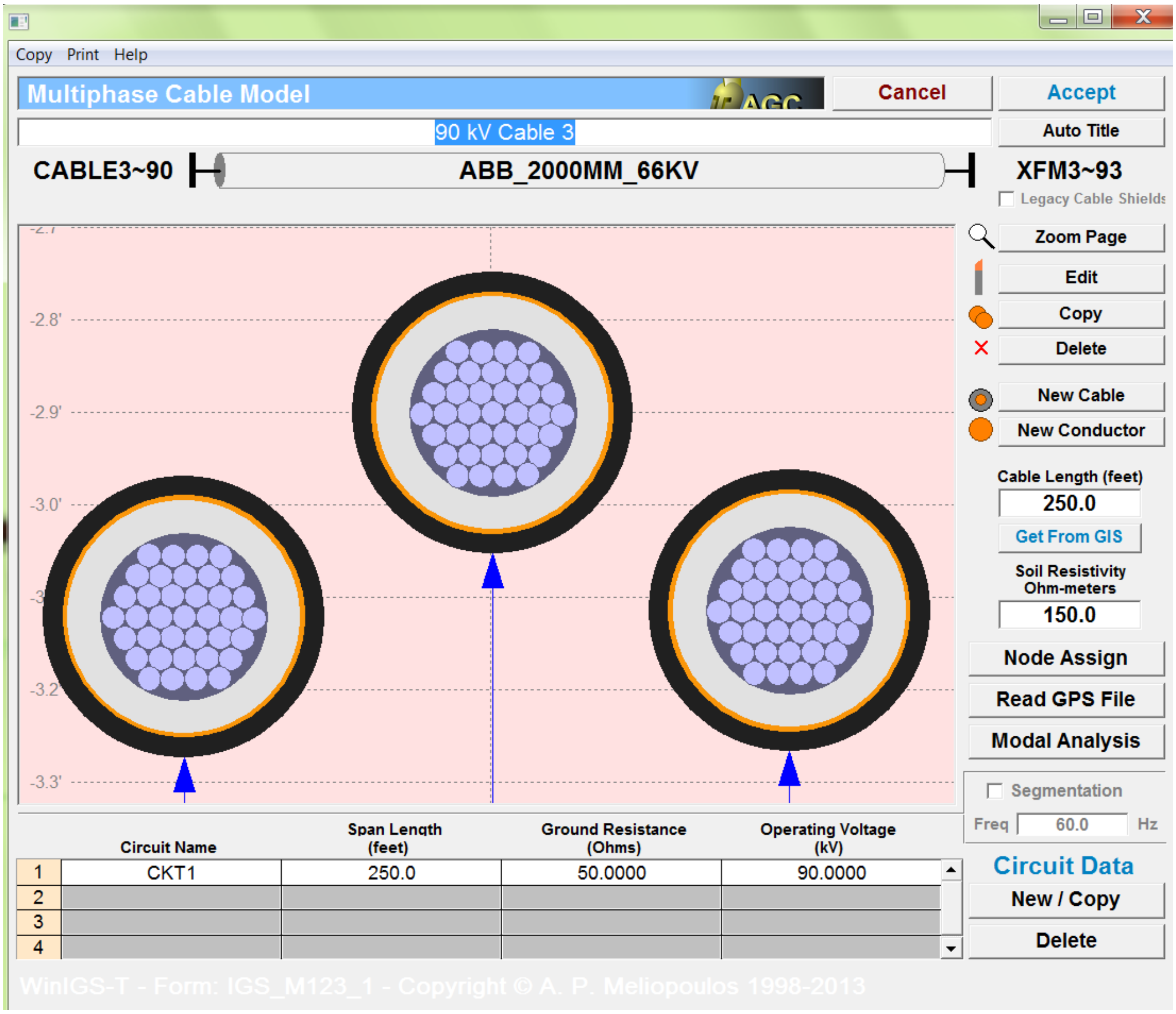


Figure D-3: 90 kV cable 3 Parameters, Inside Substation

Appendix E: 225 kV External System

The parameters of all components in the external 225 kV system are provided here. The single line diagram is shown in Figure E-1.

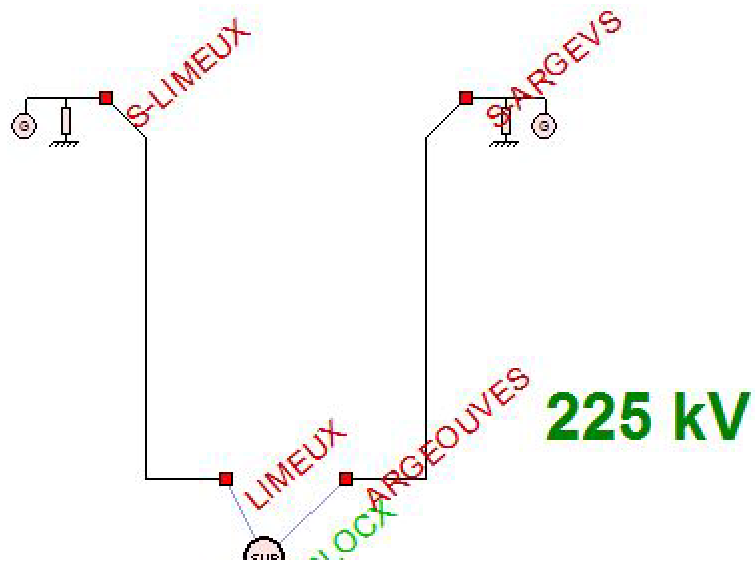


Figure E-1: Single Line Diagram of the External 225 kV System

There are two voltage sources and two transmission lines connecting the sources to the substation BLOCAUX. The parameters of the voltage sources Limeux and Argeouves are given in the Figure E-2 and Figure E-3, respectively. The 225 kV transmission line parameters are given as in Figures E-4 and Figure E-5.

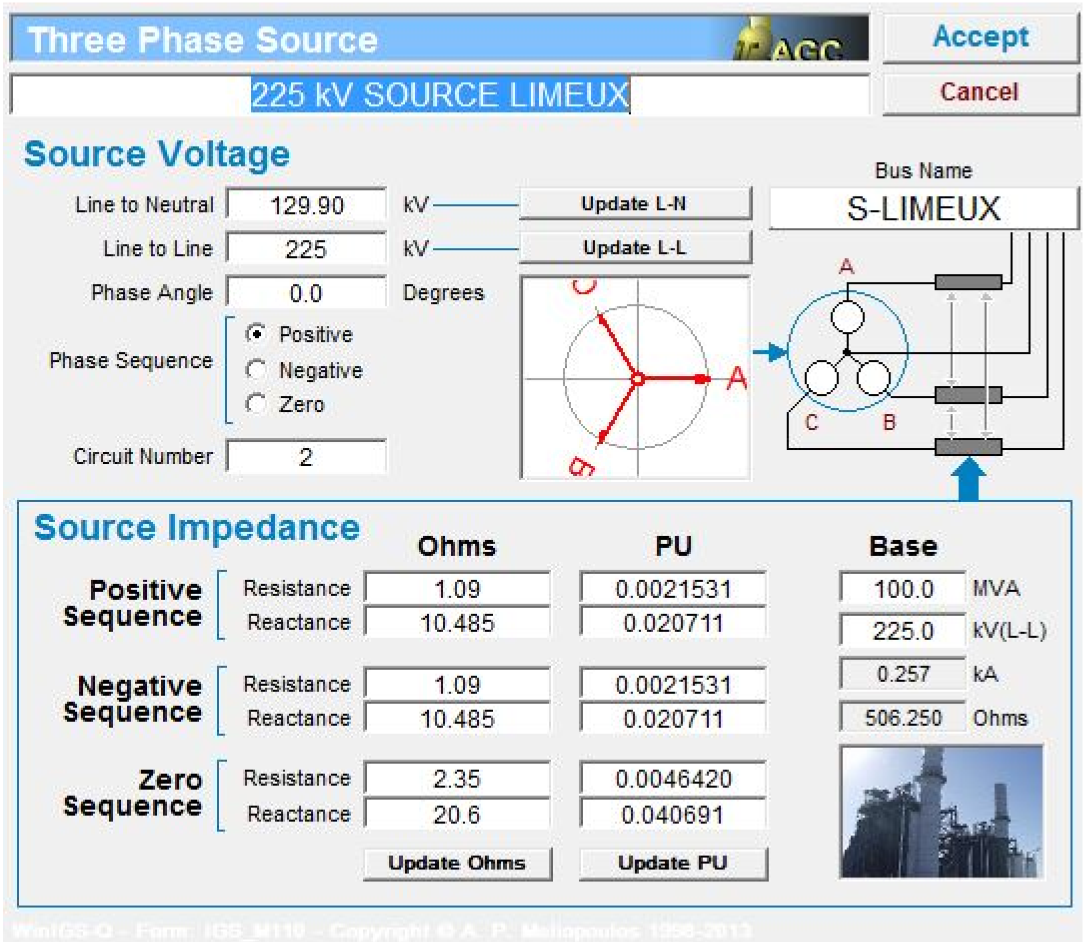


Figure E-2: 225 kV Source Limeux Parameters

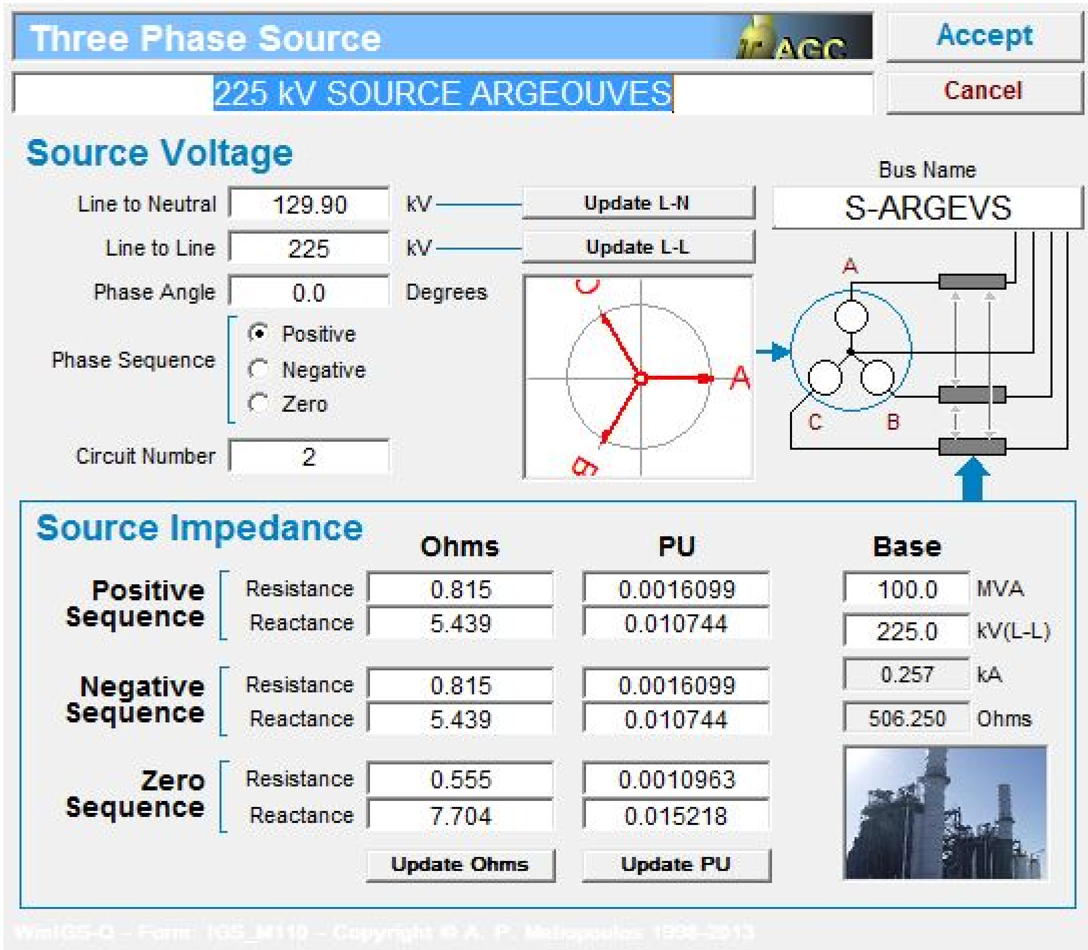


Figure E-3: 225 kV Source Argeouves Parameters

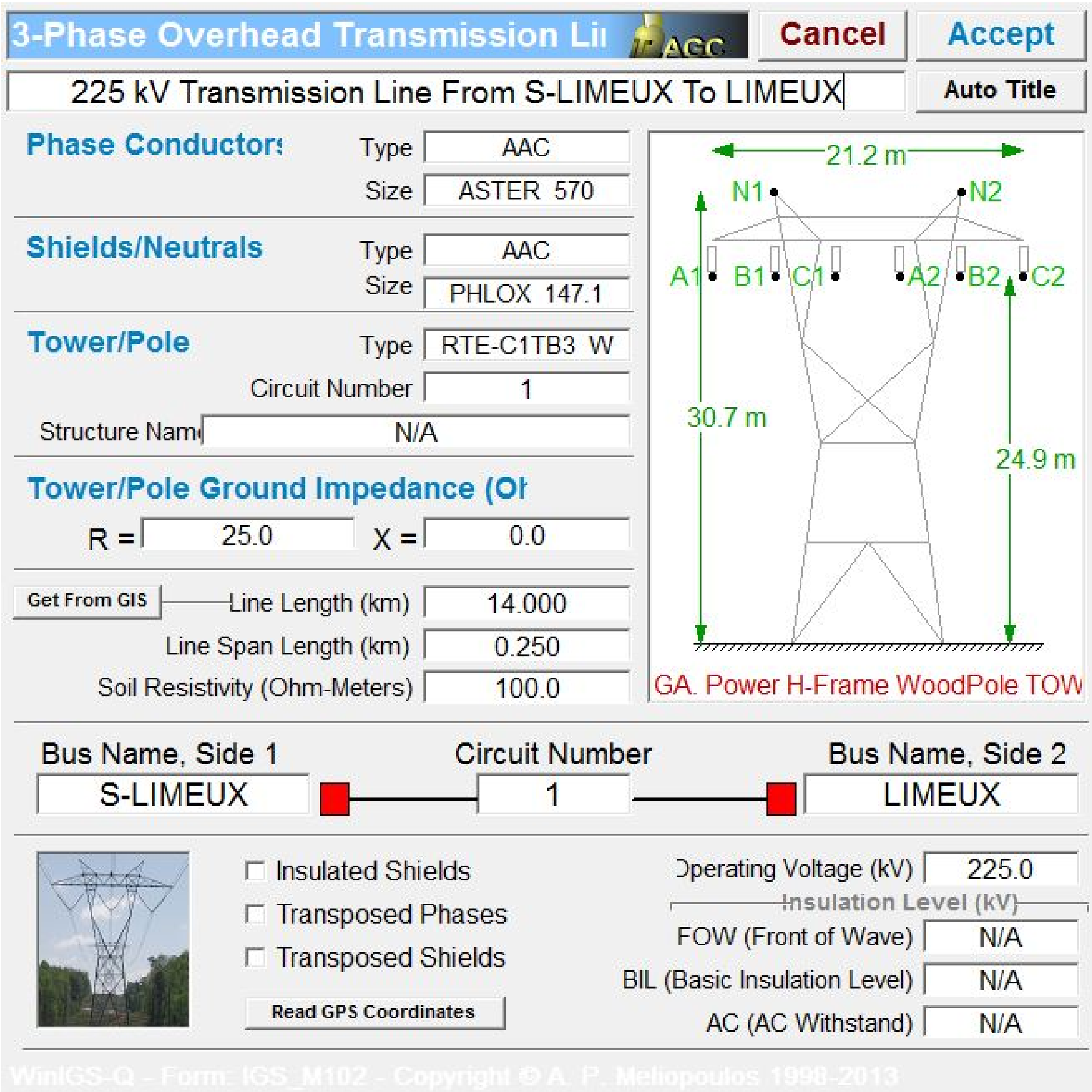


Figure E-4: 225 kV Transmission Line From S-Limeux to Limeux Parameters

The detailed data of this transmission line is not provided by Feb 05, 2017. It is modelled using the same tower structure as for line From Argeouves to BLOCAUX substation. Table below provides a comparison of the modeled line parameters with the provided data.

	blocaux limeux	**WinIGS Model**
Rd	0.721	0.813
Xd	5.419	5.242
R0	4.68	4.126
X0	7.652	14.62

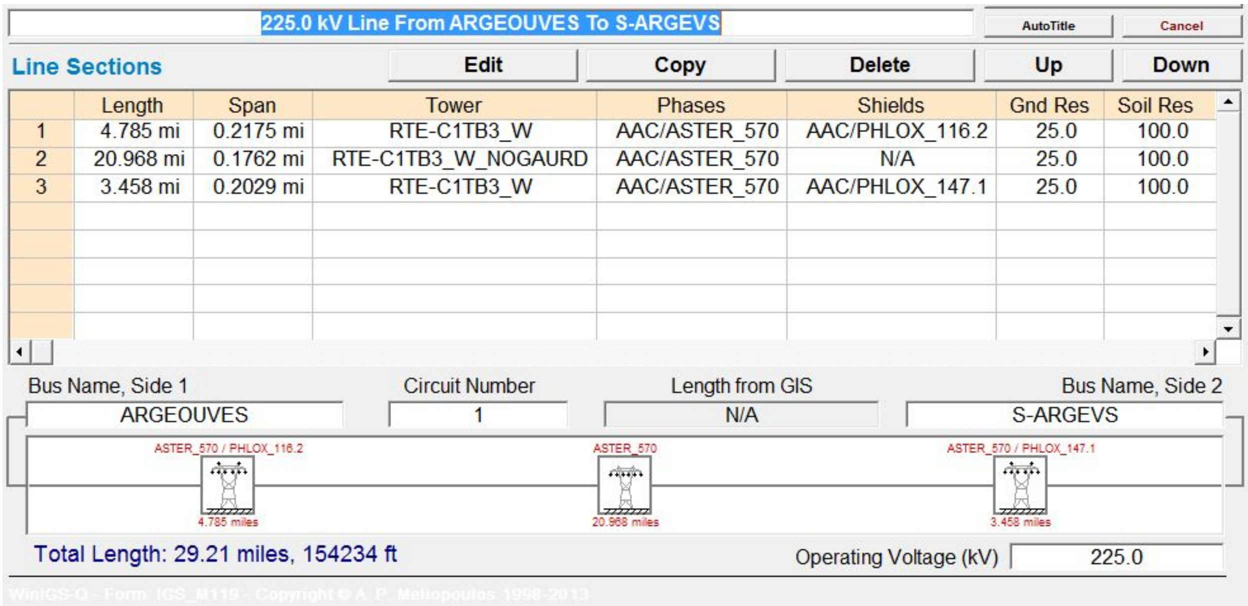


Figure E-5: 225 kV Trasmission Line From Argeouves to S-Argevs Parameters

Based on the provided data, it is seen that this line has different sections with and without the guard conductor. Also, the guard conductor is different and there are two types of those. Therefore, both guard conductor types are modelled as well as the phase conductors. Tower structure is also modified to with-guard and no-guard. Table below provides a comparison of the modeled line parameters with the provided data.

	argoeuvre blocaux	**WinIGS Model**
Rd	2.47	2.726
Xd	16.443	17.589
R0	8.79	10.841
X0	52.472	61.797

Appendix F: 90 kV External System

The parameters of all components in the external 90 kV system are provided here. The system is shown in Figure F-1.

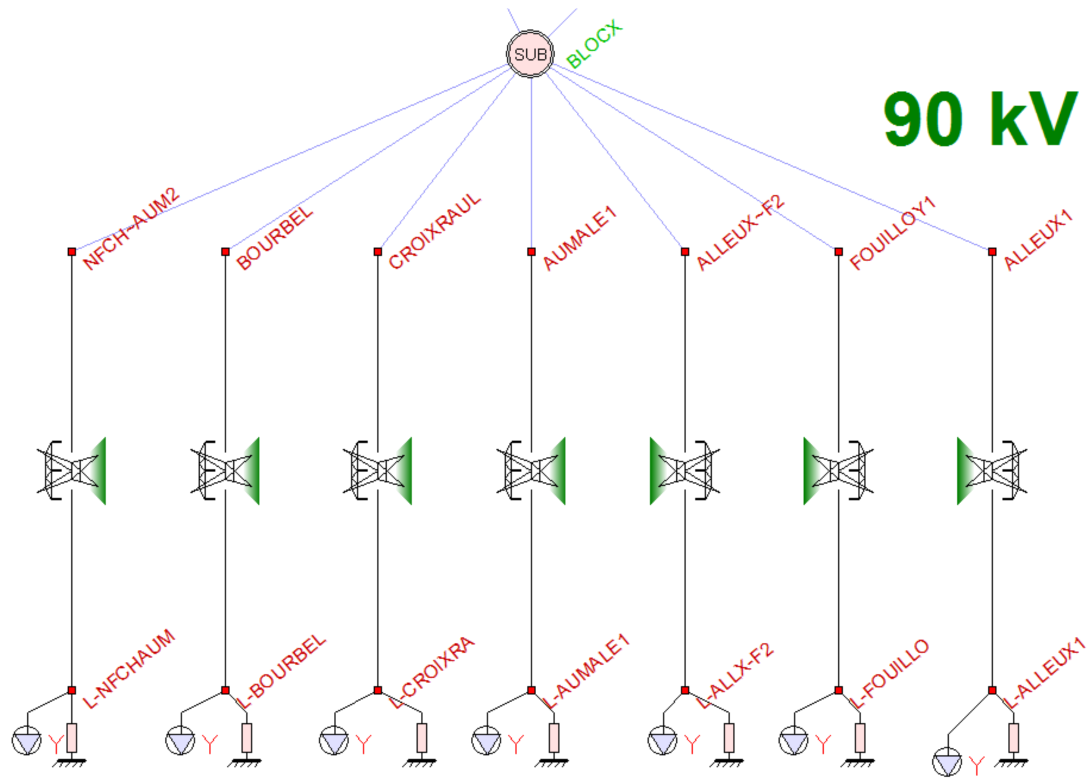


Figure F-1: Single Line Diagram of the External 90 kV System

Because of lack of information, we applied a load at the other ends of the 90 kV lines. We expect that in the final model we will have an equivalent representation of the stem at the other end of the 90 kV circuits. The parameters of the external 90 kV transmission lines are given in Figures F-2 to F-8.

