Setting-less Protection: Field Demonstration

Final Project Report

T-56G

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Setting-less Protection: Field Demonstration

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Acknowledgements

The authors wish to recognize the graduate students at the Georgia Institute of Technology who contributed to the research and creation of project reports:

- Yuan Kong
- Boqi Xie
- Jiahao Xie
- Chiyang Zhong

Executive Summary

This report is part of a series of research projects for the purpose of rethinking the overall protection and control of modern power systems. In prior projects the concept of "setting-less" protection has been introduced. Setting-less protection based on dynamic state estimation is an emerging technology that effectively uses advances in the protection and control infrastructure of modern power systems to improve protection. The two major advantages of the new technology are: (a) it drastically reduces complexity in present day protection and control systems, and (b) it does not require coordination among the protection of various protection zones. This protection approach uses simplified settings consisting of the operating limits of the devices in the protection zone. It is does not require coordination with any other protection functions of nearby protection zones and therefore drastically reduces the complexity of protection and control systems. The dynamic state estimation approach requires complex analytics to be performed on data acquired by the data acquisition system of the setting-less relay. However, the complex analytics are transparent to the user.

The setting-less protection method has been thoroughly tested in the laboratory with hardware in the loop and improved. Two filed installations and field testing are under way. At the time of writing of this report, the field demonstrations have not been completed due to installation delays beyond the control of the research team. Therefore this report does not include field results. The report describes the present status of the setting-less protective relay and presents use cases that demonstrate the process of preparing and installing a setting-less relay.

The report is organized as follows. Chapter 1 provides an introduction and elaborates on the need for new protection approaches.

Chapter 2 provides a description of the implementation of the setting-less protective relay.

Chapter 3 provides a description of the steps required to prepare and install a setting-less relay. Specifically, the relay requires a high fidelity model of the protection zone associated with the relay as well as the measurements, their location and type. No coordination with other relays is required. The steps to prepare the high fidelity model, to define the measurement system and import this information into the setting-less relay is described in this section. Naturally, these procedures are fully automated.

Chapter 4 describes testing procedures of the setting-less relay in the laboratory with hardware in the loop. The laboratory is described in some detail and several examples of setting-less relay testing are provided.

Finally, chapter 5 provides a use case for the on-going field testing of the setting-less relay. The use case describes all the steps for preparing the required data for the protection zone of the relay, uploading the data to the relay and making the setting-less relay functional.

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1. Introduction

Protection is a basic function of power systems and its proper operation leads to highly reliable power system. Since the introduction of power systems the protective system has played a pivotal role and its development and refinements are synonymous with power system reliability. The first protective relays were electromechanical relays designed for a single function. The discovery of transistors created an opportunity to transistorize numerical relays. In the 1960s, solid state relays were being developed performing the protection functions of the electro-mechanical relays. In the 1980s the introduction of microprocessors provides the cost-effective technology towards computer relaying. This efforts lead to the numerical relays. Present day numerical relays use high end microprocessors for implementing multiple functions of protection. For example, a transformer protection relay may include all the typical protection functions that are traditionally used by electromechanical relays, i.e., differential, over-current, V/Hz function, etc. Since these functions work independently, even if they are implemented on the same relay, they suffer from the same limitations as the usual single relay/single function approach. Each function must be set separately but the settings must be coordinated with other protective devices. The coordinated settings are typically selected so that can satisfy selectivity requirements that many times are conflicting and therefore a compromise must be selected. For this reason, most of the time the settings represent a compromise and occasionally may exist possible fault conditions that may lead to an undesirable relay response. The complexity of present day protection systems leads to imperfect protection systems that experience mis-operations. Relay mis-operations is a major source of system unreliability. Statistical data indicate that mis-operations constitute 10% of protection operations.

It should be understood that numerical relays have provided many more options that have drastically improved protection and control systems. However, the additional options have led increased complexity and increased possibilities of human errors, while the basic nature of the problem of selecting settings has remained the same: the settings must be selected to satisfy criteria that many times are conflicting. The natural question is whether any new technologies and trends can favorably affect protection systems.

There are technologies that can enable better, integrated approaches to the overall protection. Some of these technologies are (technology is in flux with many developments still to occur):

1. Merging units/separation of data acquisition and data processing/protection
2. GPS synchronized measurements (PMUs)
3. Data Concentrator (PDCs, switches, etc.)
4. Smarter sensors
5. Integrated (power system/relay) analysis programs that enable faster and more reliable assessment of settings
6. Data validation/state extraction

Protection and control systems around the world are experiencing an evolution driven by these new technologies. At the same time, P&C systems are called to protect and control an ever evolving power system with many new complexities arising from new energy resources, particularly renewable energy resources, power electronics conversion systems and high-voltage direct current (HVDC) transmission. According to a recent forecast, renewable energy resources

will comprise around 31.2% of total world power generation by 2035. A significant portion of these resources will come from wind and solar energy. This massive deployment of new energy resources has already led to several changes in power system characteristics, including reduced fault current levels, increased dynamics and wider frequency variations to disturbances. Such changes mandate new approaches to deal with the protection and control of the power system.

Advances in P&C technologies have increased the complexity of protection and control systems. Complexity increases the possibility of errors and reduces protection reliability. As a result, despite the great technological advances, protection mis-operations are at undesirable levels. Relay mis-operations levels are approximately 10%, as reported by the North American Electric Reliability Corporation (NERC) for the USA. Similar statistics exists for many other parts of the world. Further analysis of mis-operation statistics indicate that around 65% of mis-operations are caused by settings and logic errors and communications failures. These causes are characterized as hidden failures, which are "permanent defect[s] that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event". This definition implies that these failures cause incorrect interruption to a portion of power systems because of a fault to another part of the network. Consequently, they may initiate second level contingencies in the power system network and possibly a cascading effect. In any case, relay mis-operations drastically affect power system reliability.

The present numerical relays have a limited capability to detect hidden failures. Presently, relays are not capable to correct the effects of the hidden failures nor they have the capability to detect the true condition of the power system in the presence of hidden failures. As a result, when a hidden failure is detected the only option is to inhibit the protection function. The affected protection system depends on other protection systems, unaffected by the hidden failure(s), to take the proper action. It should be apparent the protection system reliability is decreased.

Relay manufacturers and researchers have proposed approaches that could minimize the effects of hidden failures and cope with other complexities. Along these lines, adaptive protection schemes and voting schemes have been proposed. Adaptive protection schemes have been proven to be complex and do not easily meet the speed that is required for protection. Voting schemes are not reliable as a hidden failure may affect several relays that participate in the voting – in this case the majority of relays may be taking a wrong decision.

Technology advancements have played a major role in paving the way for a new protection system capable of overcoming present day challenges. Specifically, the introduction of merging units, advancements in computational capabilities and the communication infrastructure as well as related standards enables the realization of centralized approaches for supervision of protective functions and self-healing and self-correction of the effects of hidden failures. The introduction of IEC 61850, provides the blue print to allow IEDs from various manufactures to seamlessly participate in new protection schemes. Data transfer within the substation has been standardized for any application.

The health of the protection and control system itself is of paramount importance for the reliability of the power grid. Today, the technology to monitor the condition of the protection and control system exists, however the methods are not well developed. There are several aspects of this

problem: (a) the health and accuracy of the instrumentation, (b) the accuracy of relay settings, and (c) the condition and speed of the communications.

The existence of new technologies and the quest for more reliable (secure and dependable) protection schemes has led to the investigation of dynamic state estimation protection approaches (a.k.a. setting-less relay). This investigation has shown that it is possible to develop a protection approach that does not require coordination with other protection functions and at the same time address many protection gaps. Following the verification of the basic advantages of estimation based protection, the method has been further refined and advanced to address the issue of condition monitoring of the entire protection and control system. Specifically setting-less relays can be integrated with the overall substation protection and control systems to provide a centralized substation protection capable of self-monitoring and correcting (self-healing) ion case of failures in instrumentation or the relays themselves. In this report we describe the setting-less protective relays and their characteristics that make them capable of redefining the overall protection and control system. In a companion report (project 56G) the use of the setting-less relays in the overall centralized substation protection and control is addressed.

2. Implementation of Setting-less Protection – Single Component Protection Zone

The setting-less protective relay protects a protection zone that may consists of one power component or a small number of components protected as a unit, for example generator/step-up transformer. The implementation of protection zone setting-less protective relay has been developed as object-oriented software architecture. The preferred implementation is based on merging units as shown in Figure 2.1. The data acquisition system may consist of multiple merging units. The setting-less relay includes a sampled value data concentrator that accepts the data from multiple merging units, time aligns the data and then presents the data to the logical unit of the setting-less relay. Note for reliability, redundant buffers are used for storing and retrieving the data.
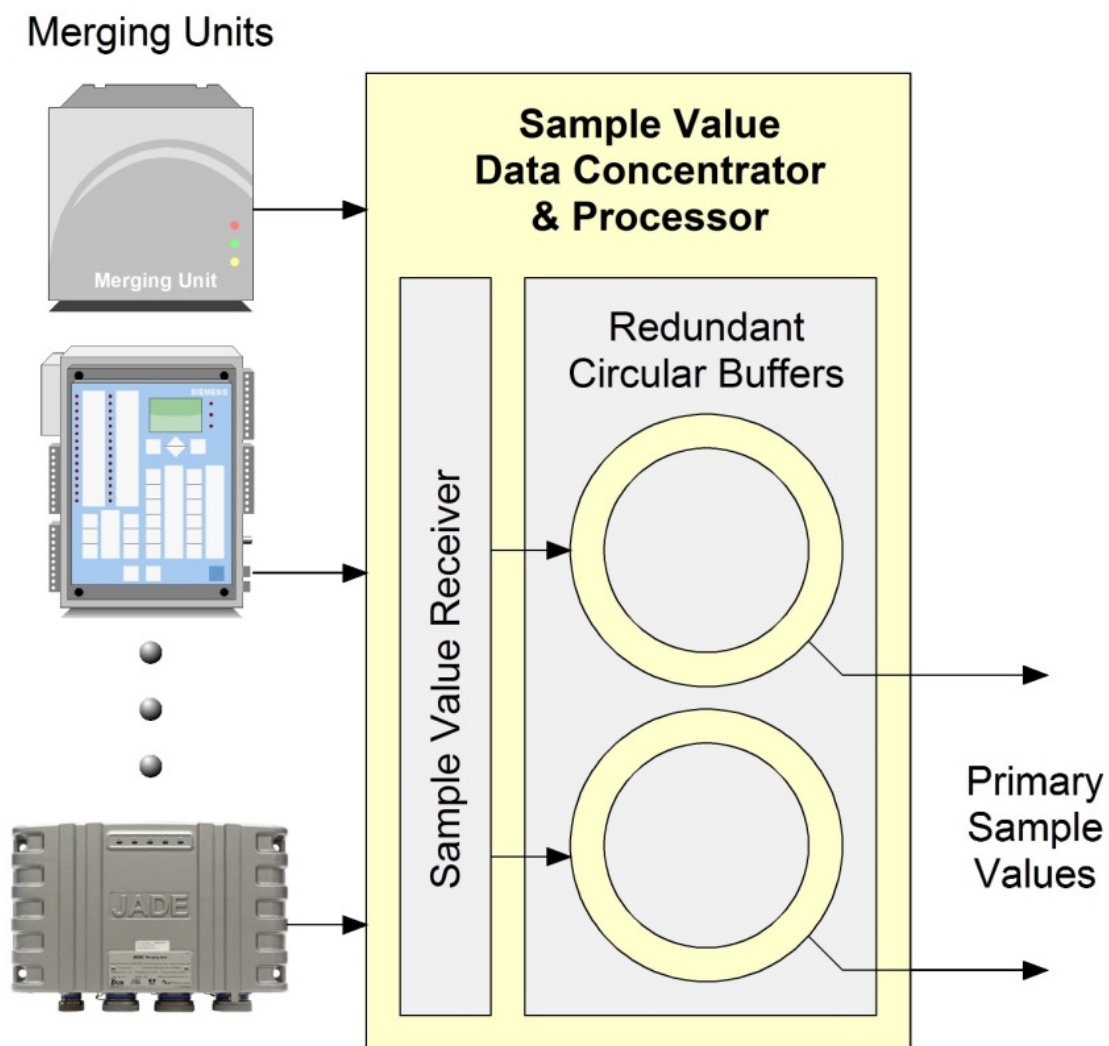
Figure 2.1: The Sampled Value Data Concentrator and Processor