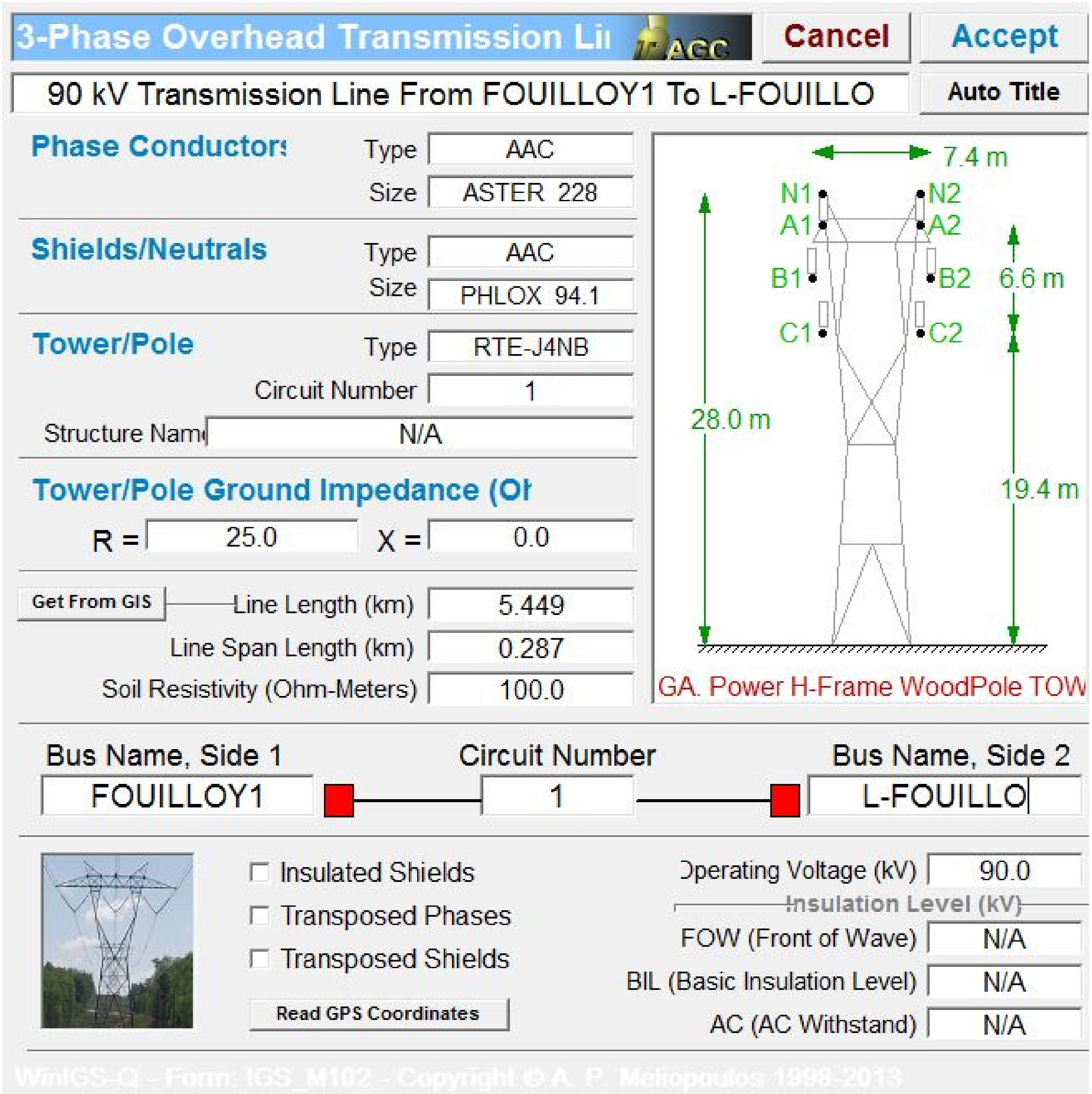


Figure F-2: 90 kV Transmission Line From Fouilloy1 to L-Fouillo Parameters

Table below provides a comparison of the modeled line parameters with the provided data.

	Blocaux - Fouil 1	**WinIGS Model**
Rd	0.79	0.809
Xd	2.11	1.954
R0	2.209	2.369
X0	6.639	5.908

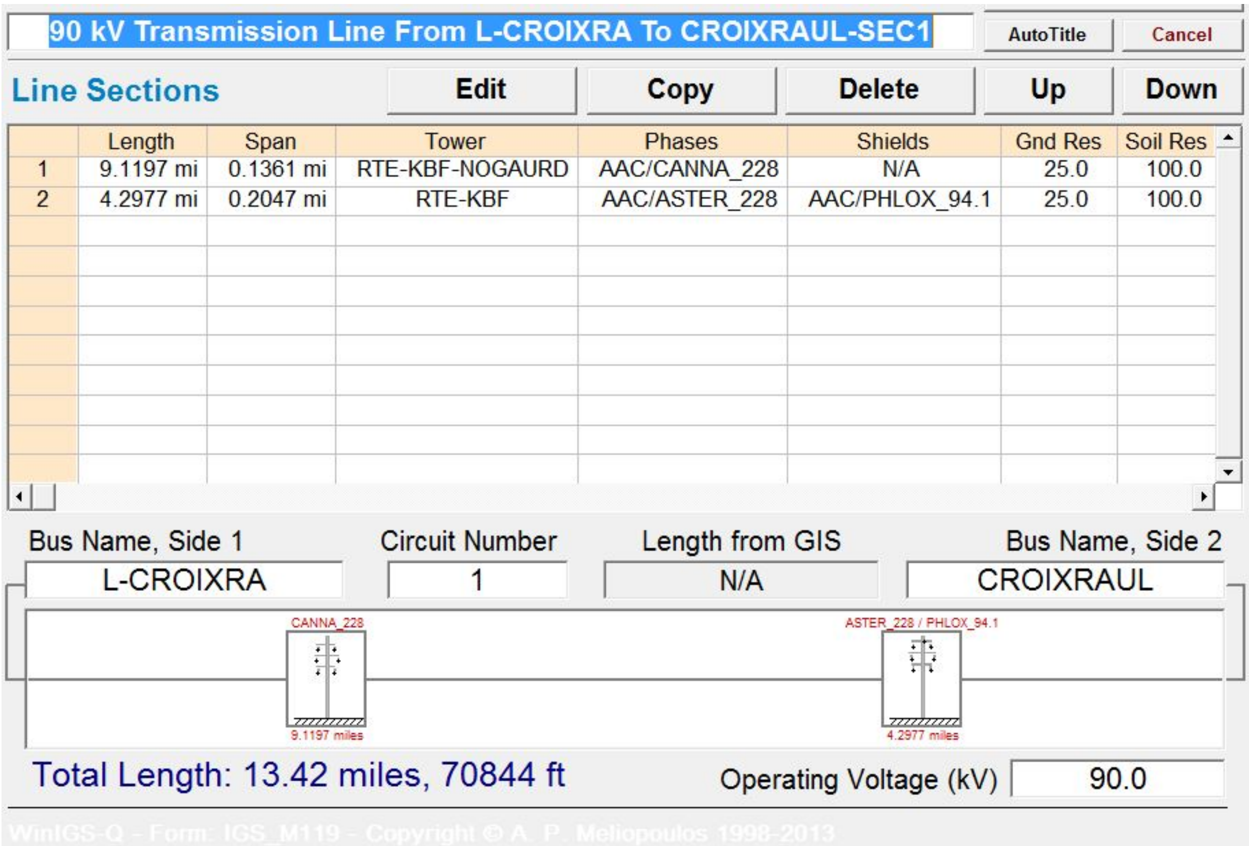
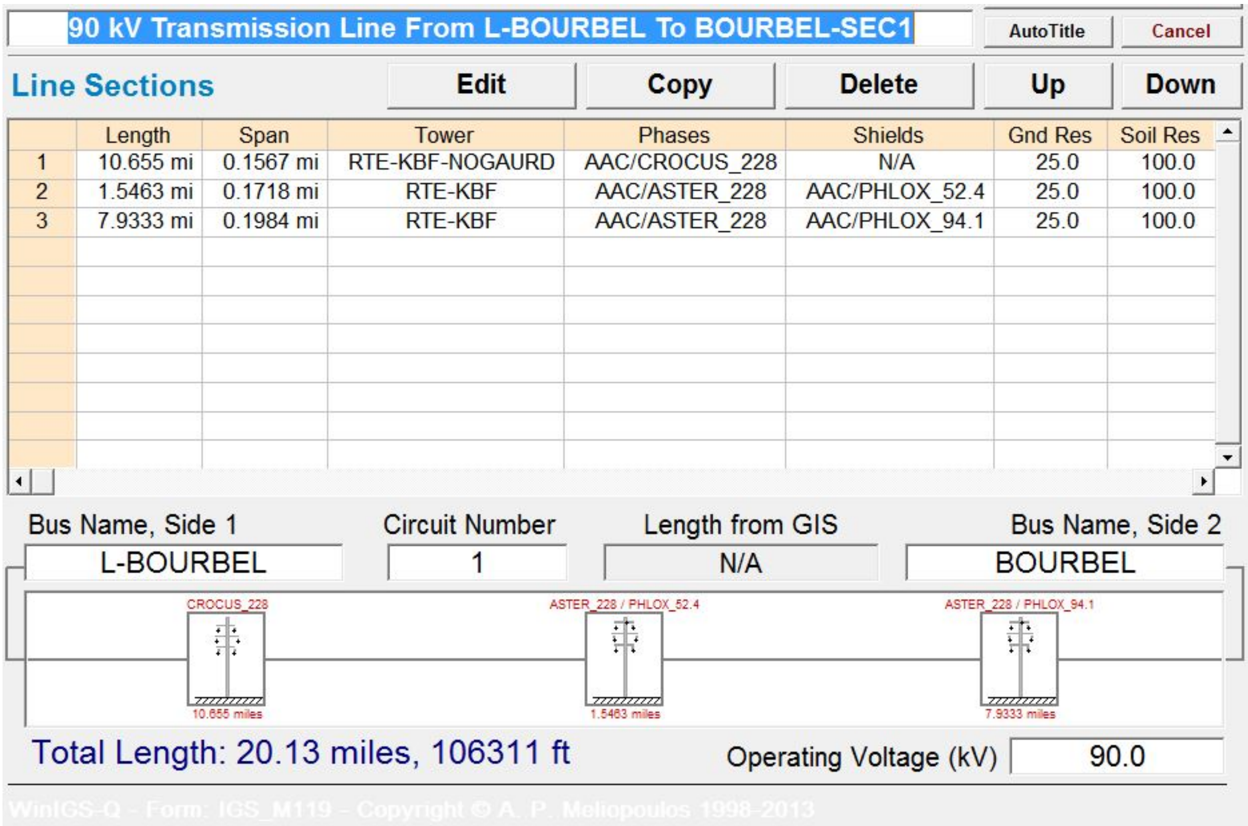


Figure F-3: 90 kV Transmission Line From L-Croixra to Croixraul Parameters

Similar to the "argoeuvre blocaux" line, this line ("blocaux croiraux") has also sections with and without guard conductor. Therefore, both cases are considered in the model. Table below provides a comparison of the modeled line parameters with the provided data.

	blocaux croiraux	**WinIGS Model**
Rd	3.28	3.328
Xd	8.44	8.063
R0	7.153	7.282
X0	28.989	29.515



	Length	Span	Tower	Phases	Shields	Gnd Res	Soil Res
1	10.655 mi	0.1567 mi	RTE-KBF-NOGAURD	AAC/CROCUS_228	N/A	25.0	100.0
2	1.5463 mi	0.1718 mi	RTE-KBF	AAC/ASTER_228	AAC/PHLOX_52.4	25.0	100.0
3	7.9333 mi	0.1984 mi	RTE-KBF	AAC/ASTER_228	AAC/PHLOX_94.1	25.0	100.0

Figure F-4: 90 kV Transmission Line From L-Bourbel to Bourbel Parameters

Table below provides a comparison of the modeled line parameters with the provided data.

	blocaux bourbel	**WinIGS Model**
Rd	3.57	4.944
Xd	9.19	11.589
R0	7.71	11.546
X0	31.167	41.915

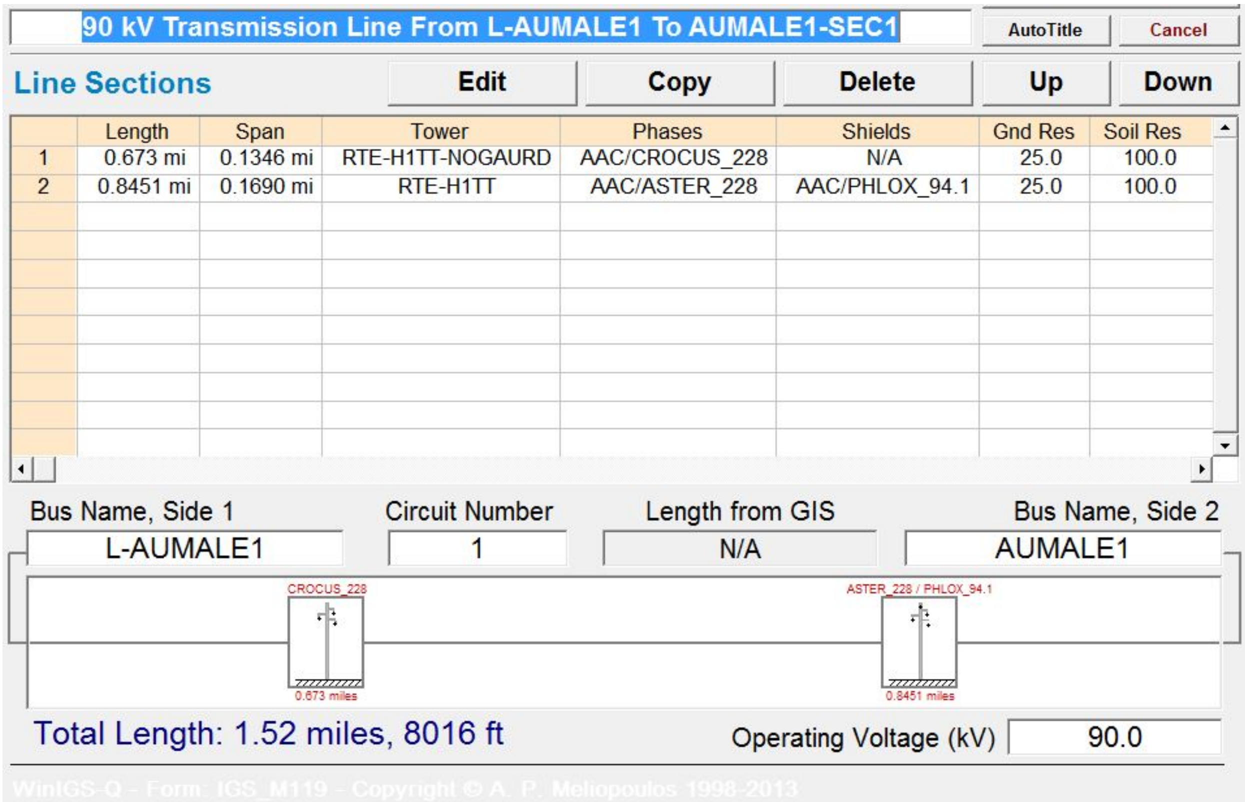
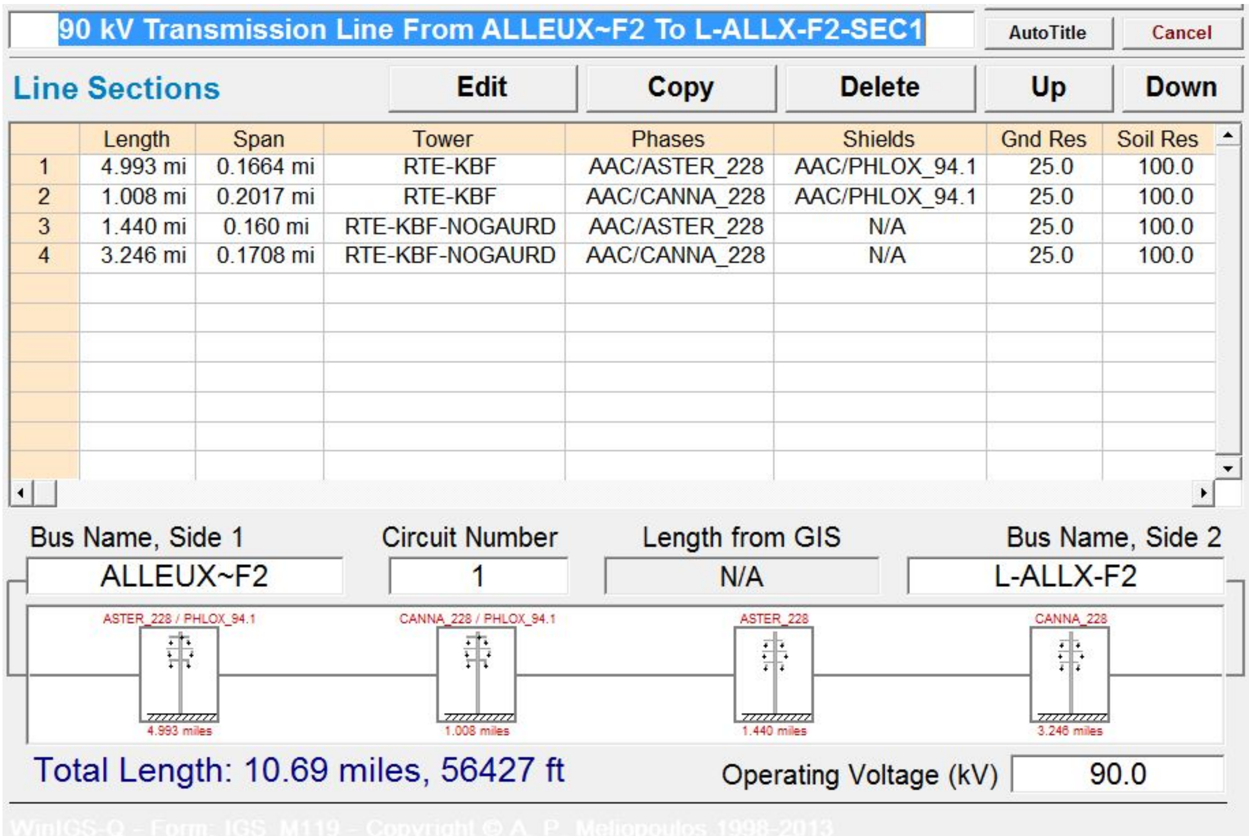


Figure F-5: 90 kV Transmission Line From L-Aumale1 to Aumale1 Parameters

Table below provides a comparison of the modeled line parameters with the provided data.

	aumal blocaux	**WinIGS Model**
Rd	0.32	0.369
Xd	0.83	0.906
R0	0.746	0.744
X0	2.778	3.355



90 kV Transmission Line From ALLEUX~F2 To L-ALLX-F2-SEC1

AutoTitle | Cancel

Line Sections | Edit | Copy | Delete | Up | Down

	Length	Span	Tower	Phases	Shields	Gnd Res	Soil Res
1	4.993 mi	0.1664 mi	RTE-KBF	AAC/ASTER_228	AAC/PHLOX_94.1	25.0	100.0
2	1.008 mi	0.2017 mi	RTE-KBF	AAC/CANNA_228	AAC/PHLOX_94.1	25.0	100.0
3	1.440 mi	0.160 mi	RTE-KBF-NOGAURD	AAC/ASTER_228	N/A	25.0	100.0
4	3.246 mi	0.1708 mi	RTE-KBF-NOGAURD	AAC/CANNA_228	N/A	25.0	100.0

Bus Name, Side 1	Circuit Number	Length from GIS	Bus Name, Side 2
ALLEUX~F2	1	N/A	L-ALLX-F2

Total Length: 10.69 miles, 56427 ft

Operating Voltage (kV) 90.0

WinIGS-Q - Form: IGS_M119 - Copyright © A. P. Meliopoulos 1998-2013

Figure F-6: 90 kV Transmission Line From Alleux~F2 to L-Allx-F2 Parameters

Table below provides a comparison of the modeled line parameters with the provided data. The difference between the provided data and the modelled values might be due to the fact that the model considers all the line sections in parameter calculation from the “Blocaux” substation up to the load at the end of the line. However, as the line name shows: “ALLEUX (GRANDVILLIERS-BLOCAUX-FOUILLIOY 2”, it has a substation on the way. Thus, it is highly probable that the provided data is only for one of these sections since they are lower than the modeled values.