The functionality of the setting-less relay is illustrated in Figure 2.2.
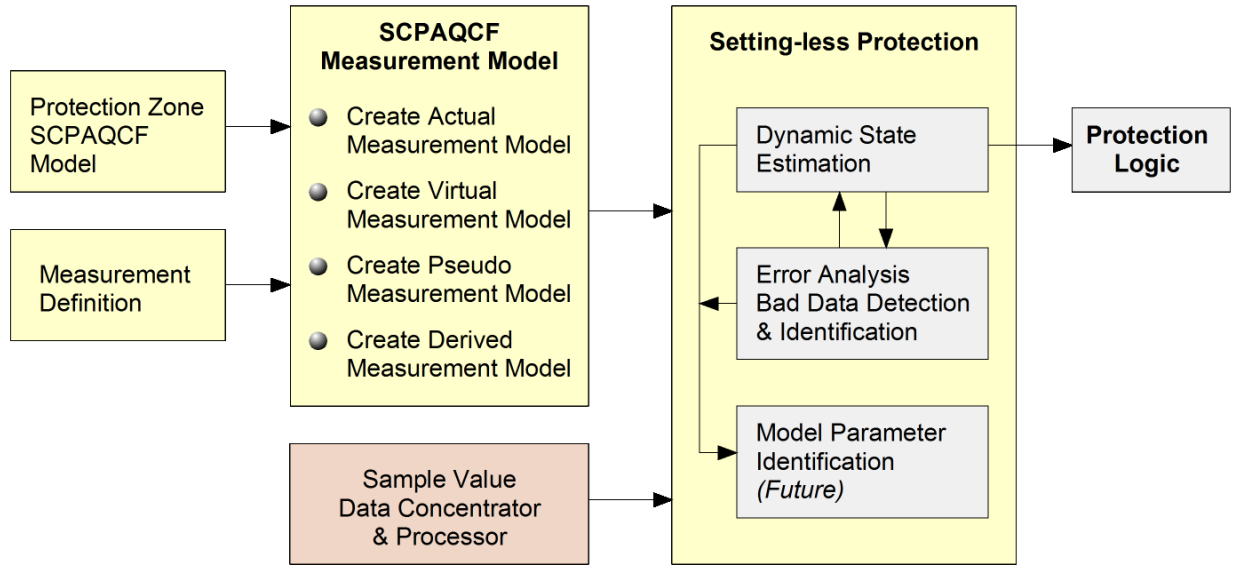
Figure 2.2: Setting-Less Protection Relay Organization

The functional blocks of the setting-less protective relay have been evaluated and have been abstracted into a number of objects. Specifically, the setting-less approach requires the following objects:

1. the mathematical model of the protection zone
2. the physical measurements that may consist of analog and digital data
3. the mathematical model of the physical measurements
4. the mathematical model of the virtual measurements
5. the mathematical model of the derived measurements
6. the mathematical model of the pseudo measurements
7. the dynamic state estimation algorithms
8. the bad data detection and identification algorithm
9. the protection logic and trip signals
10. online parameter identification method

Many of the above objects are automatically generated. The objects that need to be inputted to the setting-less relay are only object 1 and 2. These two objects can be generated by an independent program and inputted into the setting-less relay. A user manual has been created that describes how objects 1 and 2 can be created and inputted into the setting-less relay. These details are beyond the scope of this report.

In general the protection zone may comprise more than one power system component. In this case, the processing of the objects and the automatic setup of the setting-less relay involves a number of functions/procedures. Figure 2.3 illustrates the functions of the setting-less relay in more detail. The unit mathematical model consists of several components. Each component is expressed in terms of the TDSCAQCF dynamic model. In this case, the mathematical model for the unit

protection unit is formed from the models of the components and has the same form as that given in the single component, i.e. in TDSCAQCF syntax. The device models in TDSCAQCF syntax are stored in a single file with extension TDSCAQCF.

The setting-less protective relay also requires the actual measurements taken. The measurements are described in a second file. This file has the extension TDMDEF. We refer to this file as the measurement definition file.

Given these two files, the setting-less protective relay reads these files and automatically creates the protection zone (unit) model as well as the mathematical model of the actual measurements. Subsequently, it augments the measurement set with virtual measurements, derived measurements and pseudo measurements. This creation is transparent to the user.