	Blocaux - Fouil 2	**WinIGS Model**
Rd	0.78	2.601
Xd	2.08	6.280
R0	1.867	6.283
X0	6.79	22.381

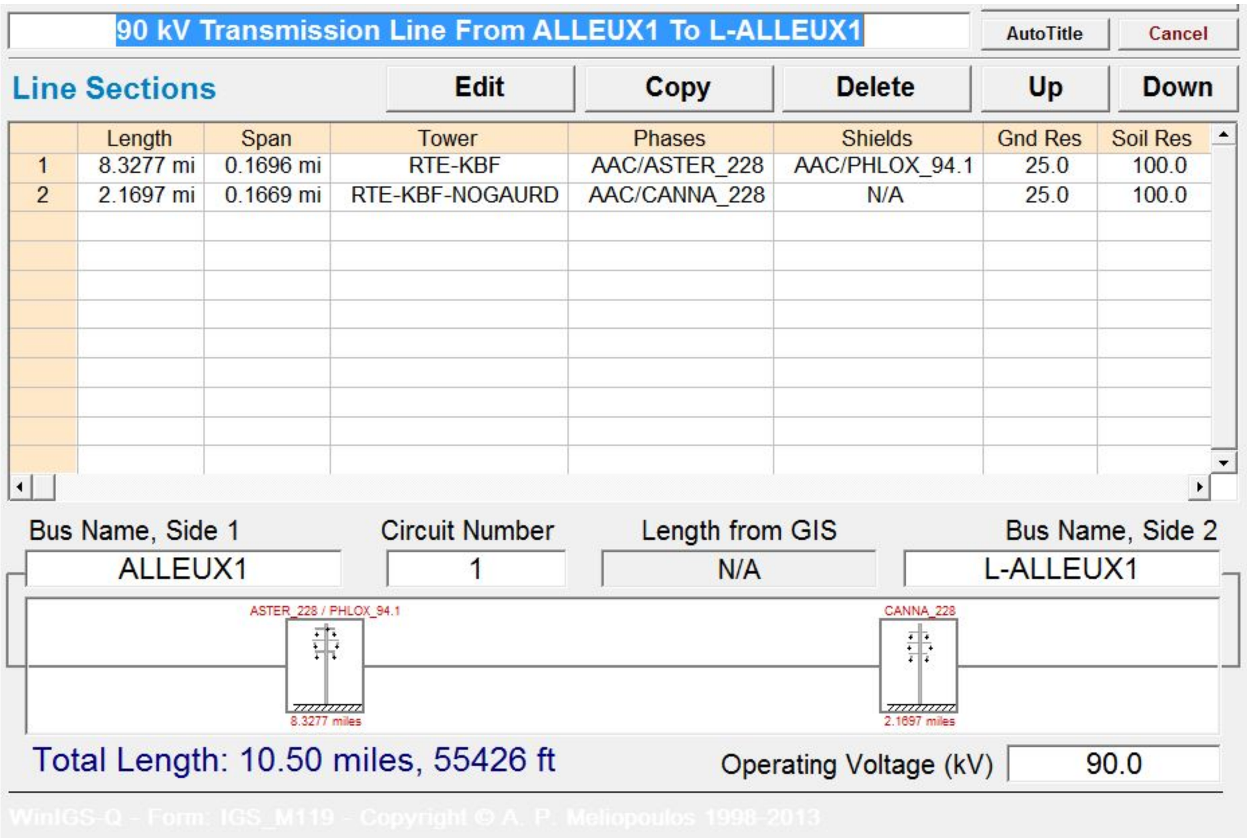


Figure F-7: 90 kV Transmission Line From Alleux1 to L-Alleux1 Parameters

Table below provides a comparison of the modeled line parameters with the provided data.

	Alleux blocaux	**WinIGS Model**
Rd	2.518	2.522
Xd	6.702	6.072
R0	6.672	6.684
X0	21.033	20.689

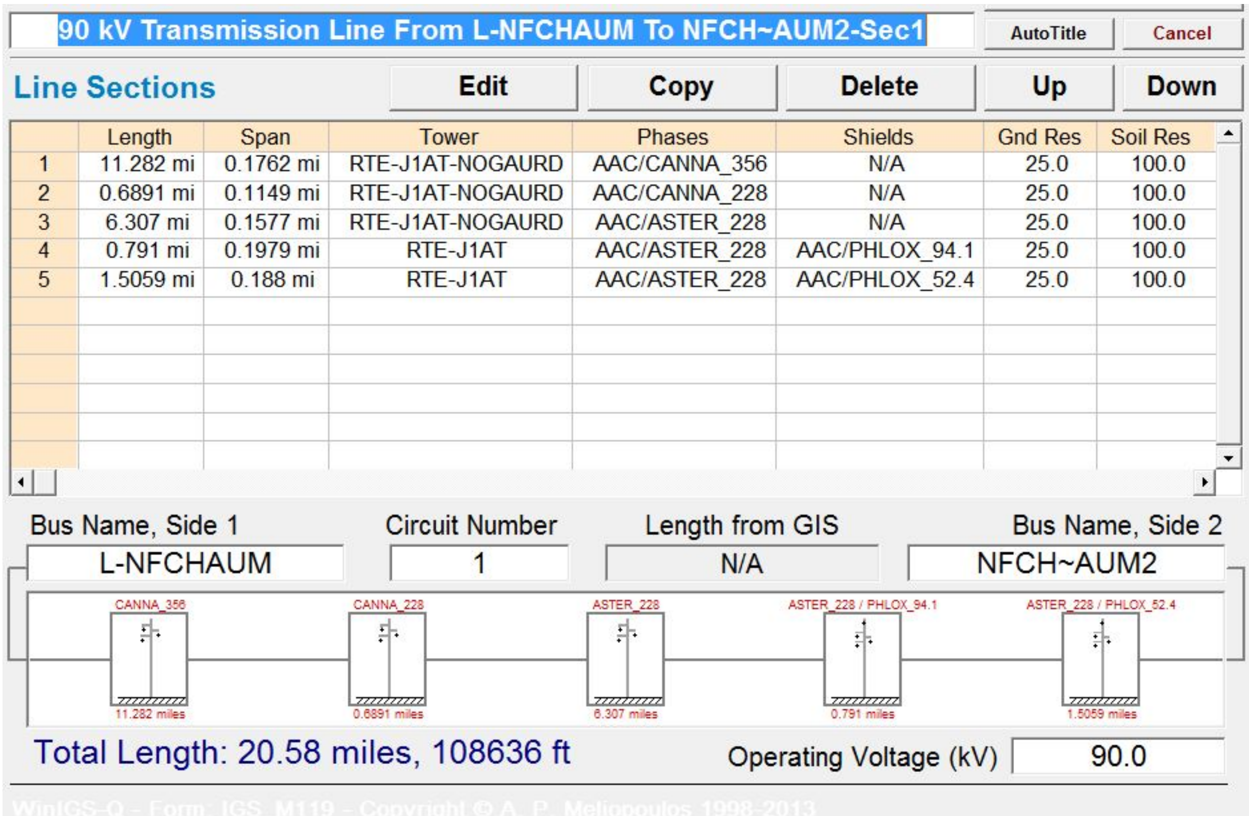


Figure F-8: 90 kV Transmission Line From L-NFCHAUM to NFCH~AUM2 Parameters

Table below provides a comparison of the modeled line parameters with the provided data. Again, since the line has passed a substation on the way to the load, the provided data that is for only one of these sections differs from the the modeled values that are calculated for the line from "Blocaux" substation to the load.

	aumal blocaux	**WinIGS Model**
Rd	0.31	4.024
Xd	0.82	12.392
R0	0.733	9.001
X0	2.685	46.476

Appendix G: Definition of Protection Zones Under Consideration

This Appendix defines four protection zones. These zones are targeted for application of the setting-less protective relay. It should be understood that these zones do not represent all the protection zones of this substation.

Each protection zone is presented in terms of the following:

1. The physical system to be protected. The protection zone is connected to the rest of the system with interrupting devices (breakers).
2. The merging units or data acquisition system that perform measurements at the protection zone. The specific measurements are identified.

Protection Zone 1

This protection zone comprises the 90 kV Cable 1 plus the 225 kV/93 kV/10.5 kV Transformer 641.

The protection zone can be isolated from the system by the breakers: the Breaker 1_1 and Breaker 1_2.

Three merging units (Merging Unit 1, 2 and 8) collect measurements to be fed into the setting-less relay.

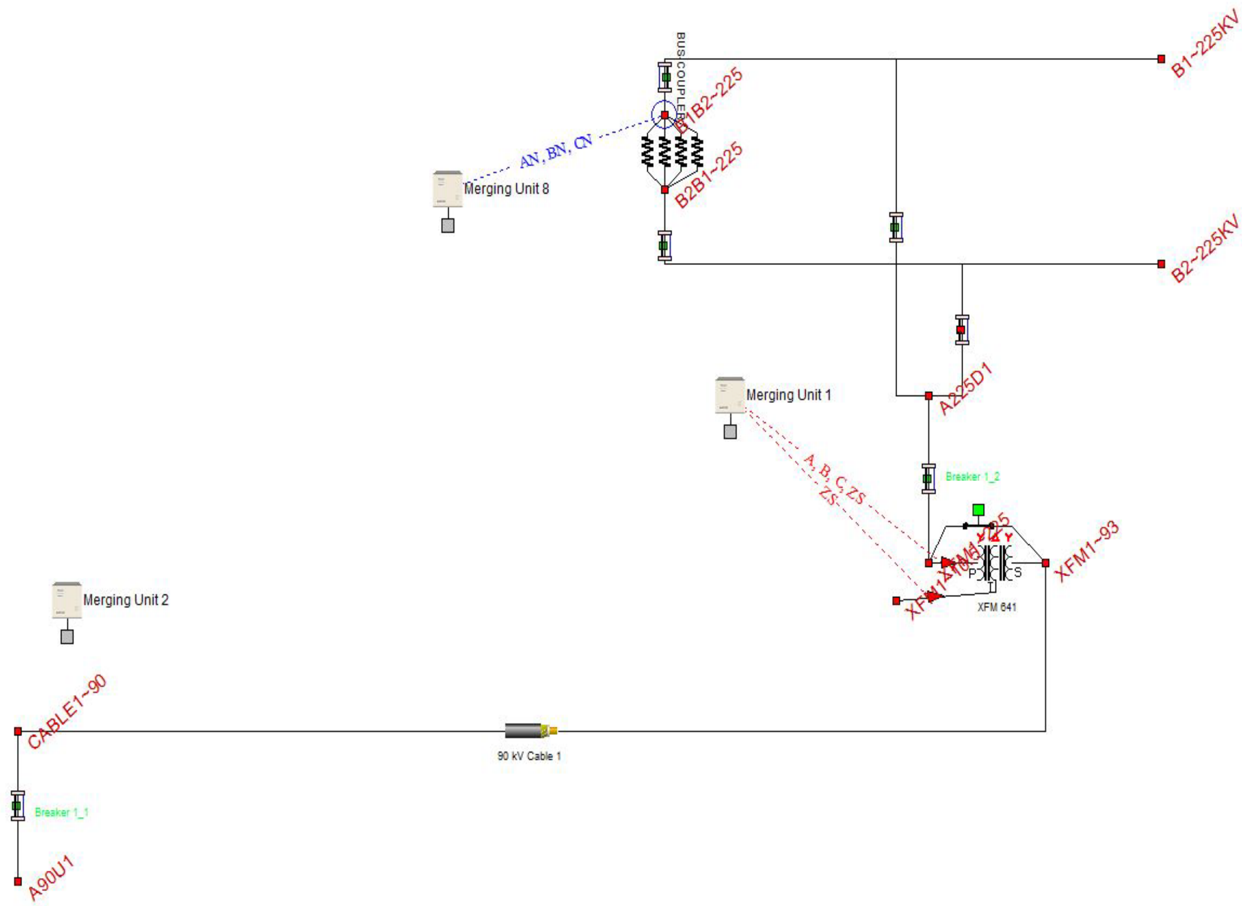


Figure G-1: Protection Zone 1

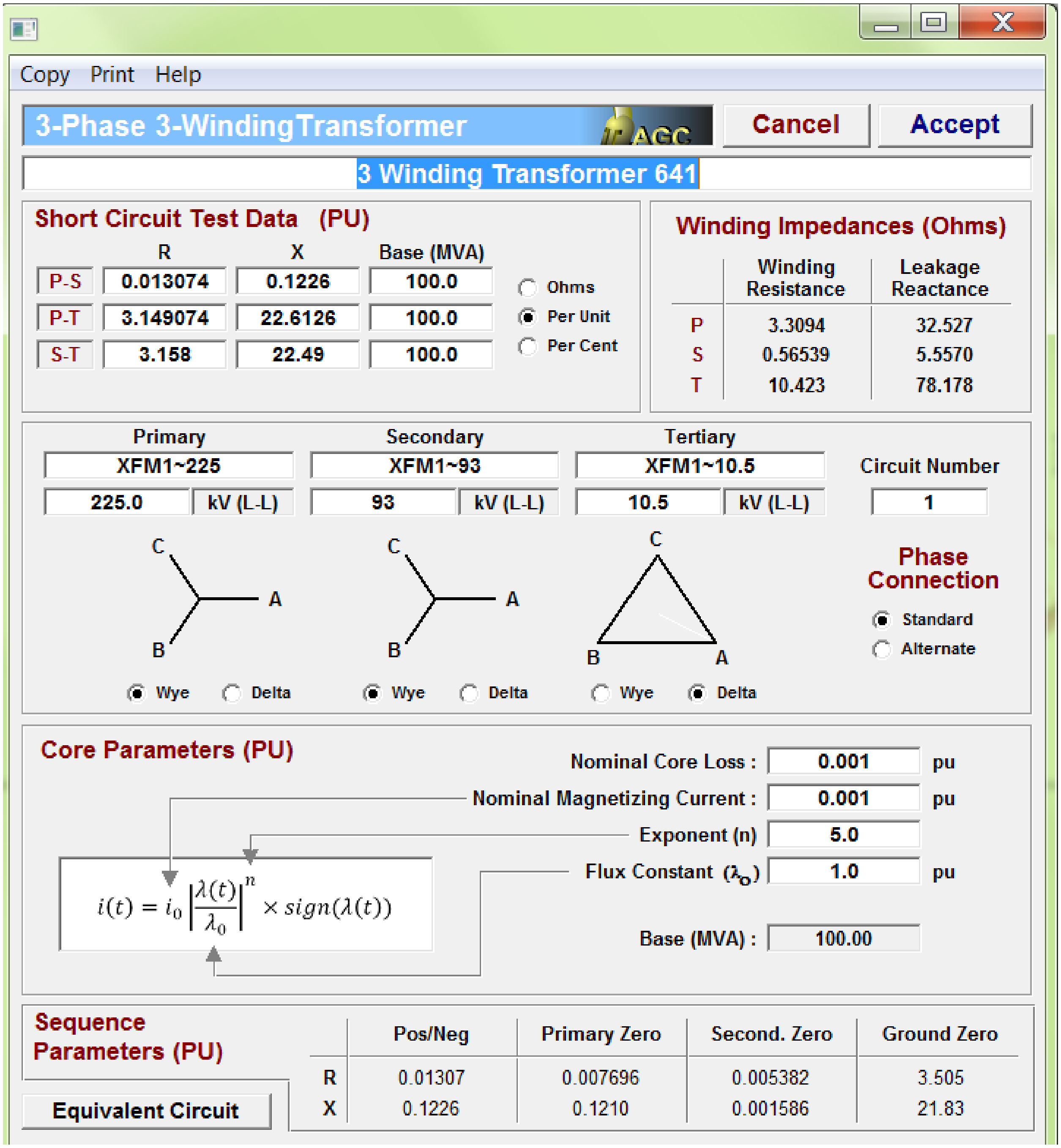


Figure G-2: 225 kV / 93 kV / 10.5 kV Transformer 641 Parameters

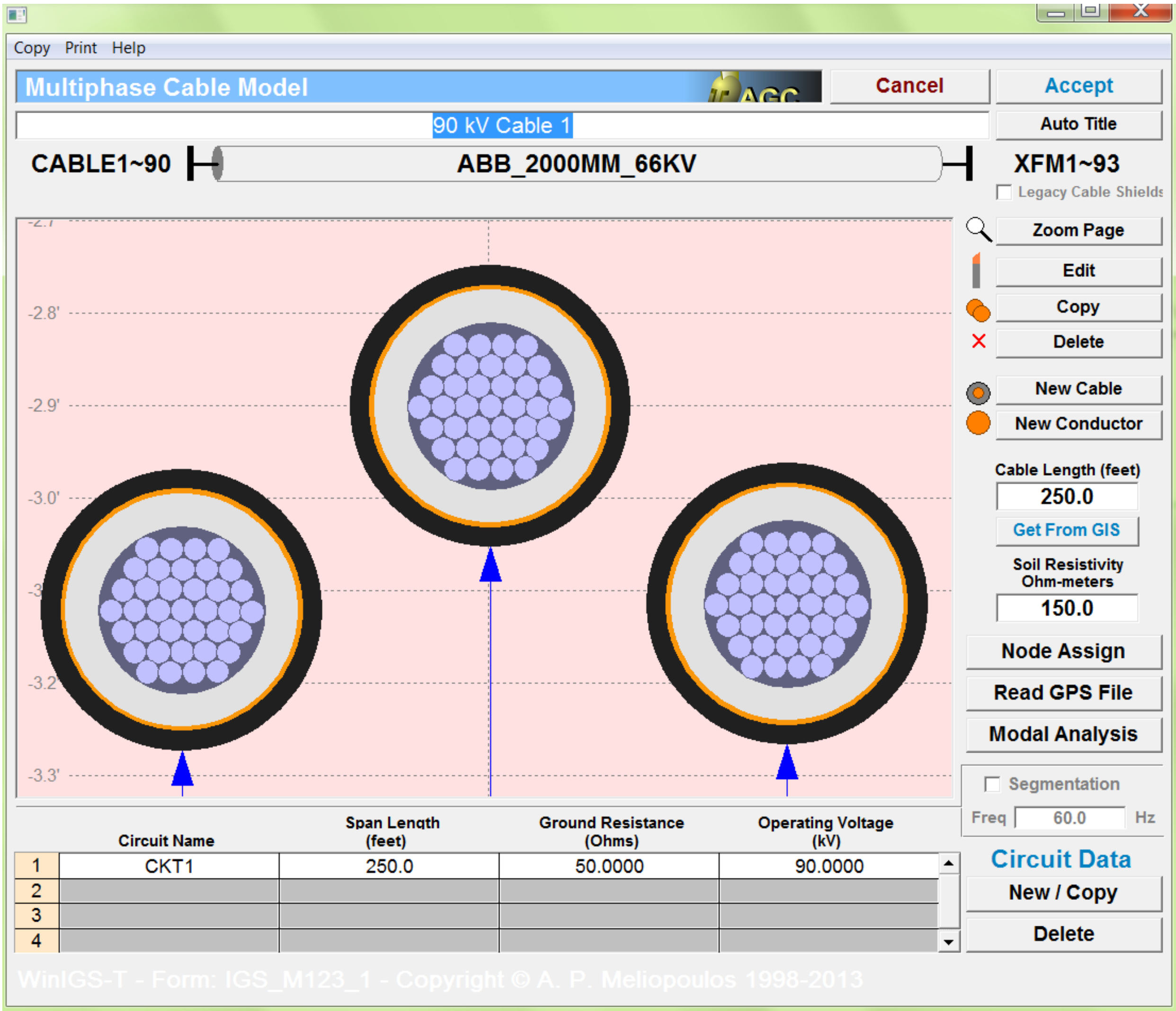


Figure G-3: 90 kV Cable 1 Parameters

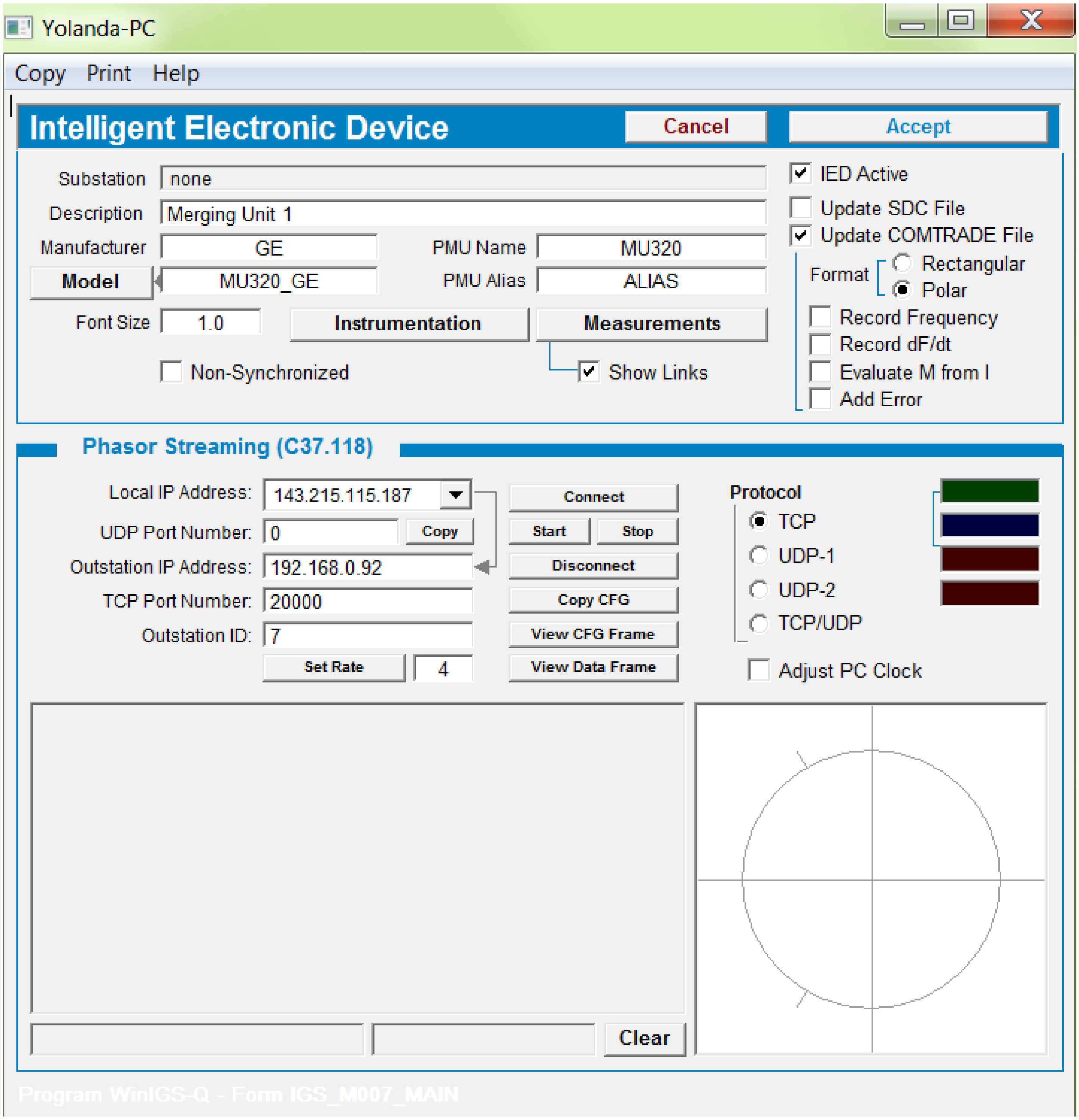


Figure G-4: Merging Unit 1 (Captures the Measurements of 225 kV/93 kV /10.5 kV Transformer 641)