Figure 2.3: Procedure of Constructing the Protection Unit Measurement Model

Figure 2.3 illustrates the program organization from importing the device model file and measurement definition file to the normalized protection unit measurement model. The dynamic

state estimation operates on the normalized protection unit measurements models. A brief description of each step is shown in Figure 2.4. Note that TDSCAQCF and TDMDEF indicate the component models and measurement definition file, respectively.

```
┌─────────────────────┐                              Dynamic State
│  1. Read Files      │                                Esimation
│ (TDSCAQCF, TDMDEF)  │                                   ↑
└─────────────────────┘                        ┌─────────────────────┐
          ↓                                     │ 7. Create SCAQCF     │
┌─────────────────────┐                         │ Protection Unit      │
│ 2. Formulate the    │                         │ Measurement Model    │
│ Protection Unit     │                         └─────────────────────┘
│ Model and the       │                                   ↑
│ Mapping Lists       │                         ┌─────────────────────┐
│ (from Device to     │                         │ 6. Normalize the     │
│ Protection Unit)    │                         │ Protection Unit      │
└─────────────────────┘                         │ Measurement Model    │
          ↓                                     └─────────────────────┘
┌─────────────────────┐                                   ↑
│ 3. Create the       │                         ┌─────────────────────┐
│ Device-Level        │                         │ 5. Create Additional │
│ Measurement Model   │    →                    │ Virtual Measurement  │
│ (Actual, Pseudo,    │                         │ Models from the      │
│ Derived, Virtual)   │                         │ Protection Unit Model│
└─────────────────────┘                         └─────────────────────┘
          ↓                                    
┌─────────────────────┐                        
│ 4. Formulate the    │   →                    
│ Protection Unit     │                        
│ Measurement Model   │                        
│ from Device-Level   │                        
│ Measurement Model   │                        
│ via Mapping Lists   │                        
└─────────────────────┘                        
```
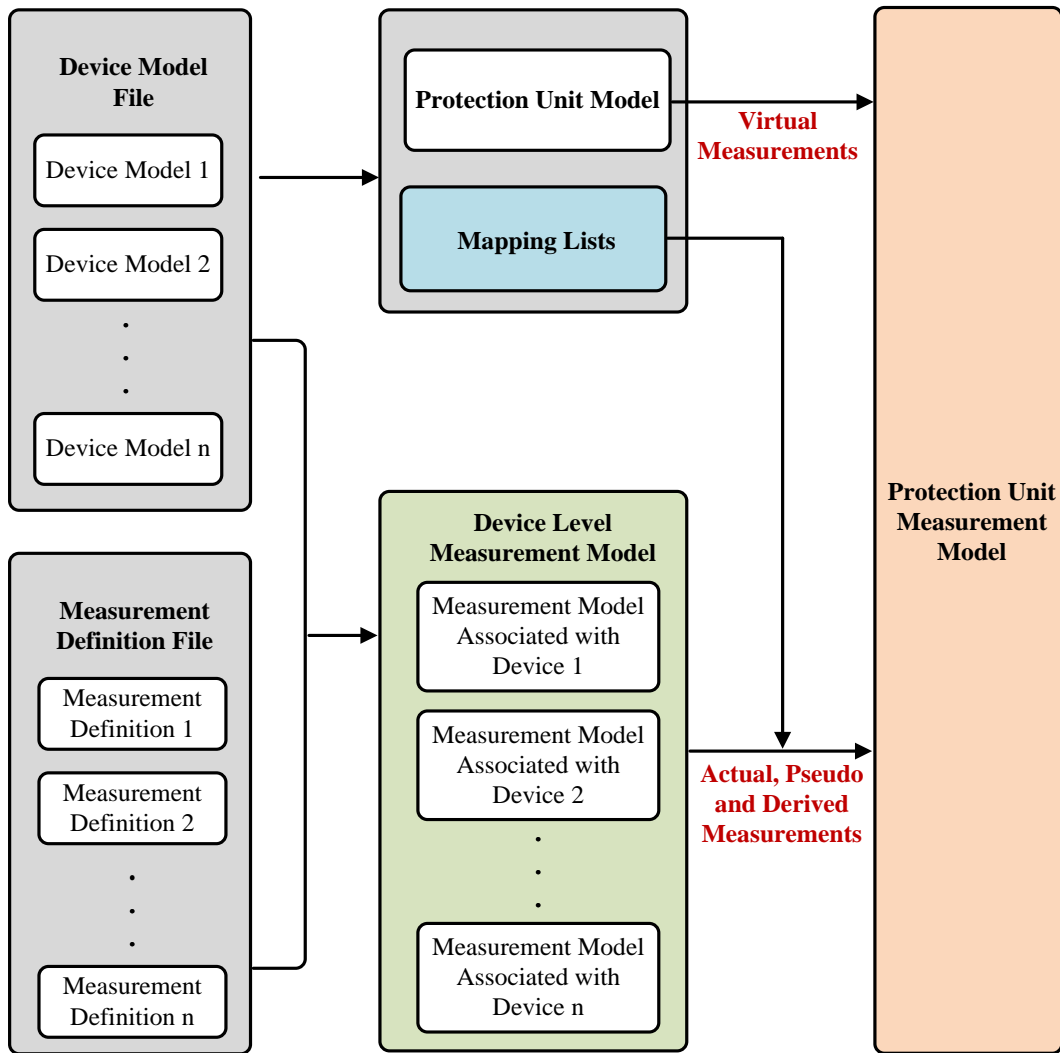
Figure 2.4: Program Organization of Constructing the Protection Unit Measurement Model

Step 1 reads the device model file and the measurement definition file for this protection unit. Note that the protection unit may consist of multiple devices.