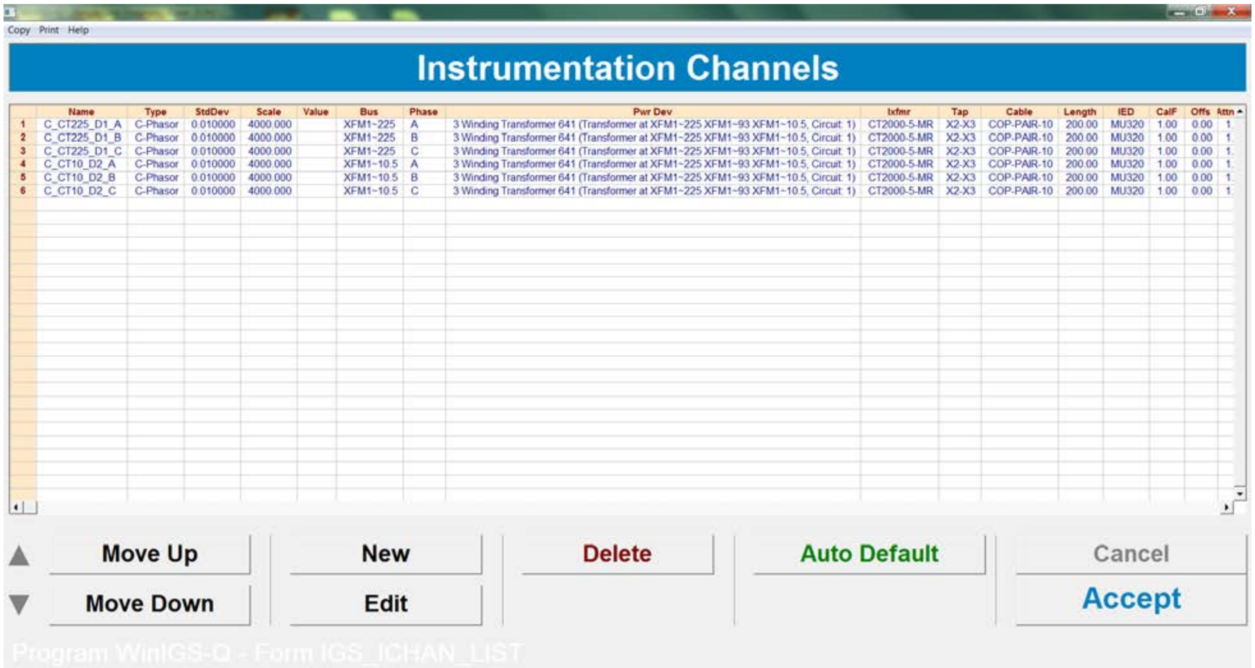


Figure G-5: Instrumentation Channels of Merging Unit 1

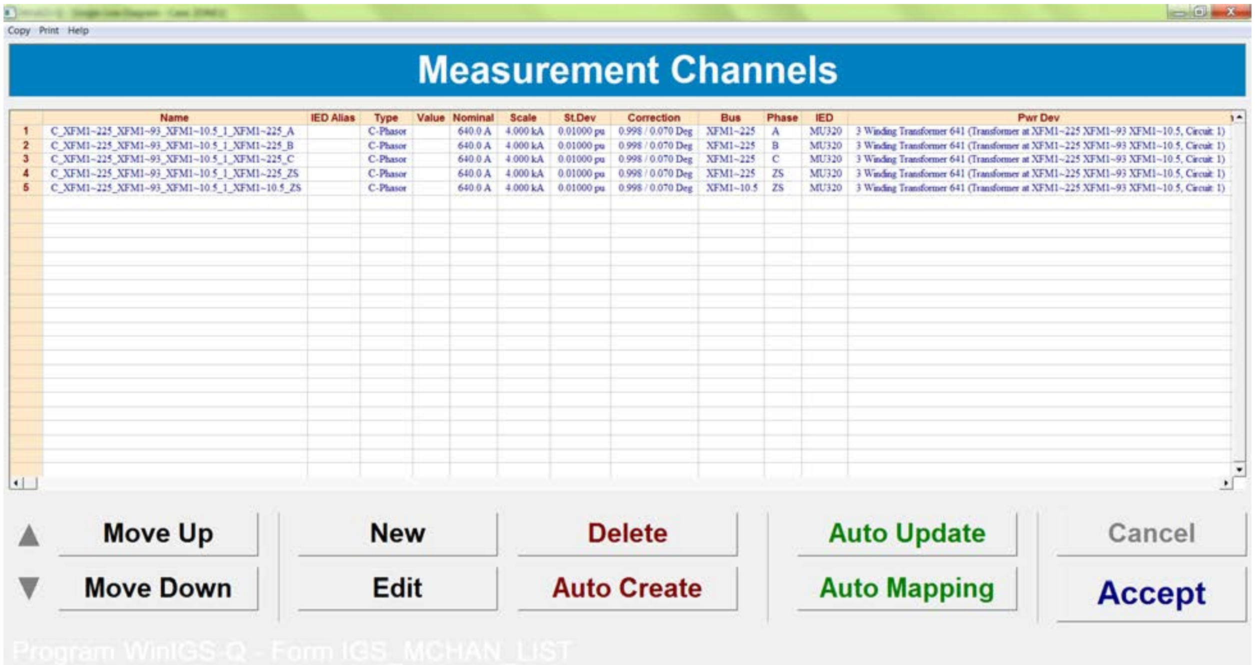


Figure G-6: Measurement Channels of Merging Unit 1

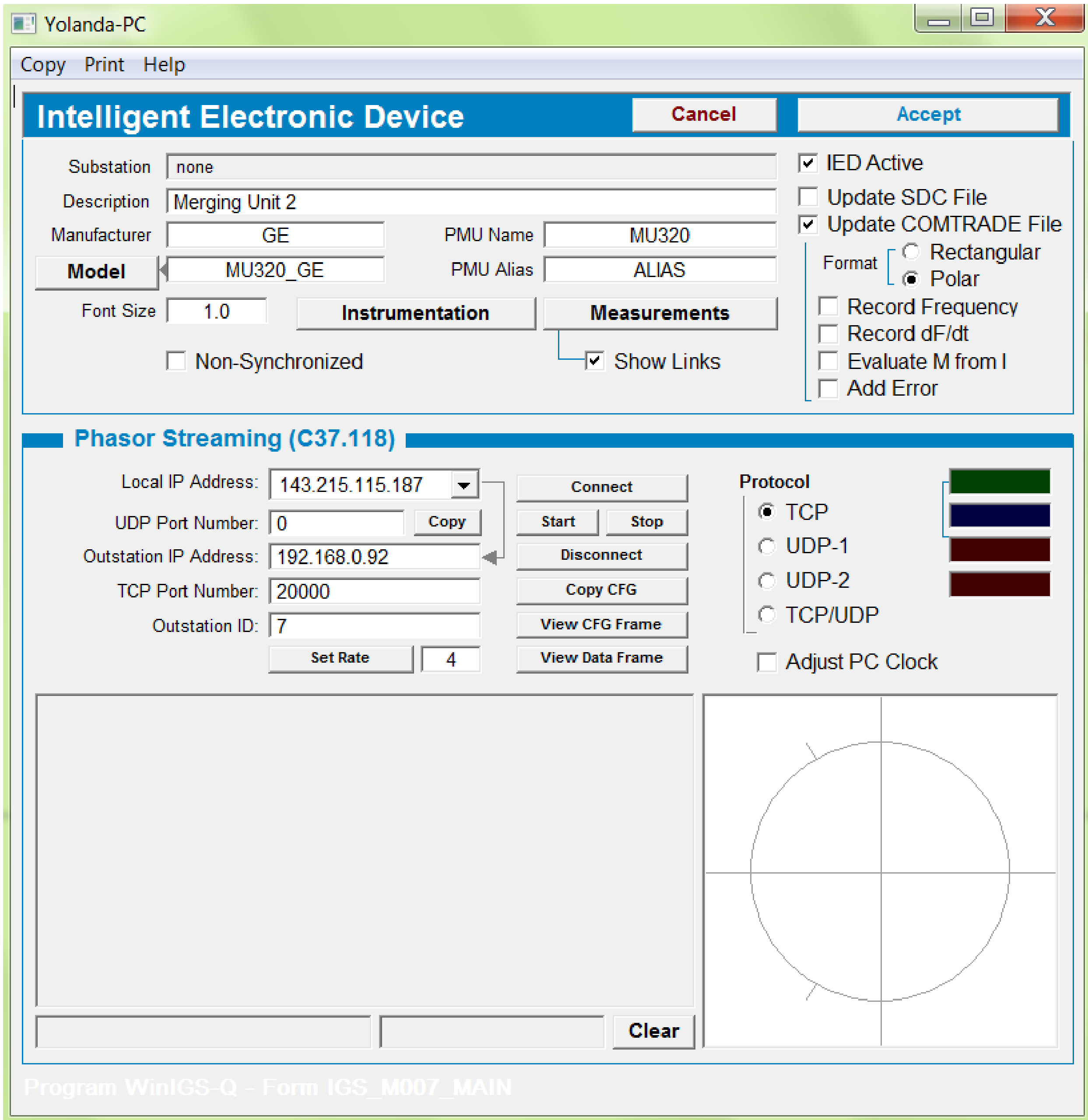
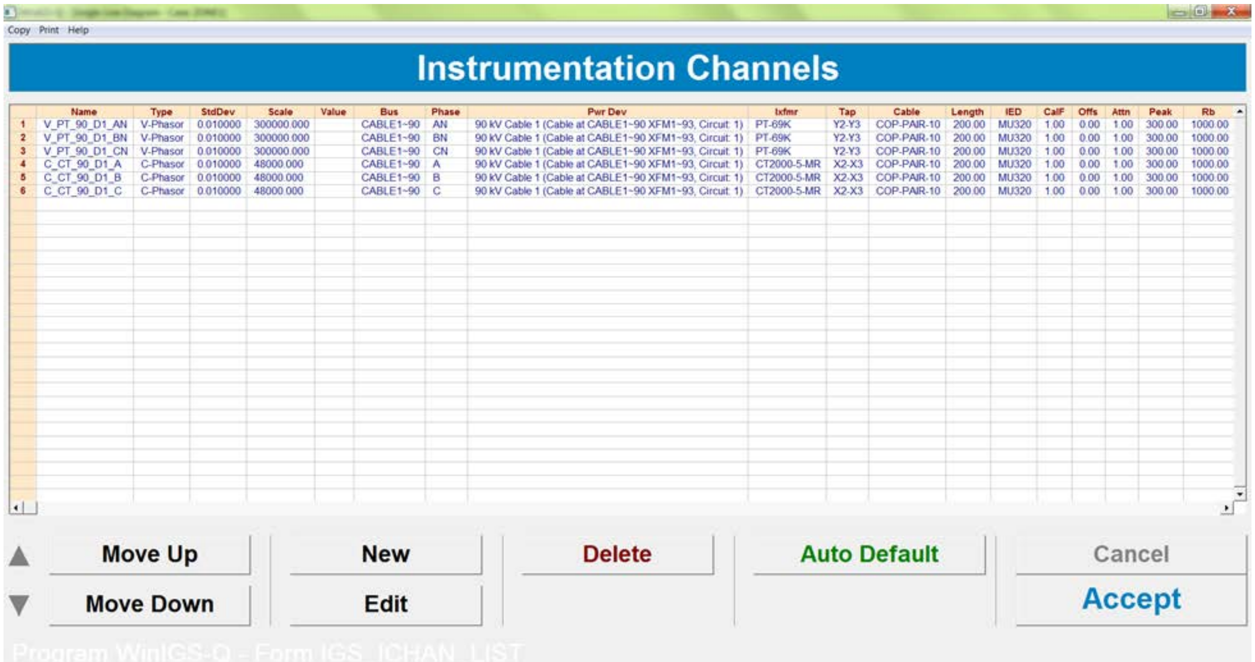
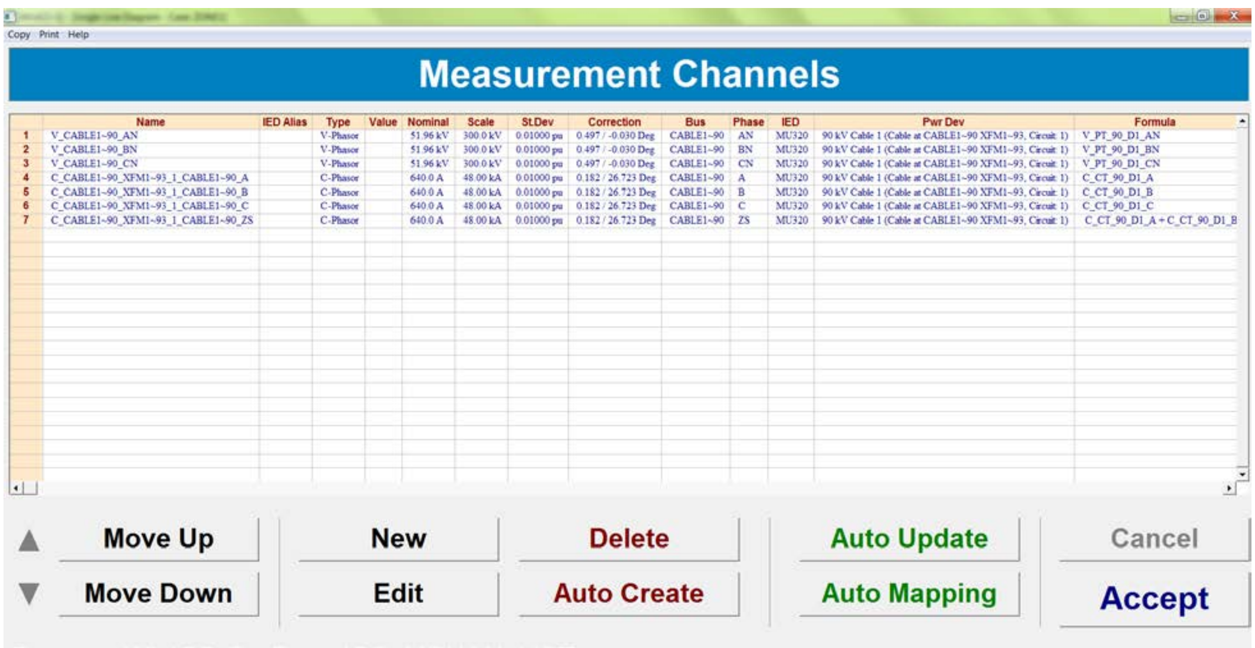


Figure G-7: Merging Unit 2 (Captures the Measurements of 90 kV Cable 1)



	Name	Type	StdDev	Scale	Value	Bus	Phase	Pwr Dev	Ixfmr	Tap	Cable	Length	IED	CalF	Offs	Attn	Peak	Rb
1	V_PT_90_D1_AN	V-Phasor	0.010000	300000.000		CABLE1~90	AN	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
2	V_PT_90_D1_BN	V-Phasor	0.010000	300000.000		CABLE1~90	BN	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
3	V_PT_90_D1_CN	V-Phasor	0.010000	300000.000		CABLE1~90	CN	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
4	C_CT_90_D1_A	C-Phasor	0.010000	48000.000		CABLE1~90	A	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
5	C_CT_90_D1_B	C-Phasor	0.010000	48000.000		CABLE1~90	B	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
6	C_CT_90_D1_C	C-Phasor	0.010000	48000.000		CABLE1~90	C	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00

Figure G-8: Instrumentation Channels of Merging Unit 2



	Name	IED Alias	Type	Value	Nominal	Scale	St.Dev	Correction	Bus	Phase	IED	Pwr Dev	Formula
1	V_CABLE1~90_AN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE1~90	AN	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	V_PT_90_D1_AN
2	V_CABLE1~90_BN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE1~90	BN	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	V_PT_90_D1_BN
3	V_CABLE1~90_CN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE1~90	CN	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	V_PT_90_D1_CN
4	C_CABLE1~90_XFM1~93_1_CABLE1~90_A		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE1~90	A	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	C_CT_90_D1_A
5	C_CABLE1~90_XFM1~93_1_CABLE1~90_B		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE1~90	B	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	C_CT_90_D1_B
6	C_CABLE1~90_XFM1~93_1_CABLE1~90_C		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE1~90	C	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	C_CT_90_D1_C
7	C_CABLE1~90_XFM1~93_1_CABLE1~90_ZS		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE1~90	ZS	MU320	90 kV Cable 1 (Cable at CABLE1~90 XFM1~93, Circuit: 1)	C_CT_90_D1_A + C_CT_90_D1_B

Figure G-9: Measurement Channels of Merging Unit 2

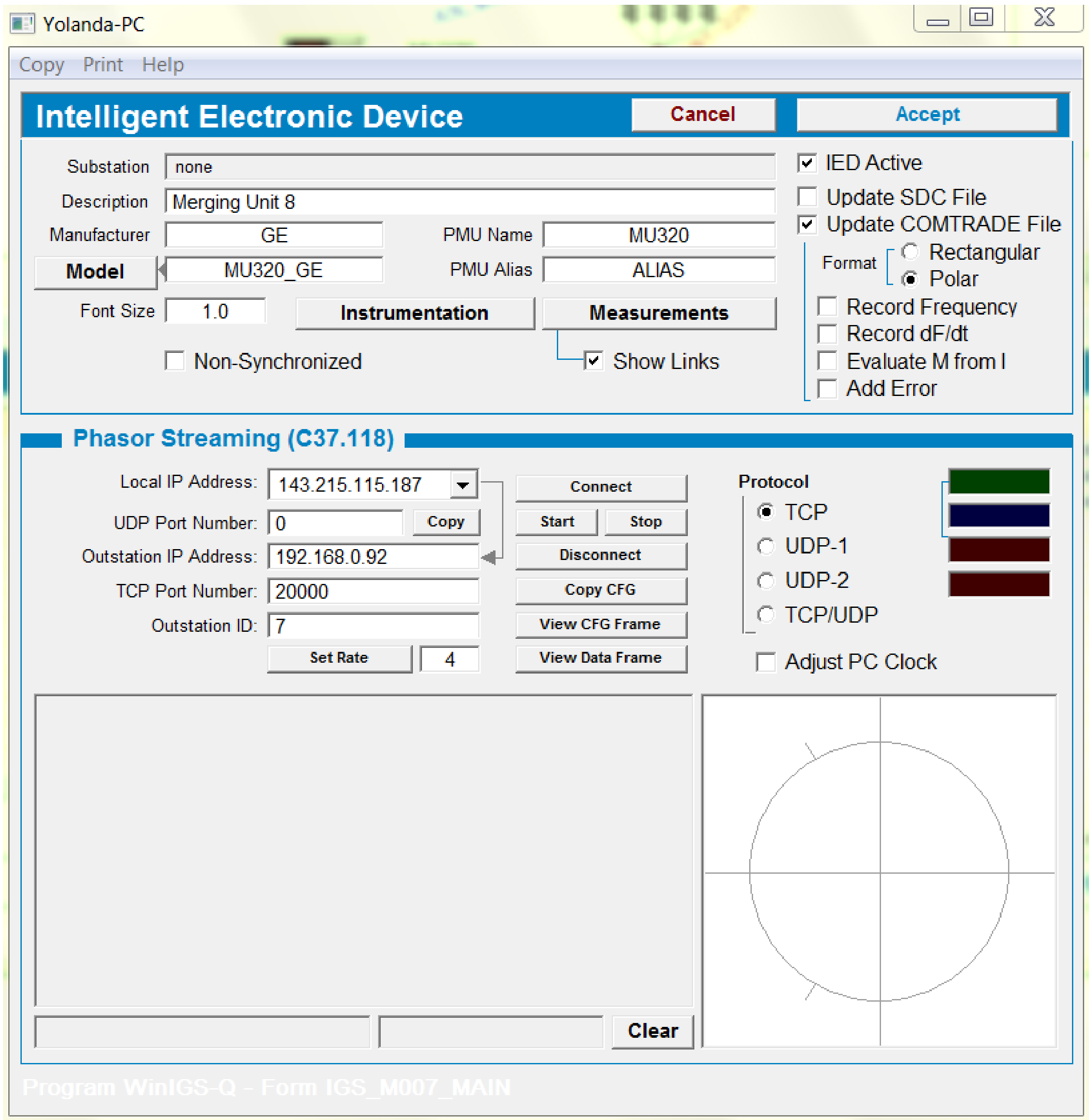


Figure G-10: Merging Unit 8 (Captures the Voltage Measurements of Bus B1B2~225 kV)