Step 2 formulates the protection unit model and creates the mapping list from devices to the protection unit based on the device model file.

Step 3 creates the device-level measurement model (actual, pseudo, derived and virtual measurements) from the model file and the measurement definition file.

Step 4 formulates the protection unit measurement model from device-level measurement model using mapping lists from device to protection unit.

Step 5 creates additional virtual measurement models from the protection unit model. Note that these additional virtual measurements include zero sum of the currents at common nodes.

Step 6 normalizes the protection unit measurement model by state, through and control normalization factors.

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Step 7 creates the SCAQCF protection unit measurement model by substituting control variables with constants. The SCAQCF protection unit measurement model is ready for the dynamic state estimation.

2.1   Protection Zone Mathematical Model

The mathematical model of the protection zone is required in a standard form. A standard has been defined in the form of the **S**tate and **C**ontrol **A**lgebraic **Q**uadratic **C**ompanion **F**orm (SCAQCF) and in a specified syntax to be defined later. The SCAQCF for a specific protection zone is derived with three computational procedures. Specifically, the dynamic model of a protection zone consists of a set of algebraic and differential equations. We refer to this model as the compact model of the protection zone. Subsequently this model is quadratized, i.e., in case there are nonlinearities of order greater than 2, additional state variables are introduced so that in the end the mathematical model consists of a set of linear and quadratic equations. We refer to this model as the quadratized model. Finally, the quadratized model is integrated using the quadratic integration method which converts the quadratized model of the protection zone into a set of algebraic (quadratic) function. This model is cast into a generalized Norton form. We refer to this model as the Algebraic Quadratic Companion Form. Since the variables in this AQCF contain all states and controls, thus it is named State and Control Algebraic Quadratic Companion Form.

The standard State and Control Algebraic Quadratic Companion Form is obtained with two procedures: (a) model quadratization, and (b) quadratic integration. The model quadratization reduces the model nonlinearities so that the dynamic model will consist of a set of linear and quadratic equations. The quadratic integration is a numerical integration method that is applied to the quadratic model assuming that the functions vary quadratically over the integration time step. The end result is an algebraic companion form that is a set of linear and quadratic algebraic equations that are cast in the following standards form:

$$
\begin{Bmatrix} I(\mathbf{x},\mathbf{u}) \\ \vdots \\ 0 \\ \vdots \end{Bmatrix} = Y_{eqx}\mathbf{x} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eqx}^i \mathbf{x} \\ \vdots \end{Bmatrix} + Y_{equ}\mathbf{u} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F_{equ}^i \mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eqxu}^i \mathbf{u} \\ \vdots \end{Bmatrix} - B_{eq} \tag{1}
$$

where $I(\mathbf{x},\mathbf{u})$ is the through variable (current) vector, $\mathbf{x} = [\mathbf{x}(t), \mathbf{x}(t_m)]$ is the external and internal state variables, $\mathbf{u} = [\mathbf{u}(t), \mathbf{u}(t_m)]$ is the control variables, t is present time, t_m is the midpoint between the present and previous time, Y_{eq} admittance matrix, F_{eq} nonlinear matrices, and

$$
B_{eq} = -N_{eqx}\mathbf{x}(t-h) - N_{equ}\mathbf{u}(t-h) - M_{eq}I(t-h) - K_{eq} \tag{2}
$$

The derivation of the standard State and Control Algebraic Quadratic Companion Form for specific protection zones is provided in the appropriate reports that describe the application of the setting-less protection schemes for specific protection zones.

This standardization allows the object-oriented handling of measurements in state estimation; in addition, it converts the dynamic state estimation into a state estimation that has the form of a static state estimation.

2.2   Object-Oriented Measurement Models

Any measurement, i.e., current, voltage, temperature, etc. can be viewed as an object that consists of the measured value and a corresponding function that expresses the measurement as a function of the state of the component. This function can be directly obtained (autonomously) from the State and Control Algebraic Quadratic Companion Form of the component. Because the algebraic companion form is quadratic at most, the measurement model will be also quadratic at most. Thus, the object-oriented measurement model can be expressed as the following standard equation:

$$
\begin{aligned}
z_k(t) = &\sum_i a_{i,t}^k \cdot x_i(t) + \sum_i a_{i,tm}^k \cdot x_i(t_m) \\
&+ \sum_{i,j} b_{i,j,t}^k \cdot x_i(t) \cdot x_j(t) \\
&+ \sum_{i,j} b_{i,j,tm}^k \cdot x_i(t_m) \cdot x_j(t_m) \\
&+ c_k(t) + \eta_k \ ,
\end{aligned}
\tag{3}
$$

where z is the measured value, t the present time, t_m the midpoint between the present and previous time, x the state variables, a the coefficients of linear terms, b the coefficients of nonlinear terms, c the constant term, and η the measurement error.

The measurements can be identified as: (a) actual measurements, (b) virtual measurements, (c) derived measurements and (d) pseudo measurements. The types of measurements will be discussed next.

Actual Measurements: In general, the actual measurements can be classified as across and through measurements. Across measurements are measurements of voltages or other physical quantities at the terminals of a protection zone such as speed on the shaft of a generator/model. These quantities are typically states in the model of the component. For this reason, the across measurements has a simple model as follows:

$$
z_j = x_i \pm x_j + \eta_j .
\tag{4}
$$

Through measurements are typically currents at the terminals of a device or other quantities at the terminals of a device such as torque on the shaft of a generator/motor. The quantity of a through measurement is typically a function of the state of the device. For this reason, the through measurement model is extracted from the algebraic companion form, i.e., the measurement model is simply one equation of the SCACQF model, as follows:

$$
z_j = \sum_i Y_{eqx,i}^k \cdot x_i + \sum_{i,j} F_{eqx,ij}^k \cdot x_i \cdot x_j + \sum_i Y_{equ,i}^k \cdot u_i + \sum_{i,j} F_{equ,ij}^k \cdot u_i \cdot u_j + \sum_{i,j} F_{eqxu,ij}^k \cdot x_i \cdot u_j - \sum_i b_{eq,i}^k \ ,
\tag{5}
$$

where the superscript k means the kth row of the matrix or the vector.