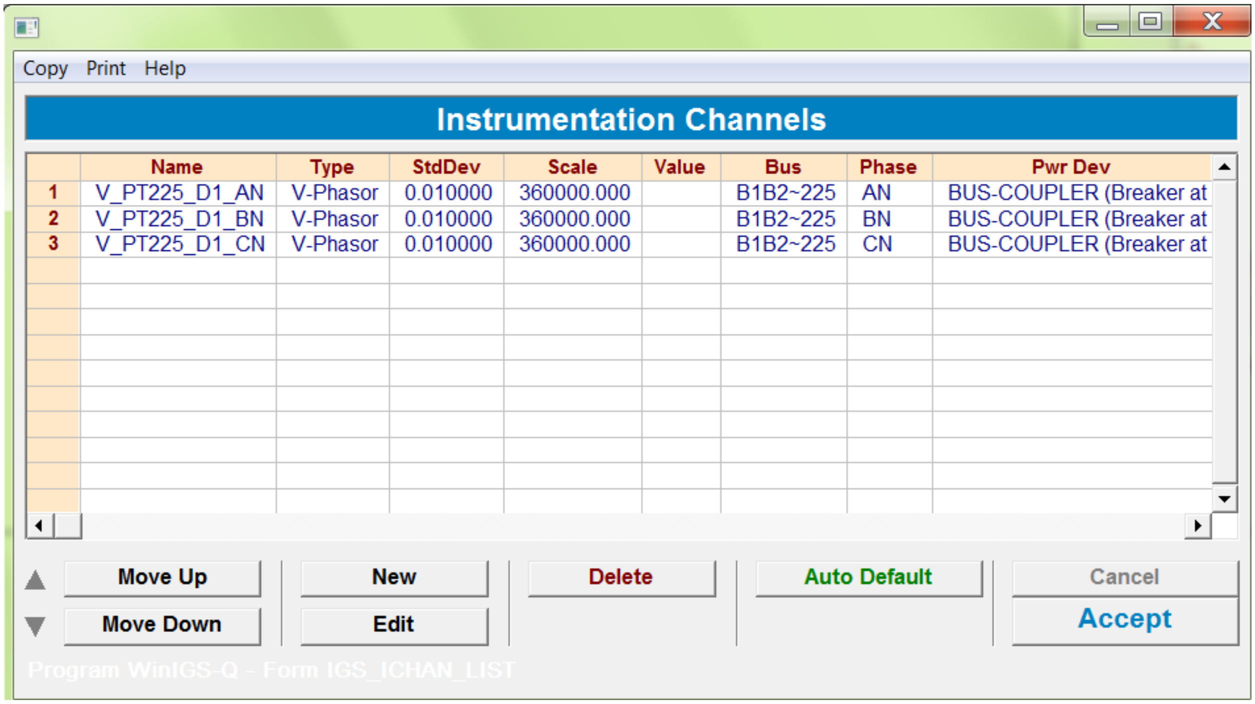


Figure G-11: Instrumentation Channels of Merging Unit 8

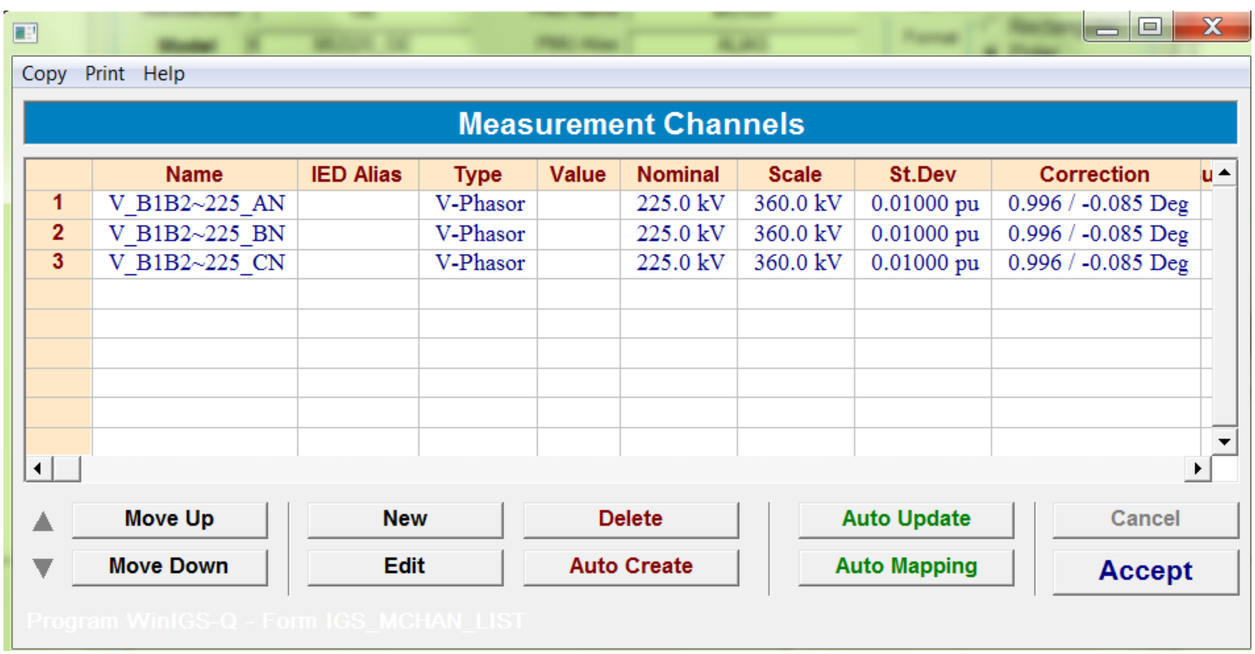


Figure G-12: Measurement Channels of Merging Unit 8

Protection Zone 2

This protection zone comprises the 90 kV Cable 2 plus the 225 kV/93 kV/9.9 kV Transformer 642.

The protection zone can be isolated from the system by the breakers: the Breaker 2_1 and Breaker 2_2.

Three merging units (Merging Unit 3, 4 and 8) collect measurements to be fed into the setting-less relay.

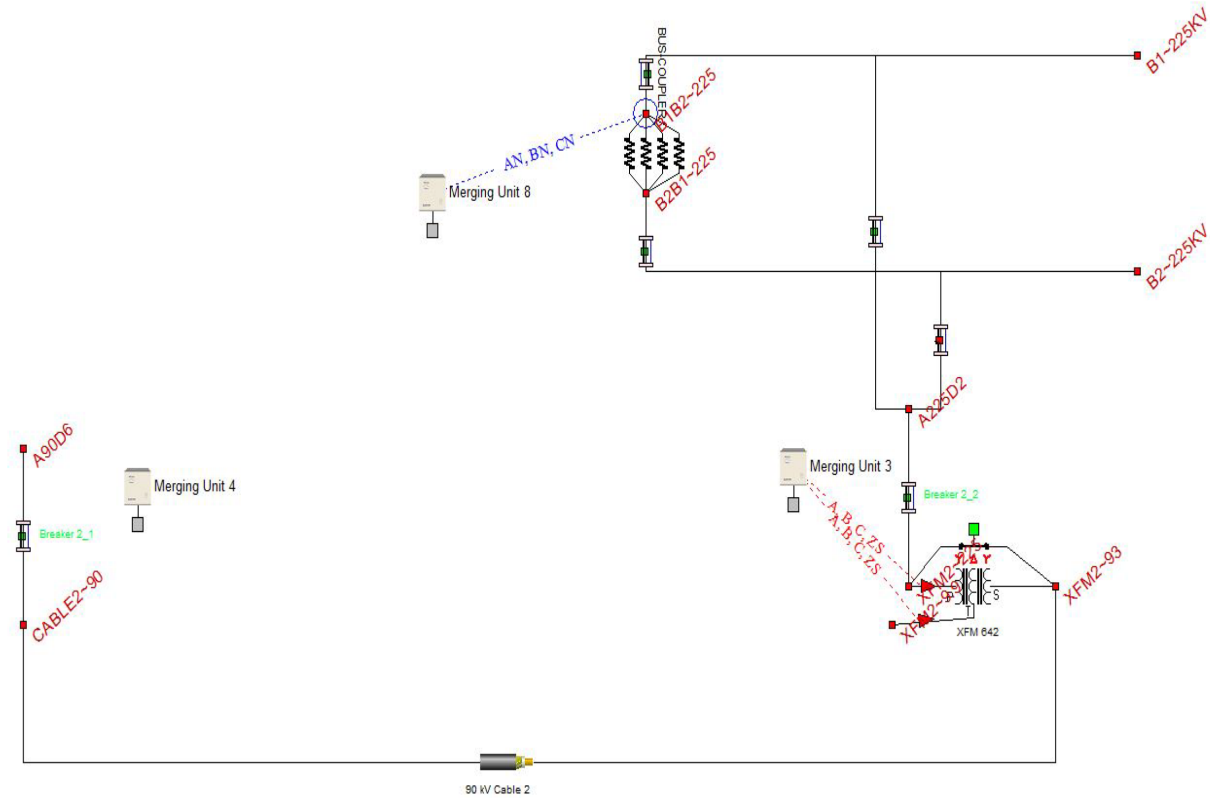


Figure G-13: Protection Zone 2

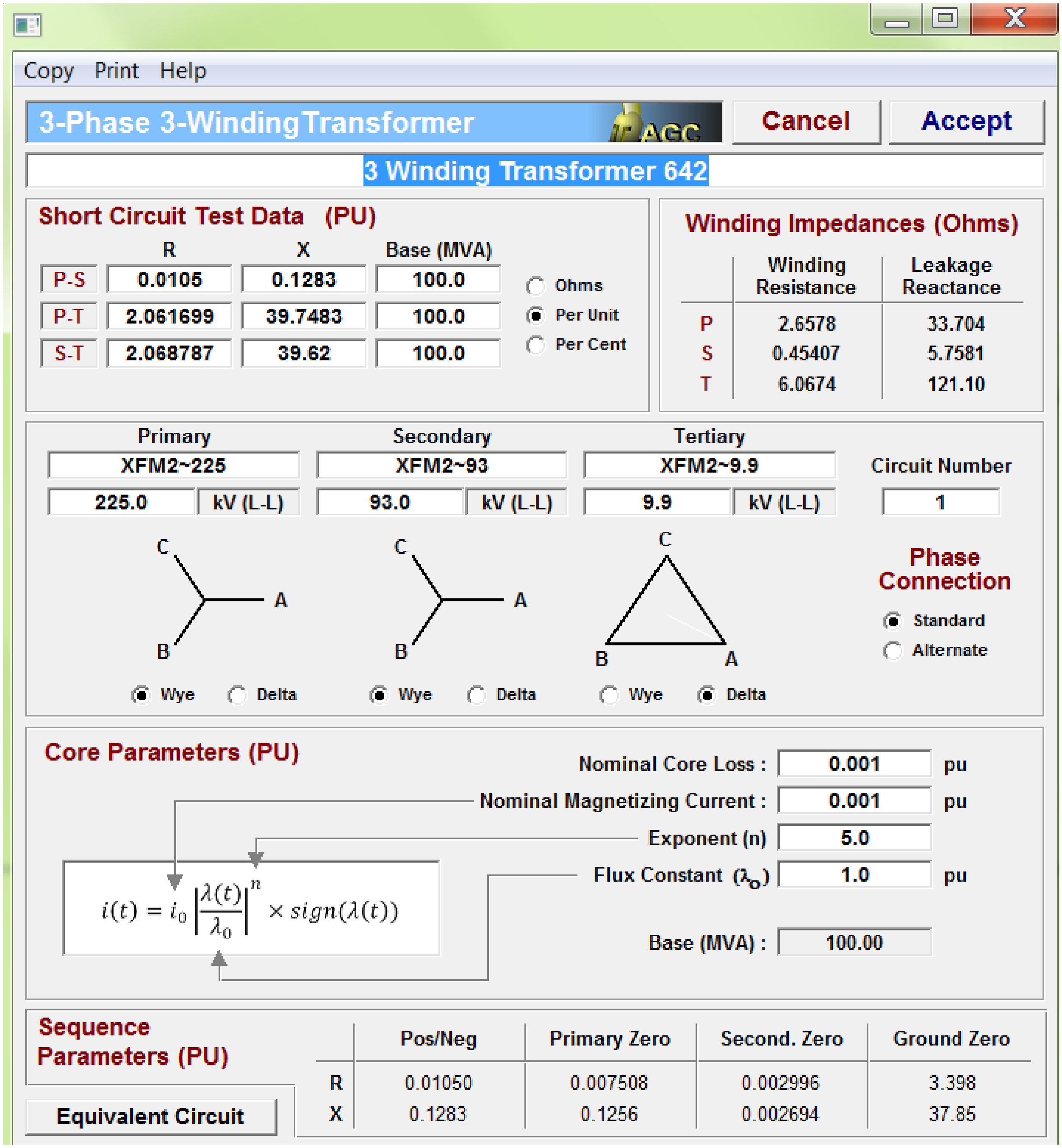


Figure G-14: 225 kV / 93 kV Transformer 642 Parameters

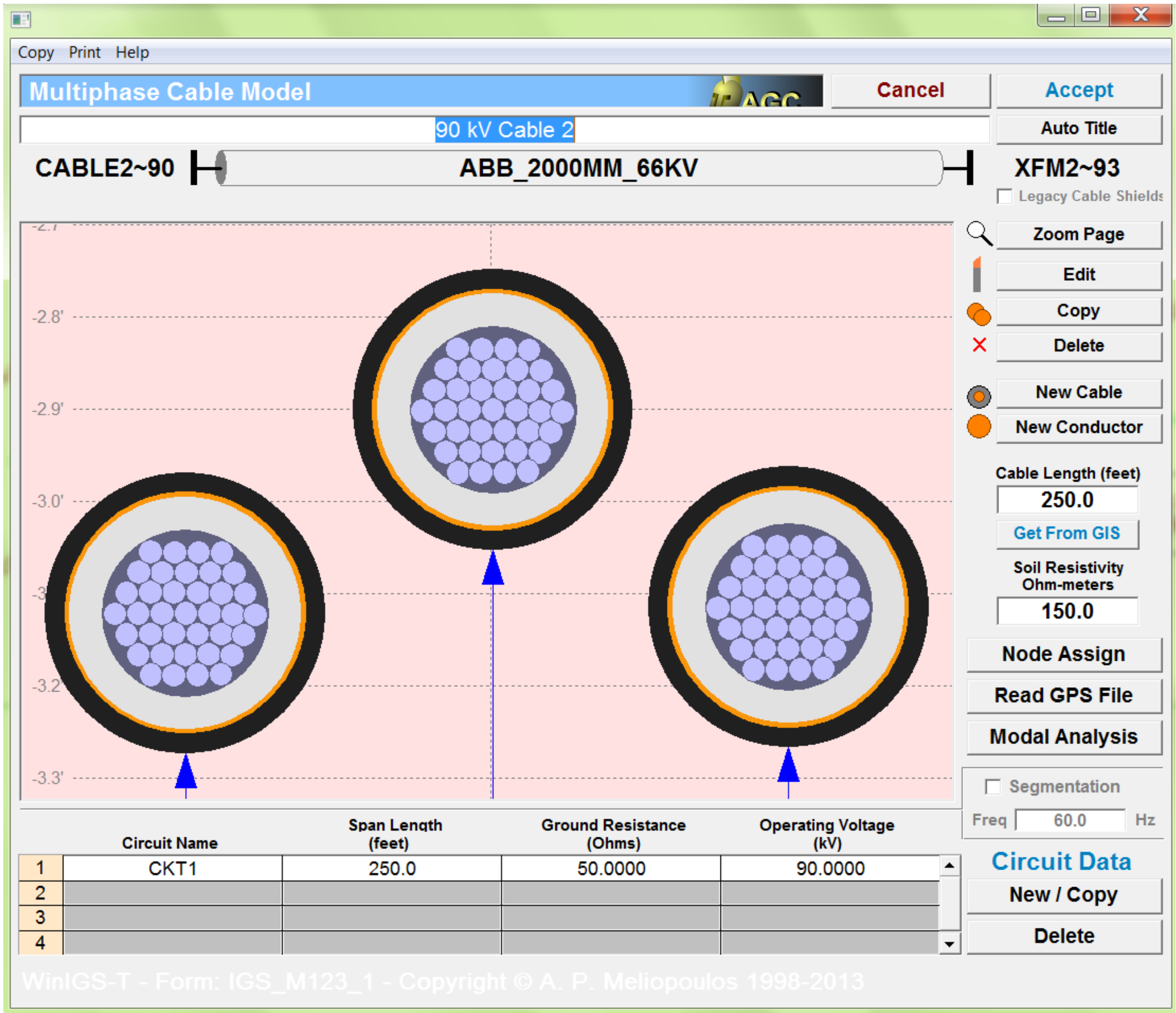


Figure G-15: 90 kV Cable 2 Parameters

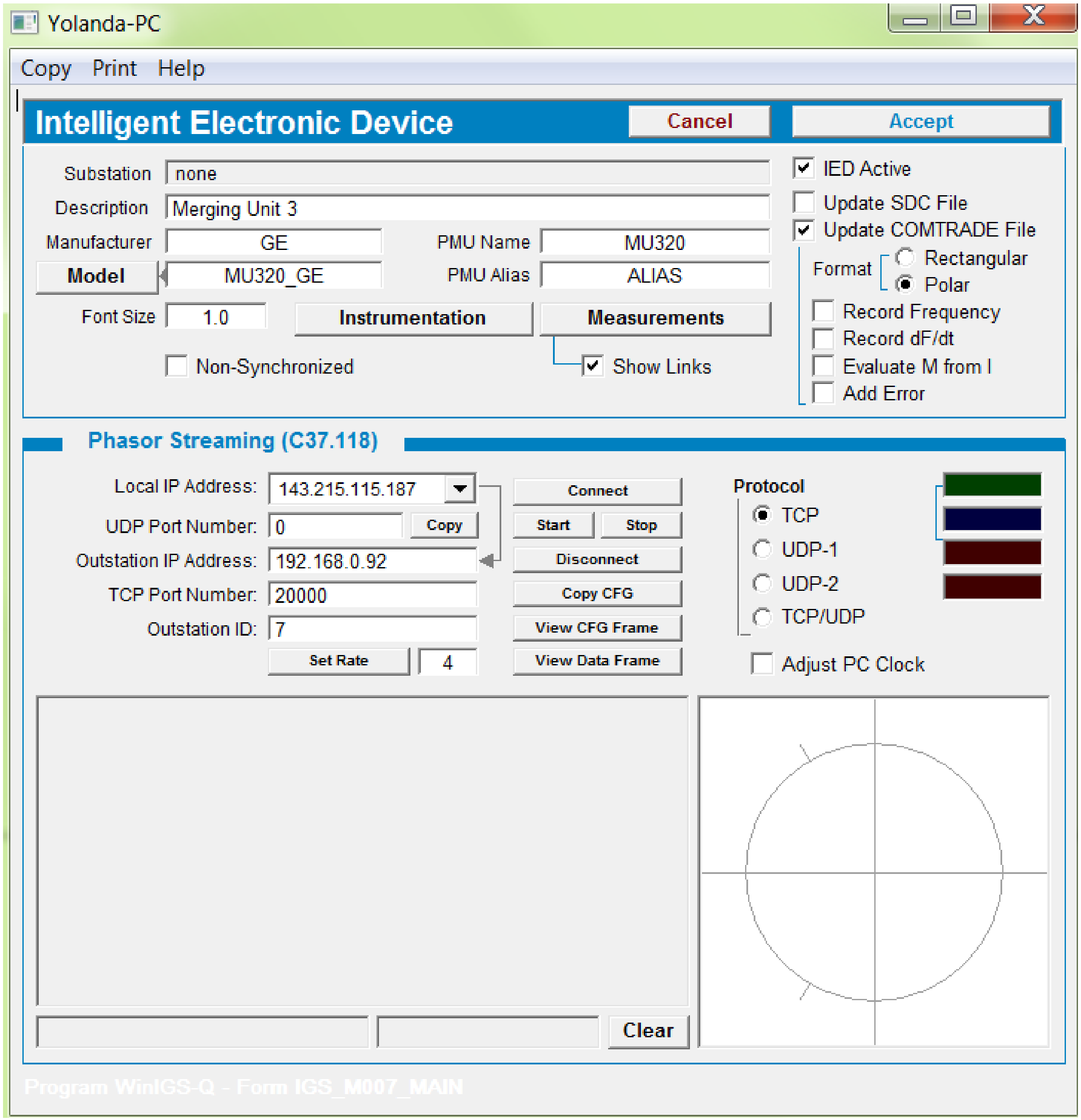


Figure G-16: Merging Unit 3 (Captures the Measurements of 225 kV/93 kV Transformer 642)

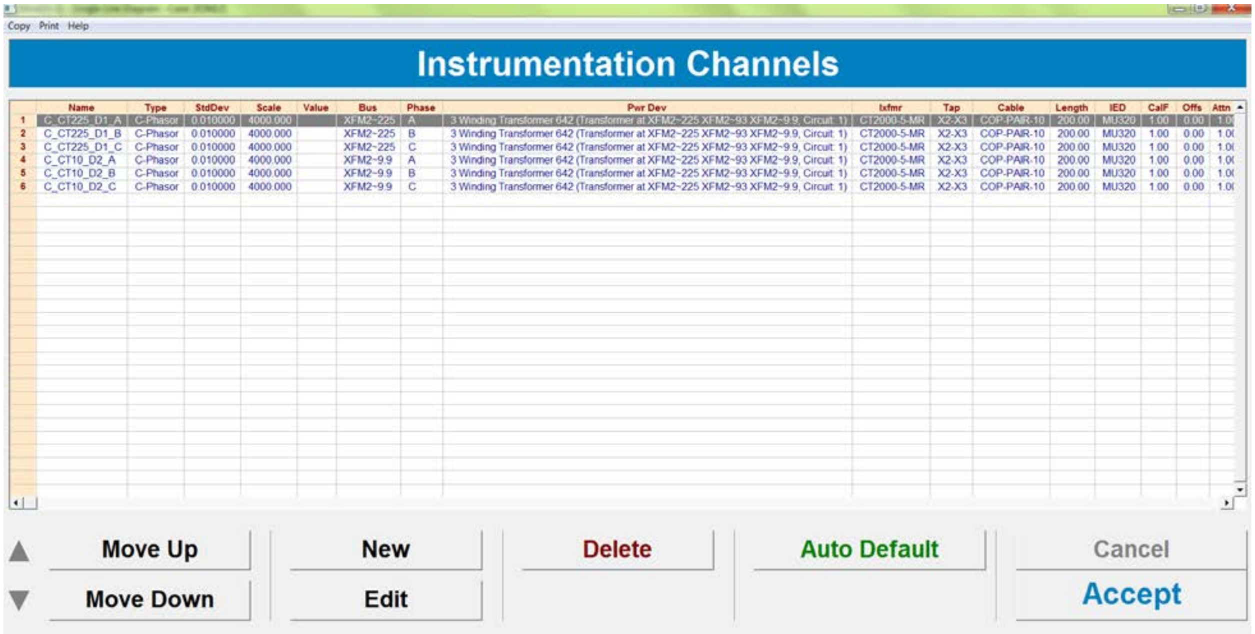


Figure G-17: Instrumentation Channels of Merging Unit 3

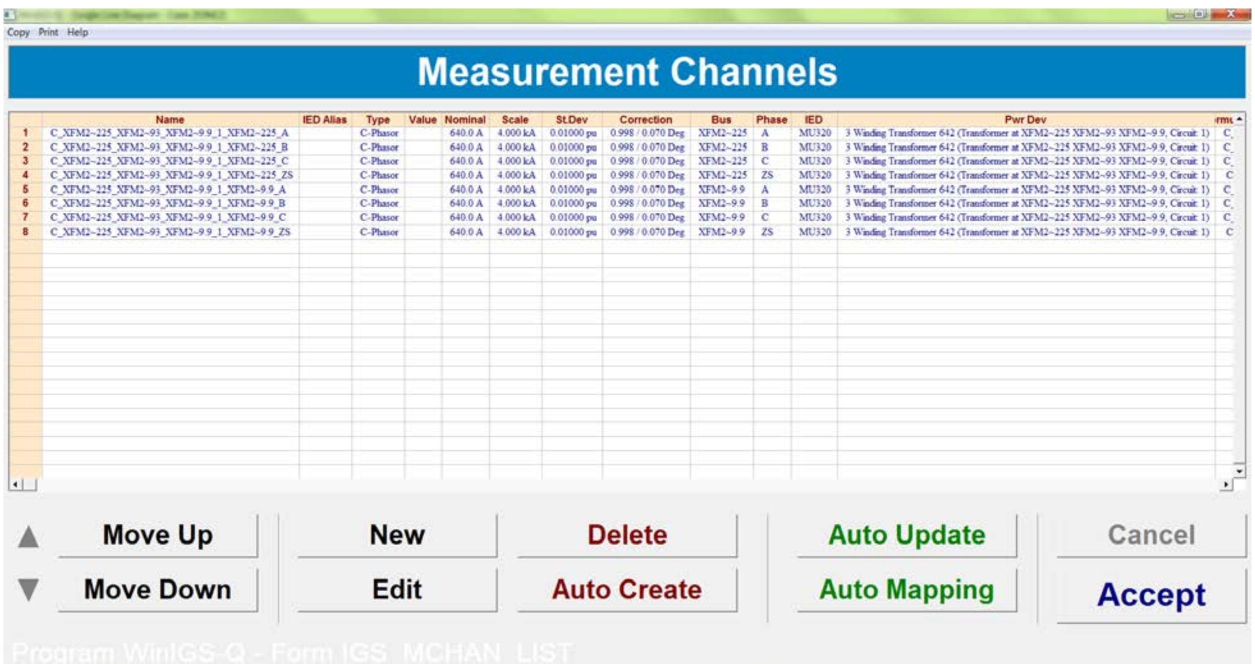


Figure G-18: Measurement Channels of Merging Unit 3

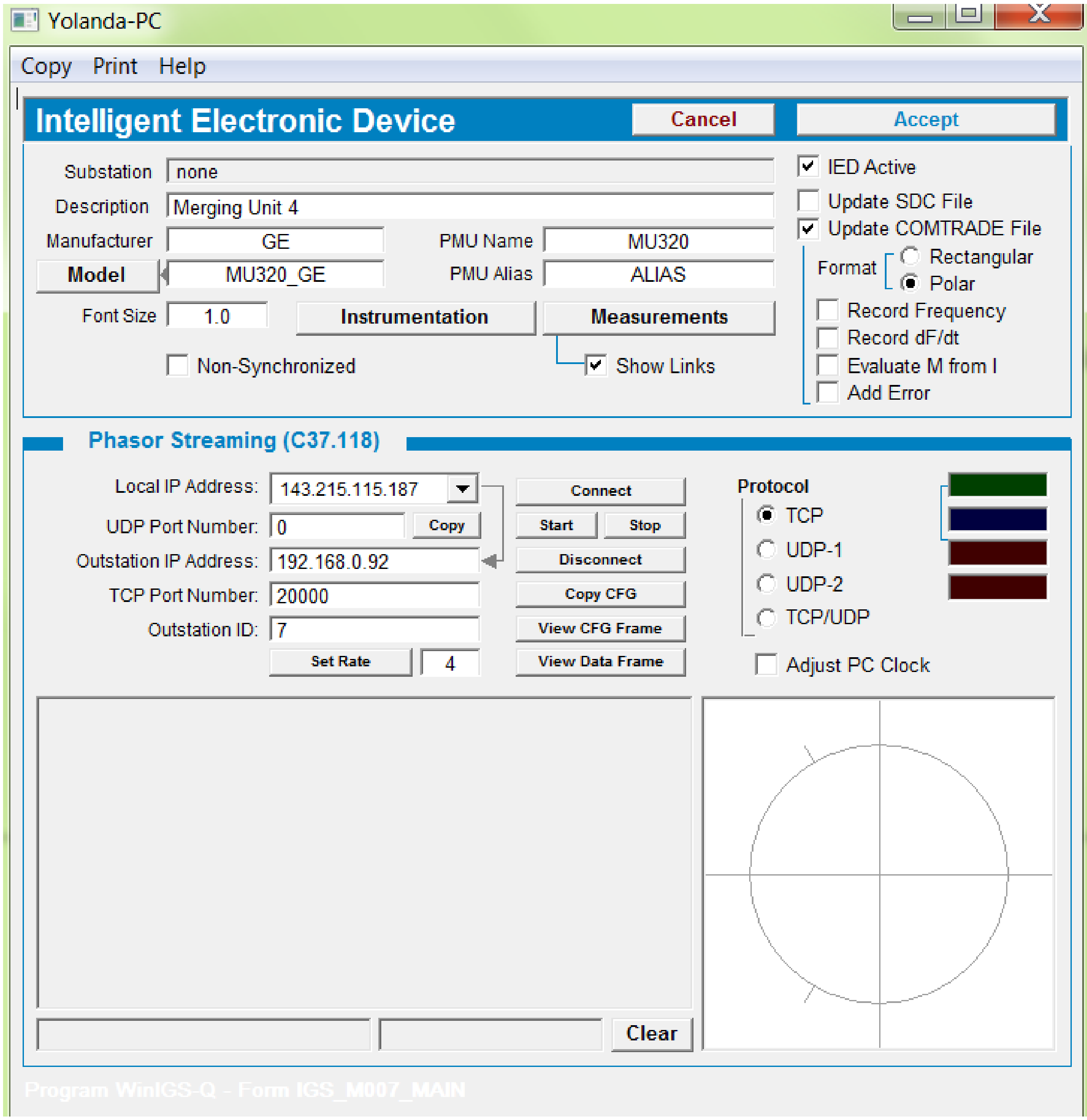
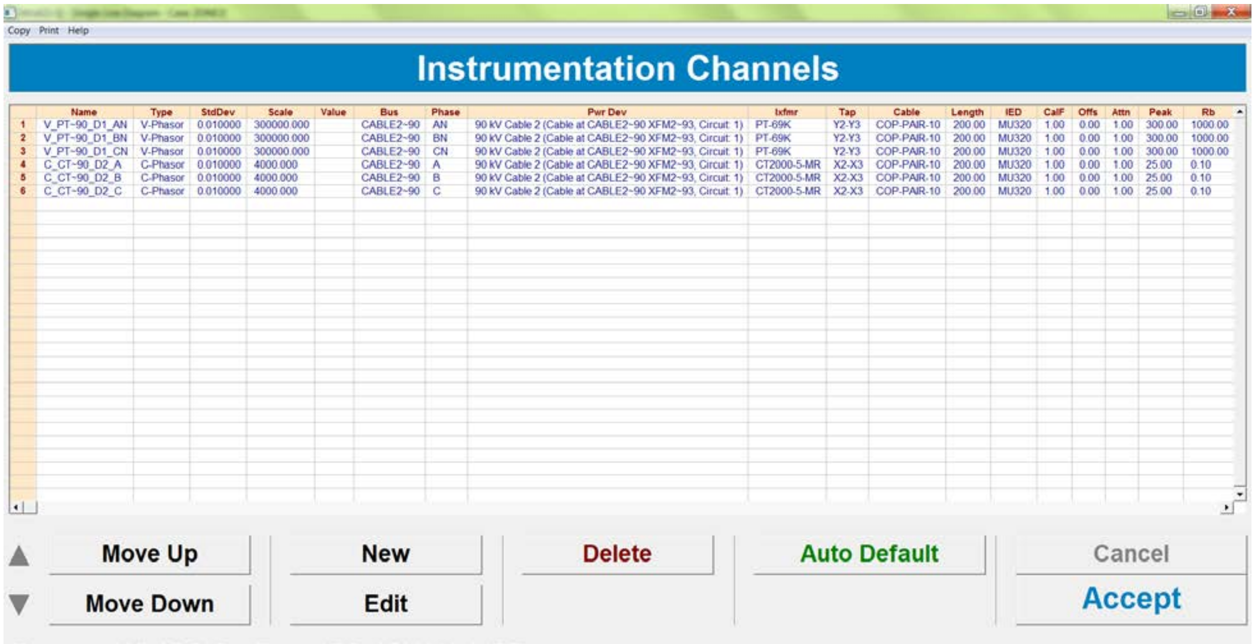


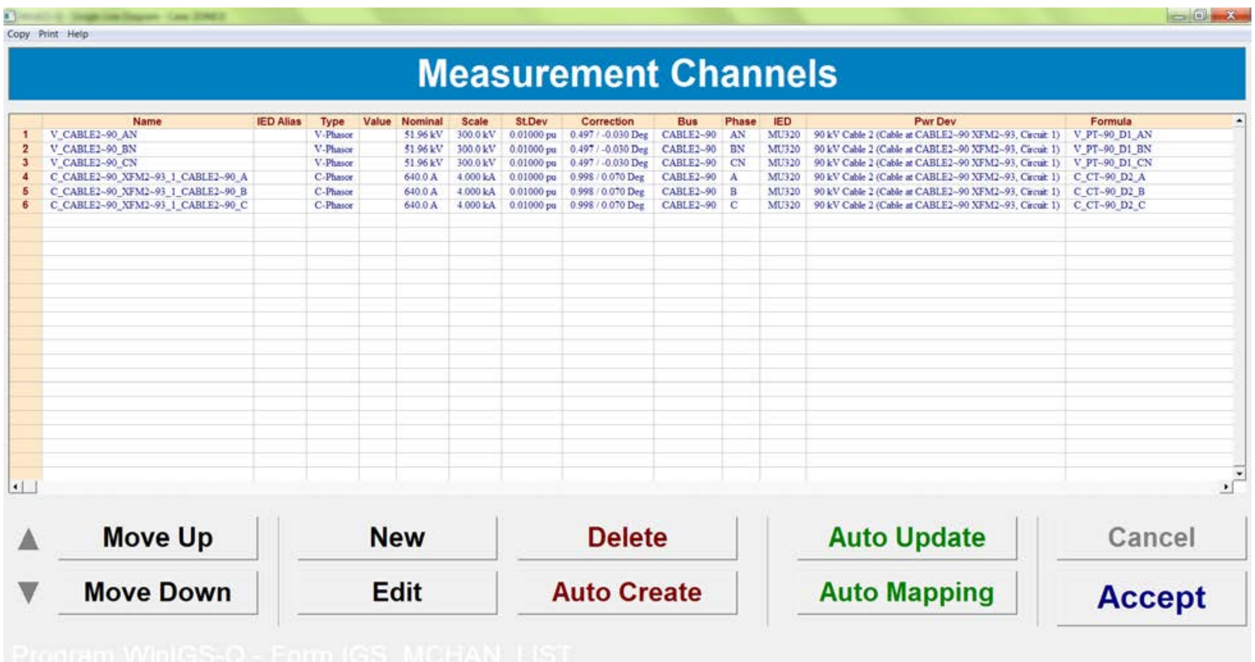
Figure G-19: Merging Unit 4 (Captures the Measurements of 90 kV Cable 2)



Instrumentation Channels

	Name	Type	StdDev	Scale	Value	Bus	Phase	Pwr Dev	Ixfmr	Tap	Cable	Length	IED	CalF	Offs	Attn	Peak	Rb
1	V_PT~90_D1_AN	V-Phasor	0.010000	300000.000		CABLE2~90	AN	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
2	V_PT~90_D1_BN	V-Phasor	0.010000	300000.000		CABLE2~90	BN	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
3	V_PT~90_D1_CN	V-Phasor	0.010000	300000.000		CABLE2~90	CN	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
4	C_CT~90_D2_A	C-Phasor	0.010000	4000.000		CABLE2~90	A	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	25.00	0.10
5	C_CT~90_D2_B	C-Phasor	0.010000	4000.000		CABLE2~90	B	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	25.00	0.10
6	C_CT~90_D2_C	C-Phasor	0.010000	4000.000		CABLE2~90	C	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	25.00	0.10

Figure G-20: Instrumentation Channels of Merging Unit 4



Measurement Channels

	Name	IED Alias	Type	Value	Nominal	Scale	St.Dev	Correction	Bus	Phase	IED	Pwr Dev	Formula
1	V_CABLE2~90_AN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE2~90	AN	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	V_PT~90_D1_AN
2	V_CABLE2~90_BN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE2~90	BN	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	V_PT~90_D1_BN
3	V_CABLE2~90_CN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE2~90	CN	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	V_PT~90_D1_CN
4	C_CABLE2~90_XFM2~93_1_CABLE2~90_A		C-Phasor		640.0 A	4.000 kA	0.01000 pu	0.998 / 0.070 Deg	CABLE2~90	A	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	C_CT~90_D2_A
5	C_CABLE2~90_XFM2~93_1_CABLE2~90_B		C-Phasor		640.0 A	4.000 kA	0.01000 pu	0.998 / 0.070 Deg	CABLE2~90	B	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	C_CT~90_D2_B
6	C_CABLE2~90_XFM2~93_1_CABLE2~90_C		C-Phasor		640.0 A	4.000 kA	0.01000 pu	0.998 / 0.070 Deg	CABLE2~90	C	MU320	90 kV Cable 2 (Cable at CABLE2~90 XFM2~93, Circuit 1)	C_CT~90_D2_C

Figure G-21: Measurement Channels of Merging Unit 4

Protection Zone 3

This protection zone comprises the 90 kV Cable 3 plus the 225 kV/93 kV/10.0 kV Transformer 643.

The protection zone can be isolated from the system by the breakers: the Breaker 3_1 and Breaker 3_2.

Three merging units (Merging Unit 5, 6 and 8) collect measurements to be fed into the setting-less relay.