Virtual Measurements: The virtual measurements represent a physical law that must be satisfied. For example, we know that at a node the sum of the currents must be zero by Kirchhoff's current law. In this case we can define a measurement (sum of the currents); note that the value of the measurement (zero) is known with certainty. This is a virtual measurement.

The model can provide virtual measurements in the form of equations that must be satisfied. Consider for example the mth SCAQCF model equation below:

$$0 = \sum_i Y_{eqx,i}^{\ k} \cdot x_i + \sum_{i,j} F_{eqx,ij}^{\ k} \cdot x_i \cdot x_j + \sum_i Y_{equ,i}^{\ k} \cdot u_i + \sum_{i,j} F_{equ,ij}^{\ k} \cdot u_i \cdot u_j + \sum_{i,j} F_{eqxu,ij}^{\ k} \cdot x_i \cdot u_j - \sum_i b_{eq,i}^{\ k} \qquad (6)$$

This equation is simply a relationship among the states the component that must be satisfied. Therefore, we can state that the zero value is a measurement that we know with certainty. We refer to this as a virtual measurement.

Derived Measurements: A derived measurement is a measurement that can be defined for a physical quantity by utilizing physical laws. An example derived measurement is shown in Figure 2.5. The figure illustrates a series compensated power line with actual measurements on the line side only. Then derived measurements are defined for each capacitor section. Note that the derived measurements enable the observation of the voltage across the capacitor sections.
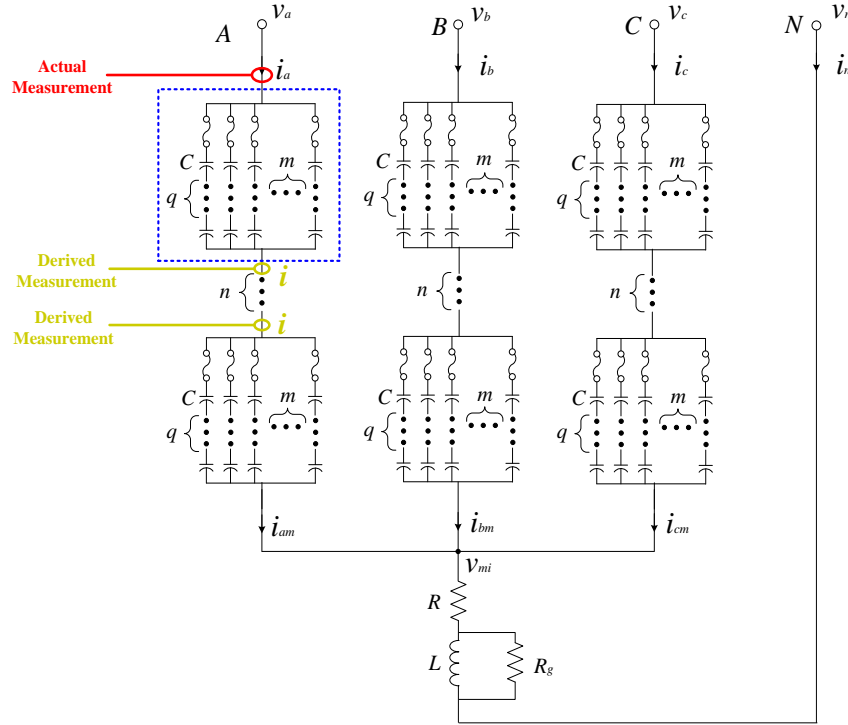

Figure 2.5: Example Derived Measurements

Pseudo Measurements: Pseudo measurements are hypothetical measurements for which we may have an idea of their expected values but we do not have an actual measurement. For example, a pseudo measurement can be the voltage at the neutral; we know that this voltage will be very small

under normal operating conditions. In this case we can define a measurement of value zero but with a very high uncertainty.

Summary: Eventually, all the measurement objects form the following measurement set:

$$z = h(x,t) + \eta = c + a^T x(t) + b^T x(t_m) + \begin{bmatrix} x^T(t) & x^T(t_m) \end{bmatrix} F \begin{bmatrix} x(t) \\ x(t_m) \end{bmatrix} + \eta,$$ (7)

where z is the measurement vector, x the state vector, h the known function of the model, a, b are constant vectors, F are constant matrices, and η the vector of measurement errors.

2.3 Object-Oriented Dynamic State Estimation

The proposed dynamic state estimation algorithm is the weighted least squares (WLS). The objective function is formulated as follows:

$$Minimize \ J(x,t) = [z - h(x,t)]^T W [z - h(x,t)],$$ (8)

where W is the diagonal matrix whose non-zero entries are the inverse of the variance of the measurement errors. The solution is obtained by the iterative method:

$$\hat{x}^{j+1} = \hat{x}^j + (H^T W H)^{-1} H^T W (z - h(\hat{x}^j, t)),$$ (9)

where $\hat{x}$ is the best estimate of states and H the Jacobian matrix of $h(x,t)$.

It is important to note that the dynamic state estimation requires only the mathematical model of all measurements. It should be also noted that for any component, the number of actual measurements and virtual, derived, and pseudo measurements exceed the number of states and they are independent. This makes the system observable and with substantial redundancy.