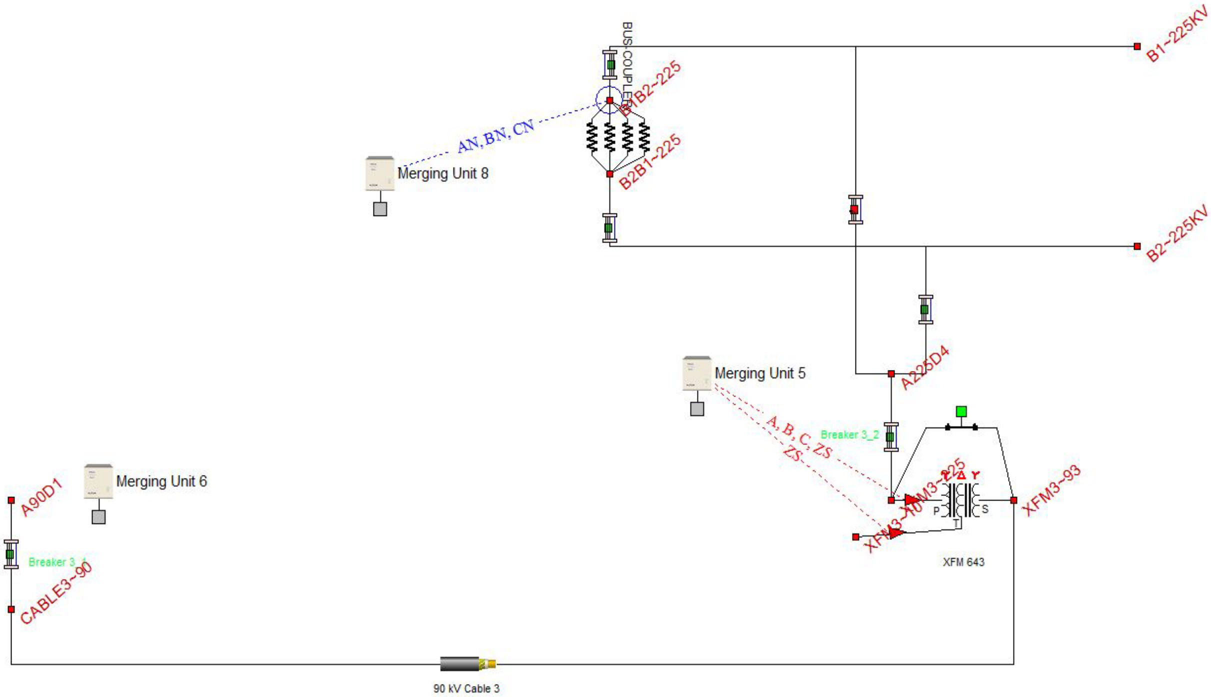


Figure G-22: Protection Zone 3

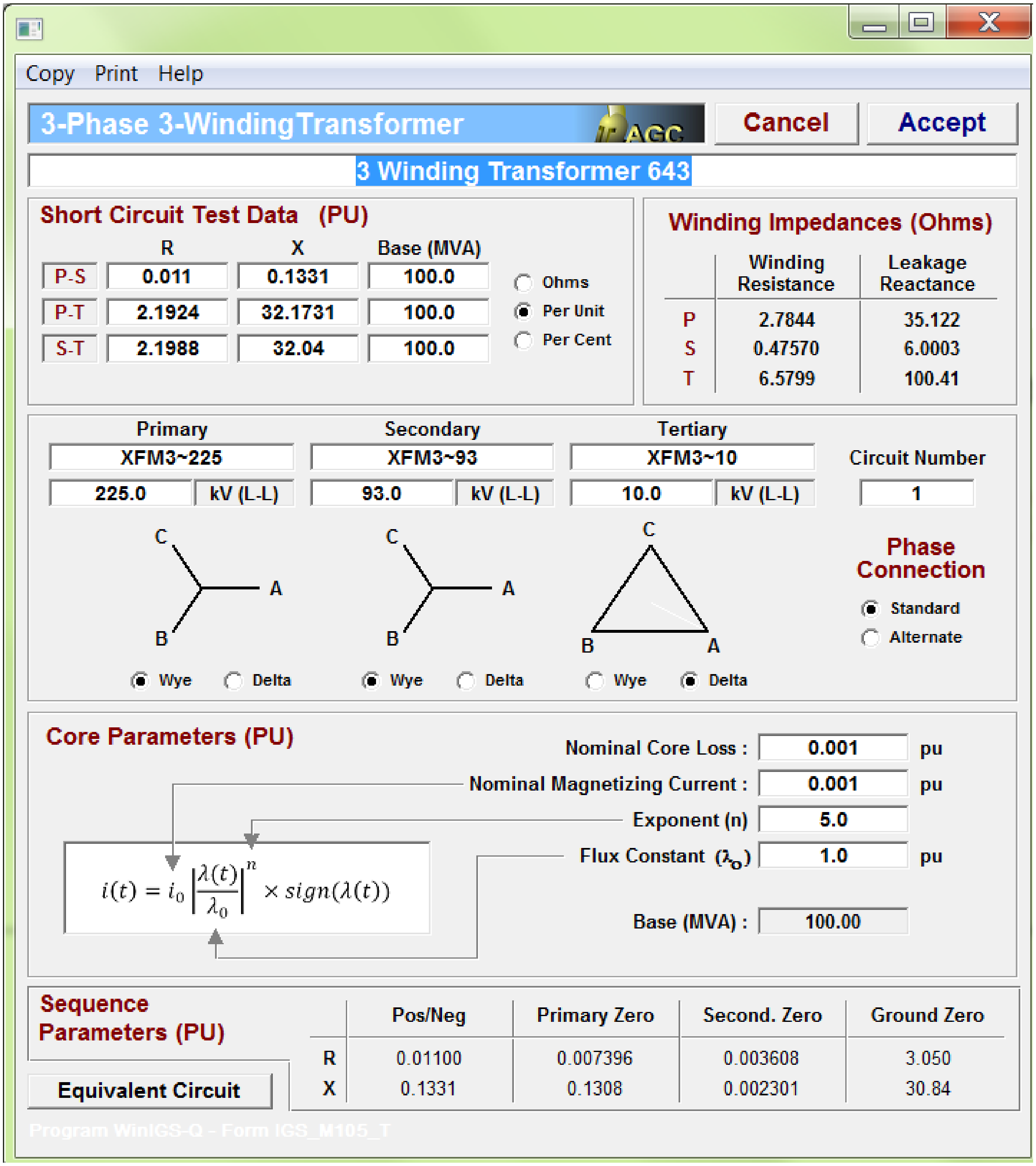


Figure G-23: 225 kV / 93 kV Transformer 643 Parameters

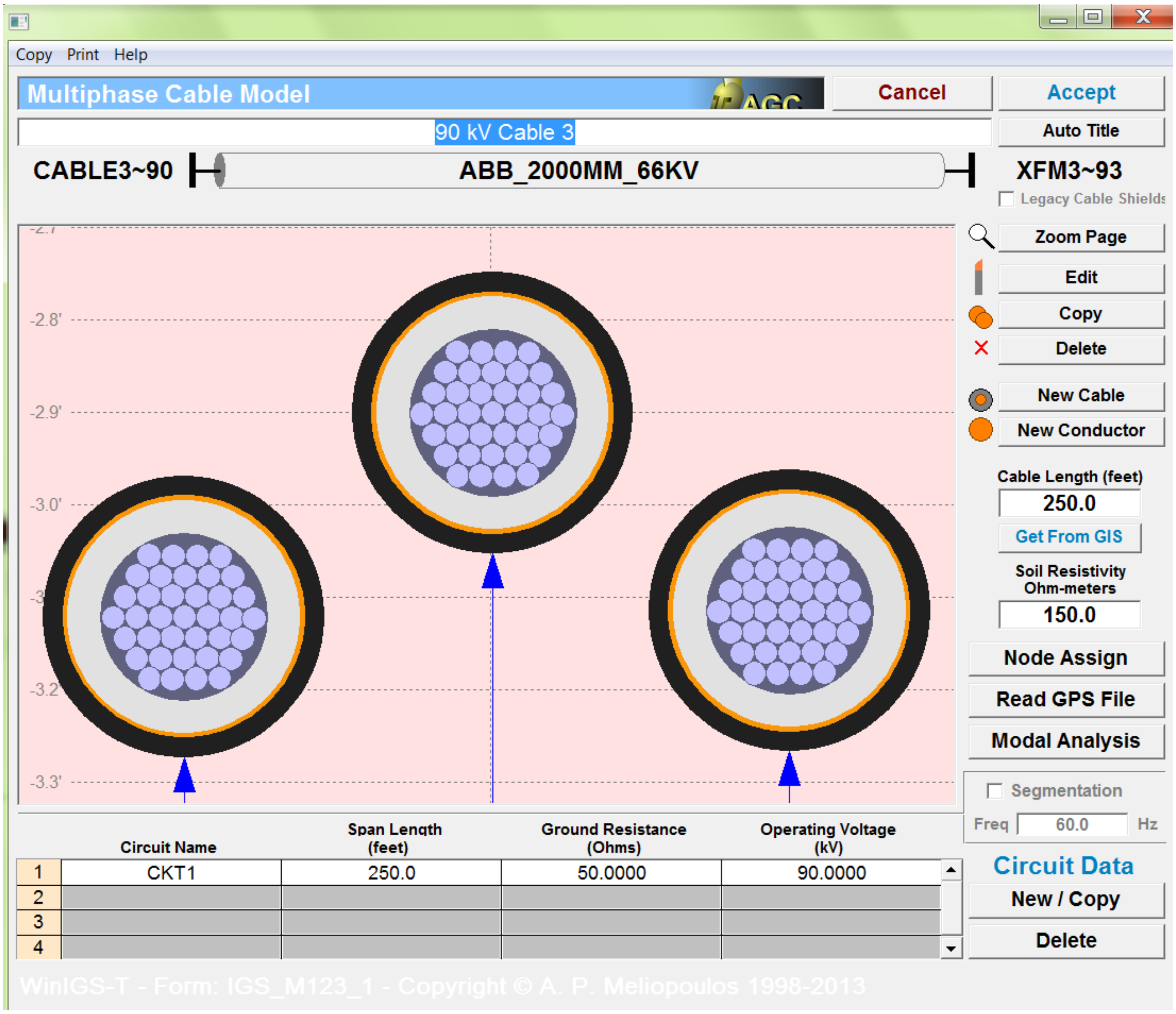


Figure G-24: 90 kV Cable 3 Parameters

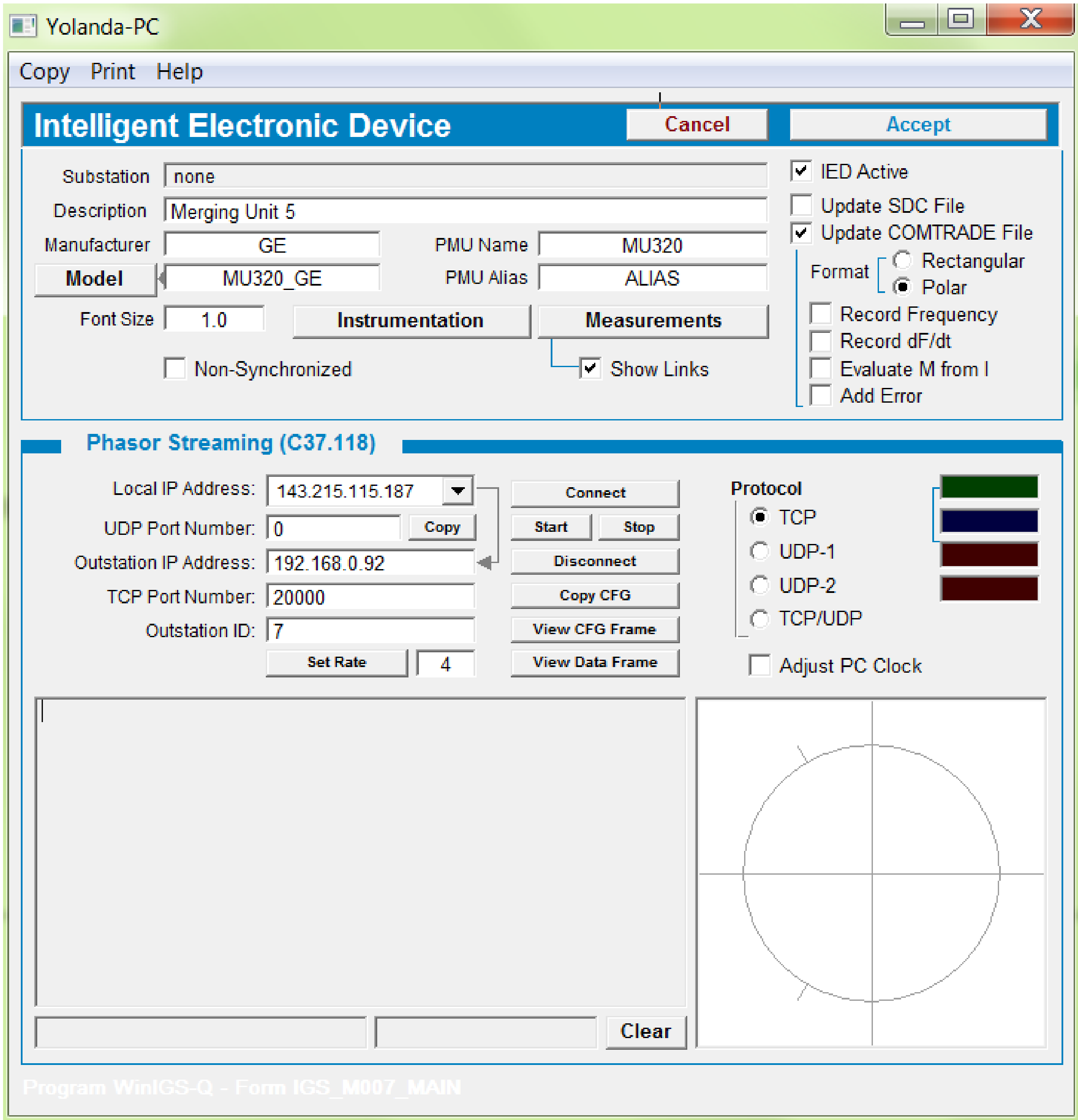


Figure G-25: Merging Unit 5 (Capture the Measurements of 225 kV/93 kV Transformer 643)

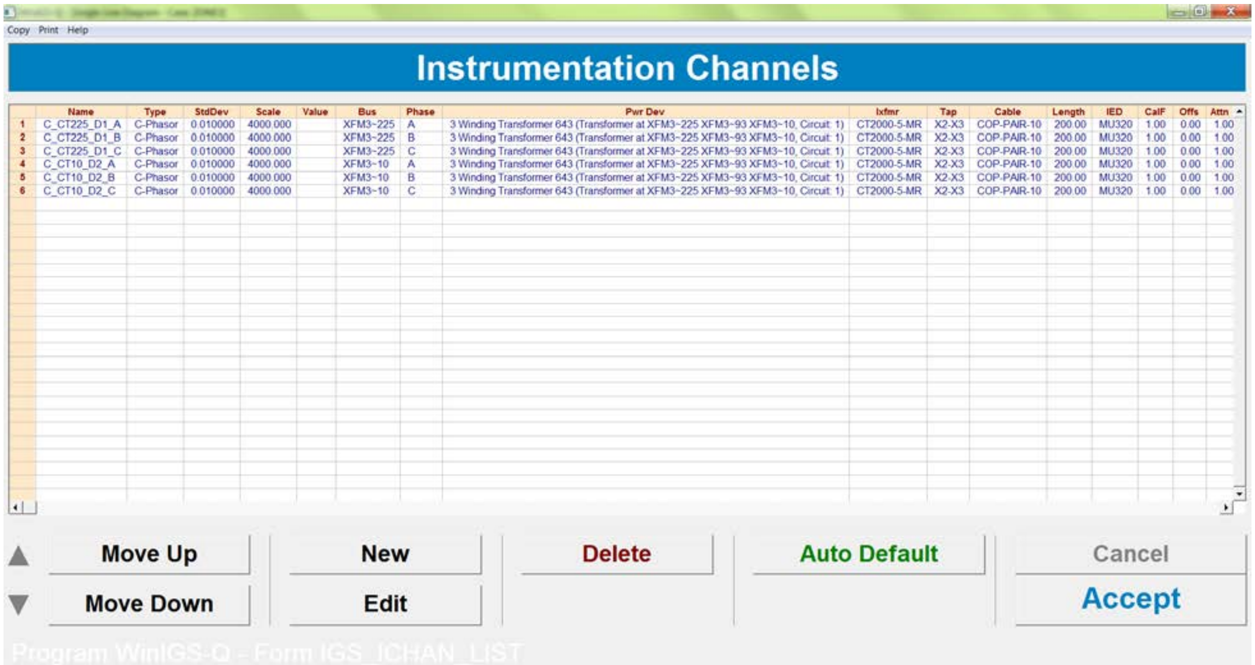


Figure G-26: Instrumentation Channels of Merging Unit 5

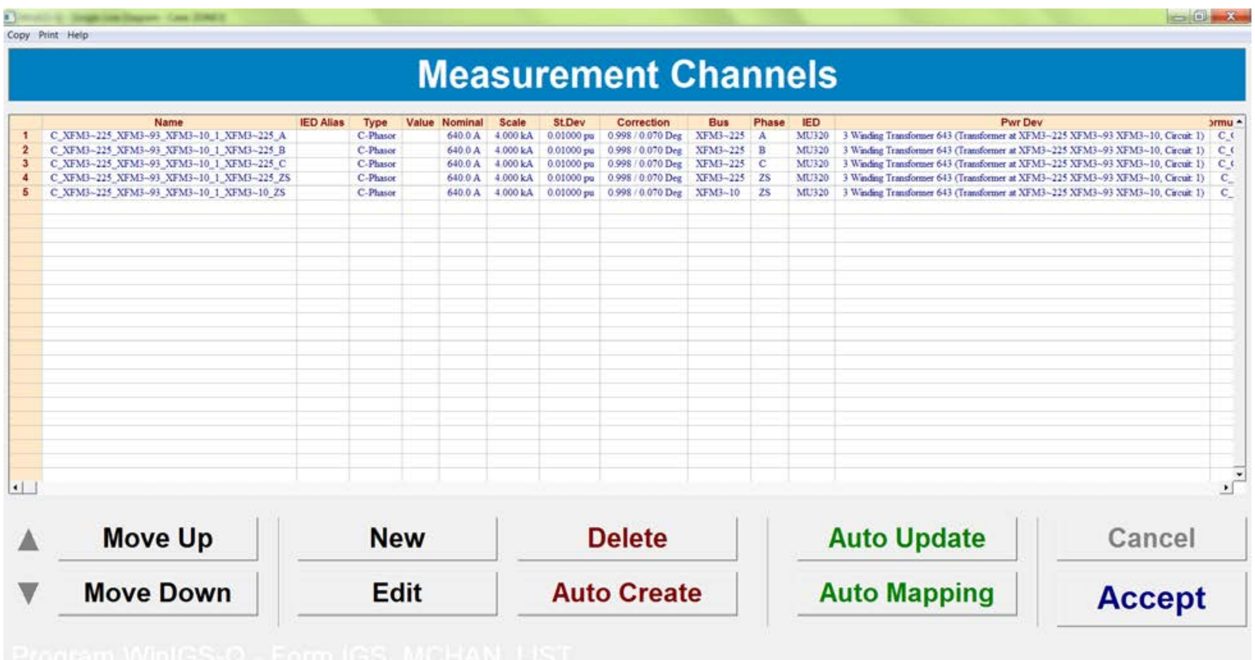


Figure G-27: Measurement Channels of Merging Unit 5

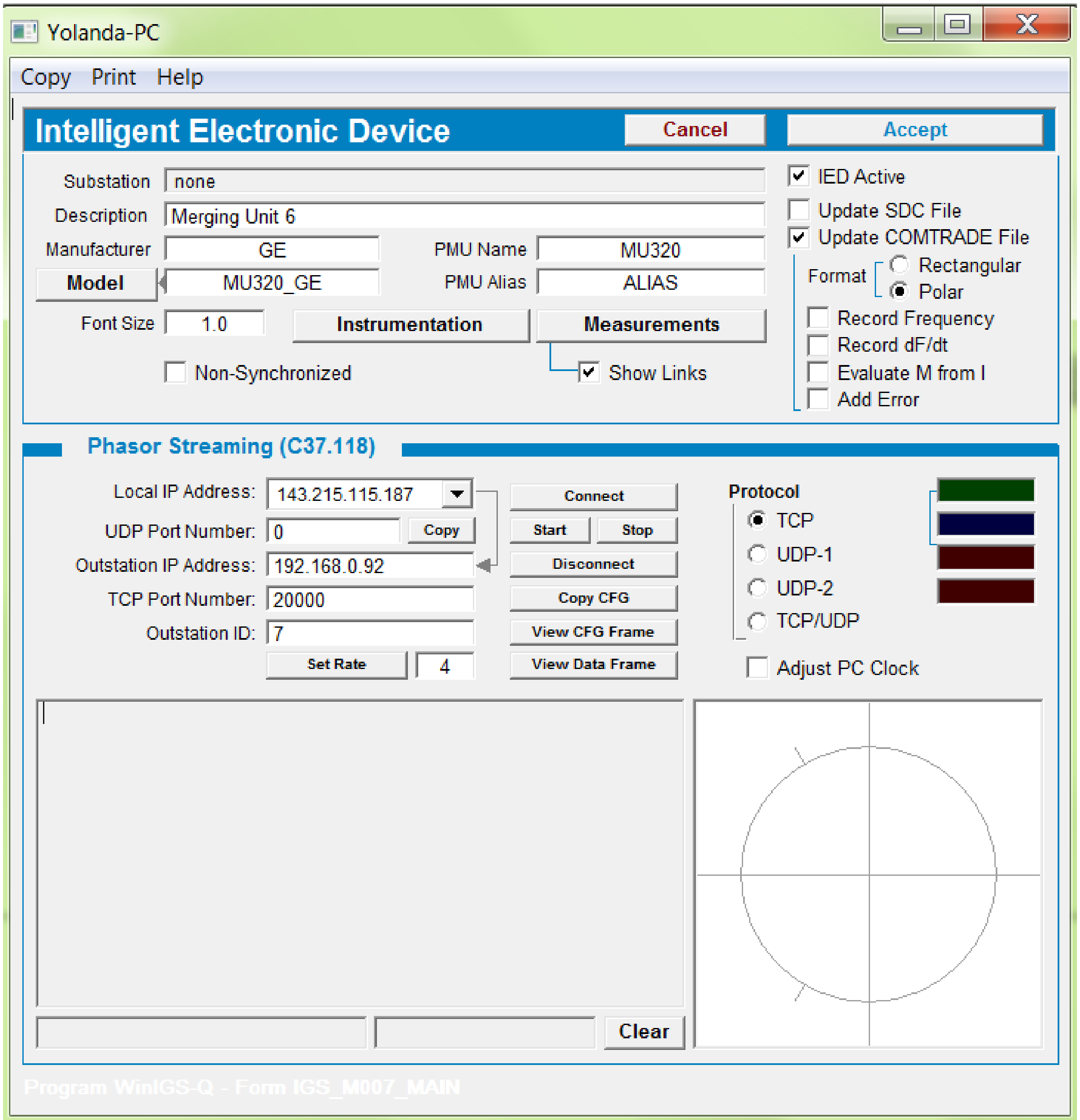
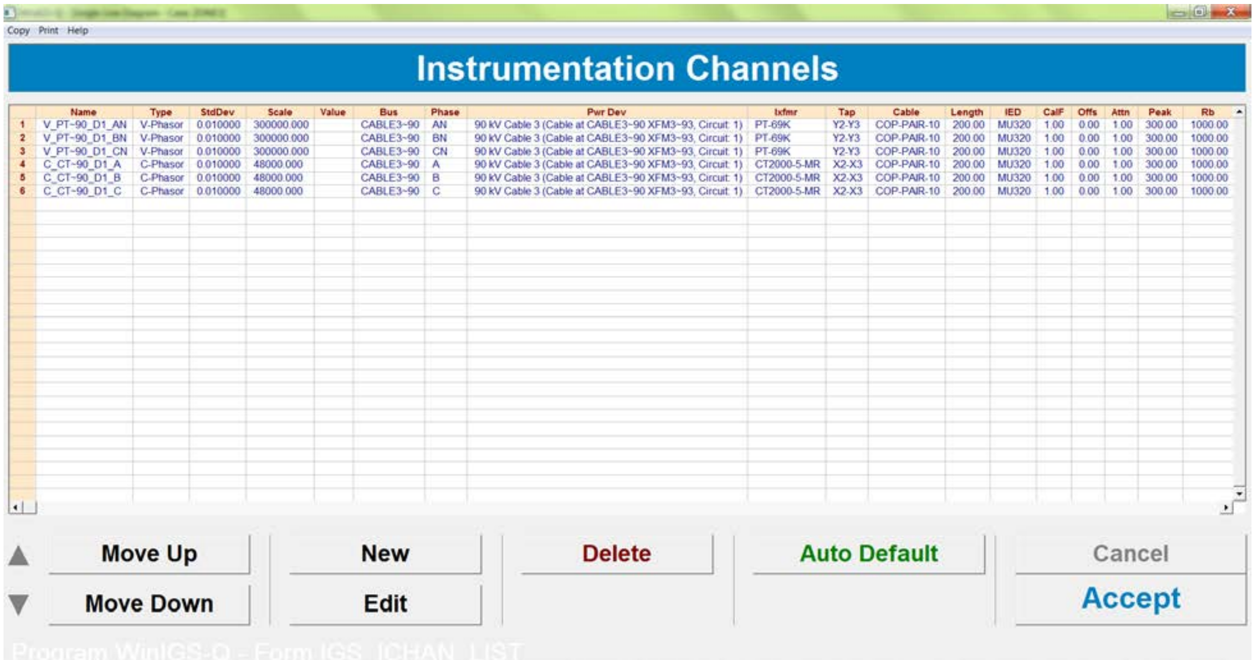
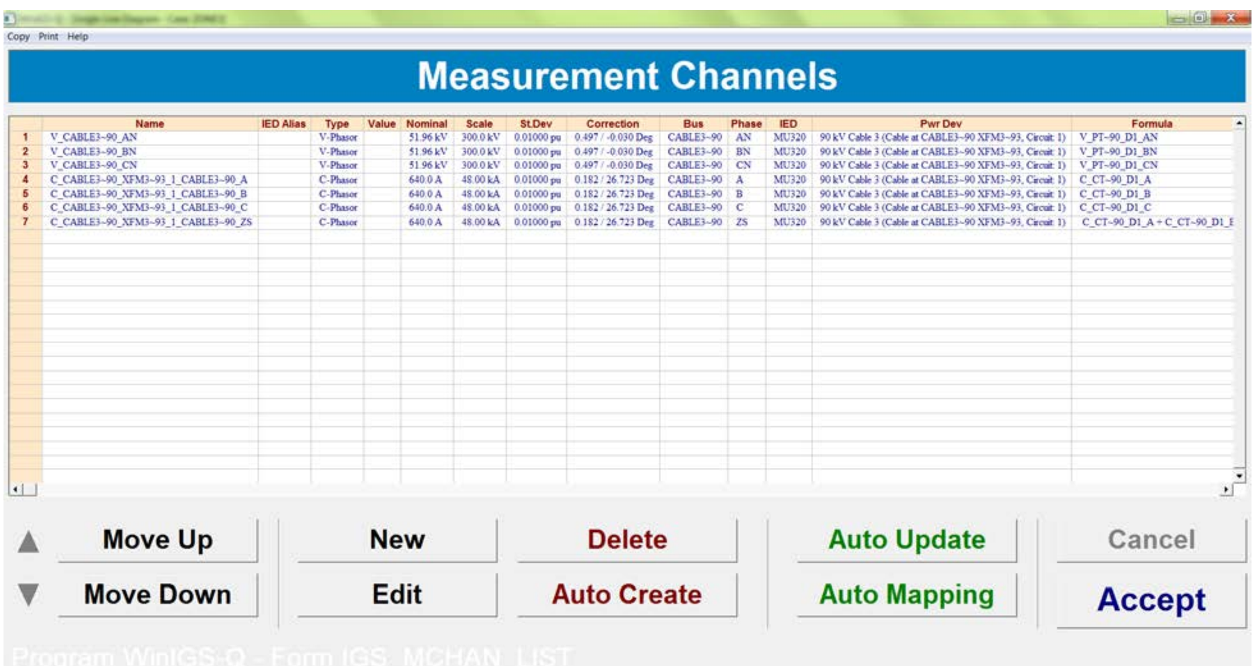


Figure G-28: Merging Unit 6 (Captures the Measurements of 90 kV Cable 3)



	Name	Type	StdDev	Scale	Value	Bus	Phase	Pwr Dev	Ixfmr	Tap	Cable	Length	IED	CalF	Offs	Attn	Peak	Rb
1	V_PT~90_D1_AN	V-Phasor	0.010000	300000.000		CABLE3~90	AN	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
2	V_PT~90_D1_BN	V-Phasor	0.010000	300000.000		CABLE3~90	BN	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
3	V_PT~90_D1_CN	V-Phasor	0.010000	300000.000		CABLE3~90	CN	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	PT-69K	Y2-Y3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
4	C_CT~90_D1_A	C-Phasor	0.010000	48000.000		CABLE3~90	A	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
5	C_CT~90_D1_B	C-Phasor	0.010000	48000.000		CABLE3~90	B	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00
6	C_CT~90_D1_C	C-Phasor	0.010000	48000.000		CABLE3~90	C	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	CT2000-5-MR	X2-X3	COP-PAIR-10	200.00	MU320	1.00	0.00	1.00	300.00	1000.00

Figure G-29: Instrumentation Channels of Merging Unit 6



	Name	IED Alias	Type	Value	Nominal	Scale	St.Dev	Correction	Bus	Phase	IED	Pwr Dev	Formula
1	V_CABLE3~90_AN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE3~90	AN	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	V_PT~90_D1_AN
2	V_CABLE3~90_BN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE3~90	BN	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	V_PT~90_D1_BN
3	V_CABLE3~90_CN		V-Phasor		51.96 kV	300.0 kV	0.01000 pu	0.497 / -0.030 Deg	CABLE3~90	CN	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	V_PT~90_D1_CN
4	C_CABLE3~90_XFM3~93_1_CABLE3~90_A		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE3~90	A	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	C_CT~90_D1_A
5	C_CABLE3~90_XFM3~93_1_CABLE3~90_B		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE3~90	B	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	C_CT~90_D1_B
6	C_CABLE3~90_XFM3~93_1_CABLE3~90_C		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE3~90	C	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	C_CT~90_D1_C
7	C_CABLE3~90_XFM3~93_1_CABLE3~90_ZS		C-Phasor		640.0 A	48.00 kA	0.01000 pu	0.182 / 26.723 Deg	CABLE3~90	ZS	MU320	90 kV Cable 3 (Cable at CABLE3~90 XFM3~93, Circuit: 1)	C_CT~90_D1_A + C_CT~90_D1_E

Figure G-30: Measurement Channels of Merging Unit 6

Protection Zone 4

This protection zone comprises the 245 kV Shunt Reactor.

The protection zone can be isolated from the system by the breaker: the Breaker 4.

Two merging unit (Merging Unit 7 and 8) collect measurements to be fed into the setting-less relay.

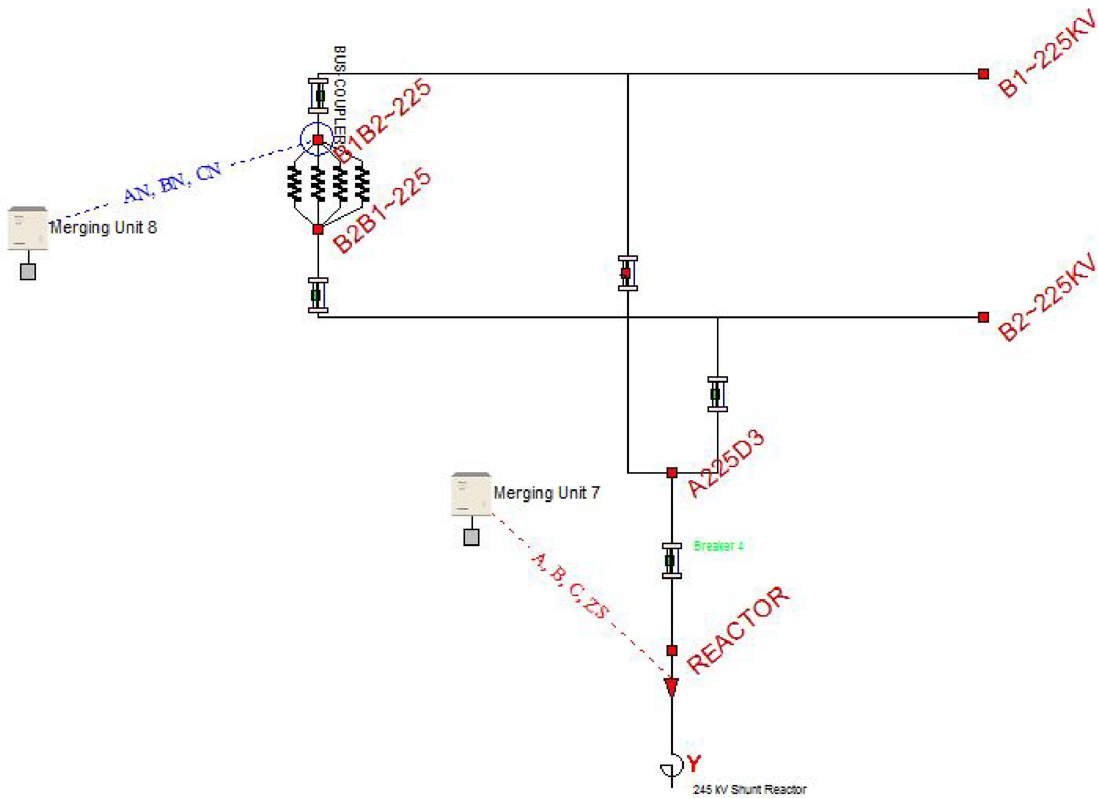


Figure G-31: Protection Zone 4

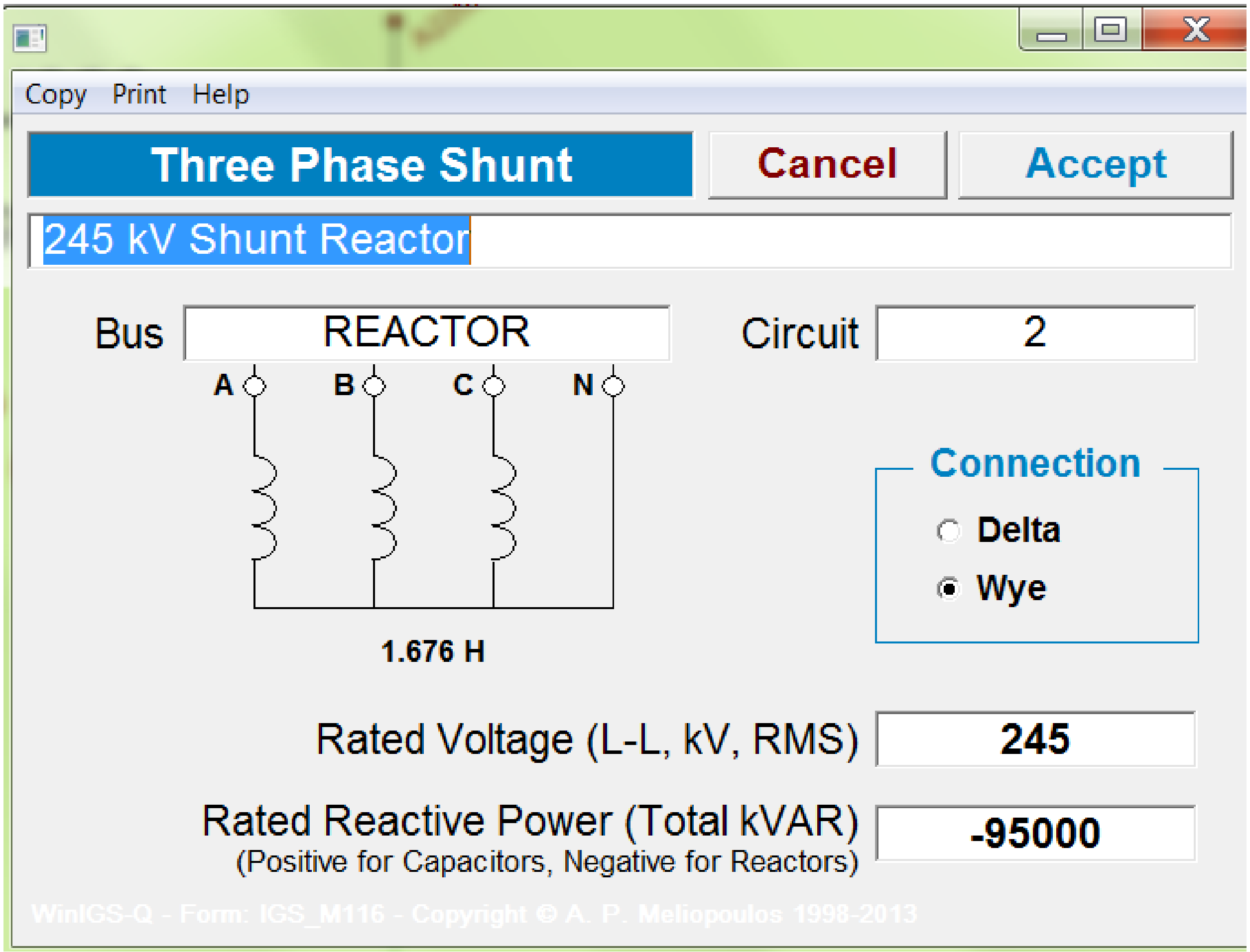


Figure G-32: 245 kV Shunt Reactor Parameters

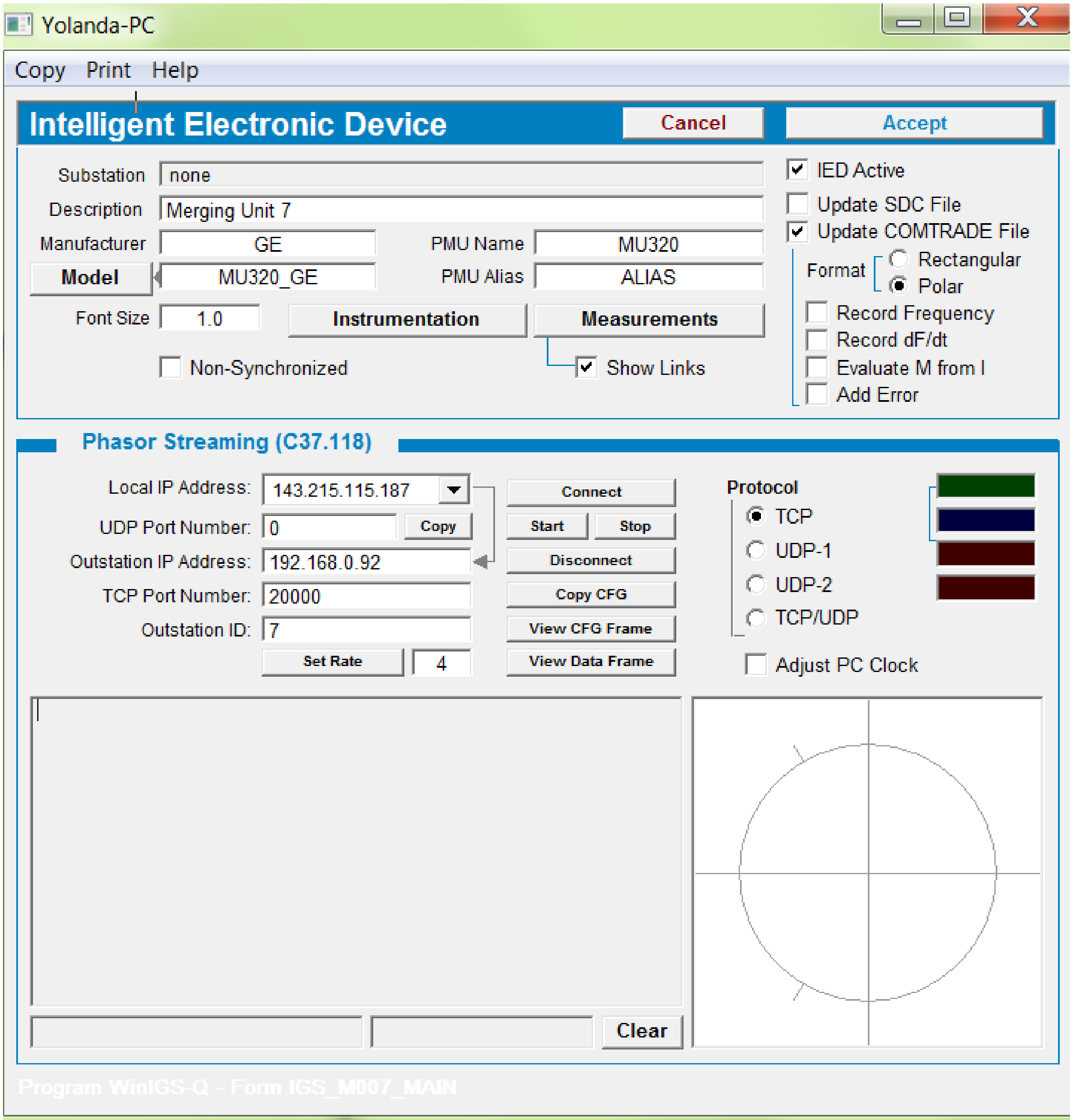


Figure G-33: Merging Unit 7 (Captures the Measurements of 245 kV Shunt Reactor)

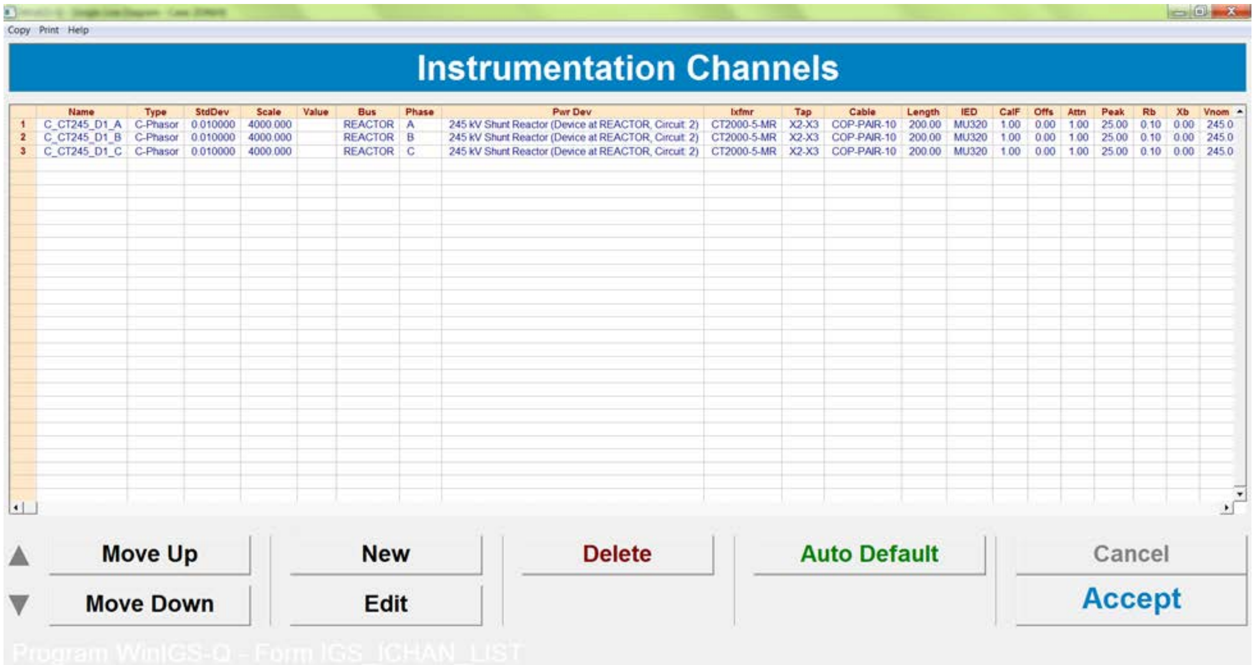


Figure G-34: Instrumentation Channels of Merging Unit 7

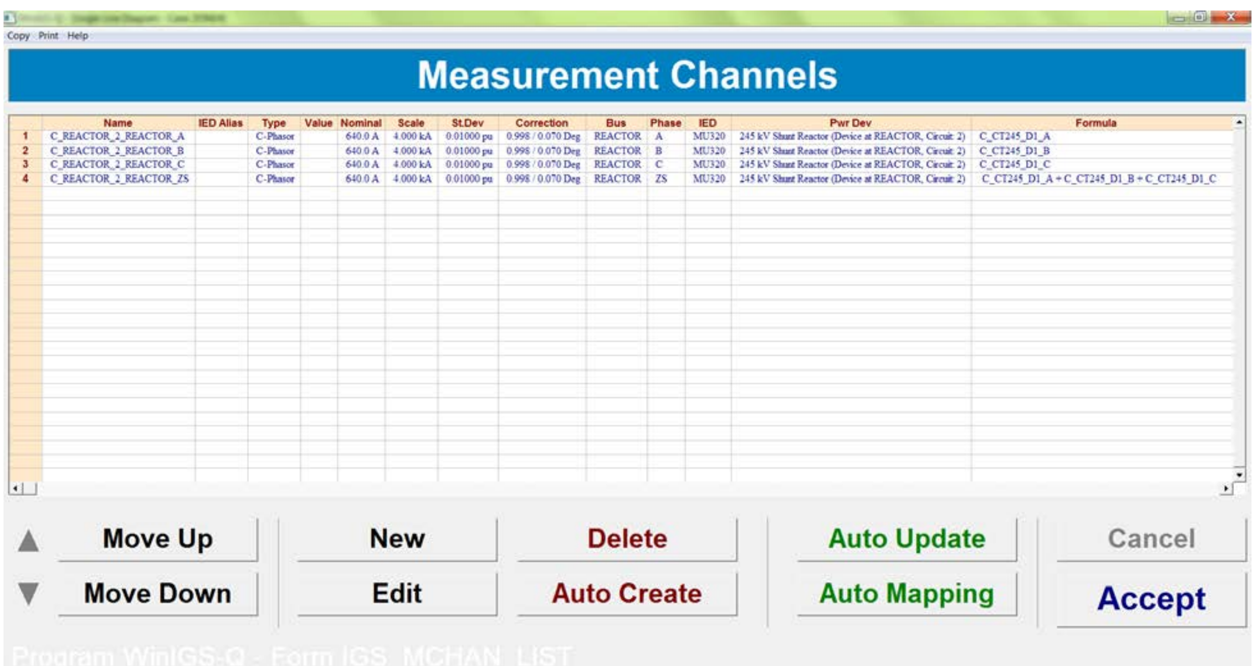


Figure G-35: Measurement Channels of Merging Unit 7

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