2.4 Bad Data Detection and Identification

It is possible that the streaming measurements may include bad data. In this case the algorithm must detect the bad data and identify the data. For the case of setting-less protection, it is important to recognize that in case of a component internal fault, all data may appear as bad data. It is important to determine whether any detected bad data are coming from instrumentation and meter errors or from altered component model due to internal faults. This topic is still under investigation as to what the best approach would be.

2.5 Protection Logic / Component Health Index

The solution of the dynamic state estimation provides the best estimate of the dynamic state of the component. The well-known chi-square test provides the probability that the measurements are consistent with the dynamic model of the component. Thus the chi-square test quantifies the goodness of fit between the model and measurements (i.e., confidence level). The goodness of fit is expressed as the probability that the measurement errors are distributed within their expected range (chi-square distribution). The chi-square test requires two parameters: the degree of freedom

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(*v*) and the chi-square critical value (ζ). In order to quantify the probability with one single variable, we introduce the variable k in the definition of the chi-square critical value:

$$v = m - n, \qquad \zeta = \sum_{i=1}^{m} \left(\frac{h_i(\hat{x}) - z_i}{k\sigma_i} \right)^2 , \qquad (10)$$

where *m* is the number of measurements, *n* the number of states, and $\hat{x}$ the best estimate of states. Note that since m is always greater than n, the degrees of freedom are always positive. Note also that if k is equal to 1.0 then the standard deviation of the measurement error corresponds to the meter error specifications. If k equals 2.0 then the standard deviation will be twice as much as the meter specifications, and so on. Using this definition, the results of the chi square test can be expressed as a function of the variable k. Specifically, the goodness of fit (confidence level) can be obtained as follows:

$$\Pr[\chi^2 \geq \zeta(k)] = 1.0 - \Pr[\chi^2 \leq \zeta(k)] = 1.0 - \Pr(\zeta(k), v) . \qquad (11)$$

A sample report of the confidence level function (horizontal axis) versus the chi-square critical value k, (vertical axis) is depicted in Figure 2.6.
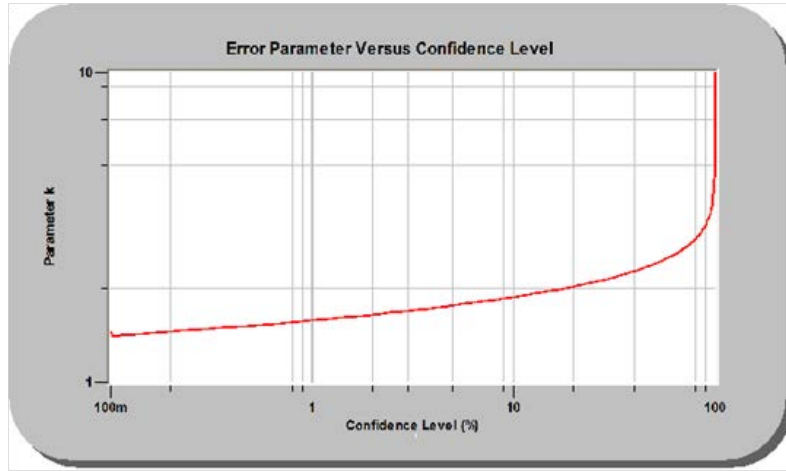
Figure 2.6: Confidence Level (%) vs Parameter k

The proposed method uses the confidence level as the health index of a component. A high confidence level indicates good fit between the measurement and the model, and thus we can conclude that the physical laws of the component are satisfied and the component has no internal fault. A low confidence level, however, implies inconsistency between the measurement and the model; therefore, we can conclude that an abnormality (internal fault) has occurred in the component and has altered the model. The discrepancy is an indication of how different the faulty model of the component is as compared to the model of the component in its healthy status.

It is important to point out that the component protection relay must not trip circuit breakers except when the component itself is faulty (internal fault). For example, in case of a transformer, inrush currents or over-excitation currents, should be considered normal and the protection system should not trip the component. The proposed protection scheme can adaptively differentiate these

phenomena from internal faults. Similarly, the relay should not trip for start-up currents in a motor, etc.

2.6   Online Parameter Identification

The dynamic state estimation can be extended to include as states parameters of components. In this case, the parameters of the components can be identified from measurements. This represents a fine tuning of the component model.

This option should not be continuously applied. Instead, it should be exercised only when there is doubt about the correctness of the component parameters. The issue will be addressed in greater detail in the filed applications of the setting-less protective relay.

2.7   Summary and Comments

The previous subsections have presented the approach for setting-less protection. The method is based on dynamic state estimation. The dynamic state estimation requires a detail model of the component under protection (protection zone) and a data acquisition system that acquires data with sufficient speed, such as 2,000 samples per second or higher. The accuracy of the data acquisition system is important, the more accurate it is the better the selectivity of the relay.

The proposed protection approach has been applied to several types of components (i.e., transformers, transmission lines, capacitor banks, etc.). We present examples in the next section.

3. Setting-less Protection Setup

This section describes the procedure for preparing the data required by a setting-lees protective relay, loading the data to the relay, initializing and arming the setting-less protective relay for example protection zones (single component or protection unit).

The creation of the models and measurement definition is performed in the program WinIGS-T. Many of the description below apply to the program WinIGS-T. For further studying of the procedures employed to define a setting-less relay, the reader should become familiar with the program WinIGS-T.

3.1 Single Component Protection Zone

The relay setup includes several steps, which are given with an example of the protection of a 300 MVA, 765/345 kV single-phase transformer. Figure 3.1 shows the Marcy Substation in NYPA system used for the estimation based protection (EBP) simulations. The single-phase transformer under protection is between buses MRC-AT1H and MRC-NSB1. It is circled and shown in an enlarged view. Instantaneous voltages and currents are measured at both sides of the transformer, with sampling rate 80 samples per cycle (4.8 kilo-samples per second).
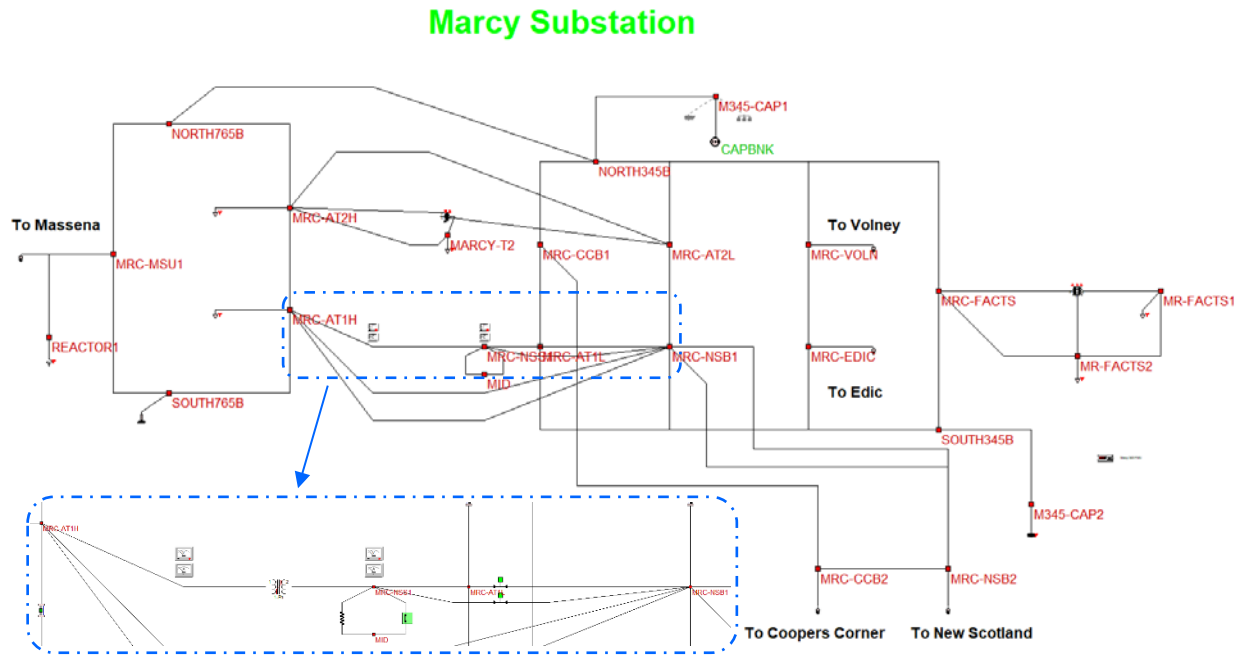
Figure 3.1: Single-Phase Transformer EBP Simulation System

The steps of preparing the model data, the measurement definition data, loading this information to the setting-less protective relay (EBP relay) are as follows.

Step 1: Prepare Device Model Files

Open the .NMT file (ProtectionExample1.NMT) of the transmission system. Click the 'IGS->XFM' button ![IGS XFM] and select the line under protection. Next, click the 'Export' button to export the device SCQDM/SCAQCF models of the line under protection. The details are given in Appendix C. The file name that contains these models is "ProtectionExample1.TDSCAQCF".

Step 2: Prepare Measurement Model Files

Open the .NMT file (ProtectionExample1.NMT) of the substation system. Click the 'IGS->XFM' button and ![IGS XFM] select the IEDs that summarize the measurements of the transformer under protection. Next, click the 'Export' button to export the measurement models of the transformer under protection. The details are given in Appendix D. The file name that contains the measurement models is "ProtectionExample1.TDMDEF".

Step 3: Import Device Model Files

Click the 'Import' button on the 'Estimation Based Protection' interface, 'Device & Measurement Model' block. An example pop-up window is shown in Figure 3.2. After that, check the device model file format (i.e., .TDCSAQCF), click 'Device & Measurement Model Files', select files, and click 'Import'. Typically the measurement model files are imported at the same time, as long as we also check the measurement model file format, '.TDMDEF', before we click 'Device & Measurement Model Files', select files, and click 'Import' (the measurement model file should have the same name as the device model file expect the extension). Finally, check the 'active' box inside the 'Select Protected Device' block to activate the devices under protection.

Figure 3.2: Importing Device or Measurement Files, Single Component Protection Case

Step 4: Import Measurement Model Files

Click the 'Import' button on the 'Estimation Based Protection' interface, 'Device & Measurement Model' block. An example pop-up window is shown in Figure 3.2. After that, check the measurement model file format (i.e., .TDMDEF), click 'Device & Measurement Model Files', select files, and click 'Import'. Typically the device model files are imported at the same time, as long as we also check the device model file format, i.e., '.TDSCAQCF', before we click 'Device & Measurement Model Files', select files, and click 'Import' (the device model file should have the same name as the measurement model file expect the extension). Finally, check the 'active' box inside the 'Select Protected Device' block to activate the devices under protection.

Step 5: Provide Settings for the EBP Relay

Click the 'Relay Settings' button inside the 'Device & Measurement Model' block. The pop-up window is shown in Figure 3.3. Here the two settings are 50 ms for the reset time (T_r) and 20 ms for the delay time (T_d). Also, the number N is selected to be 2.

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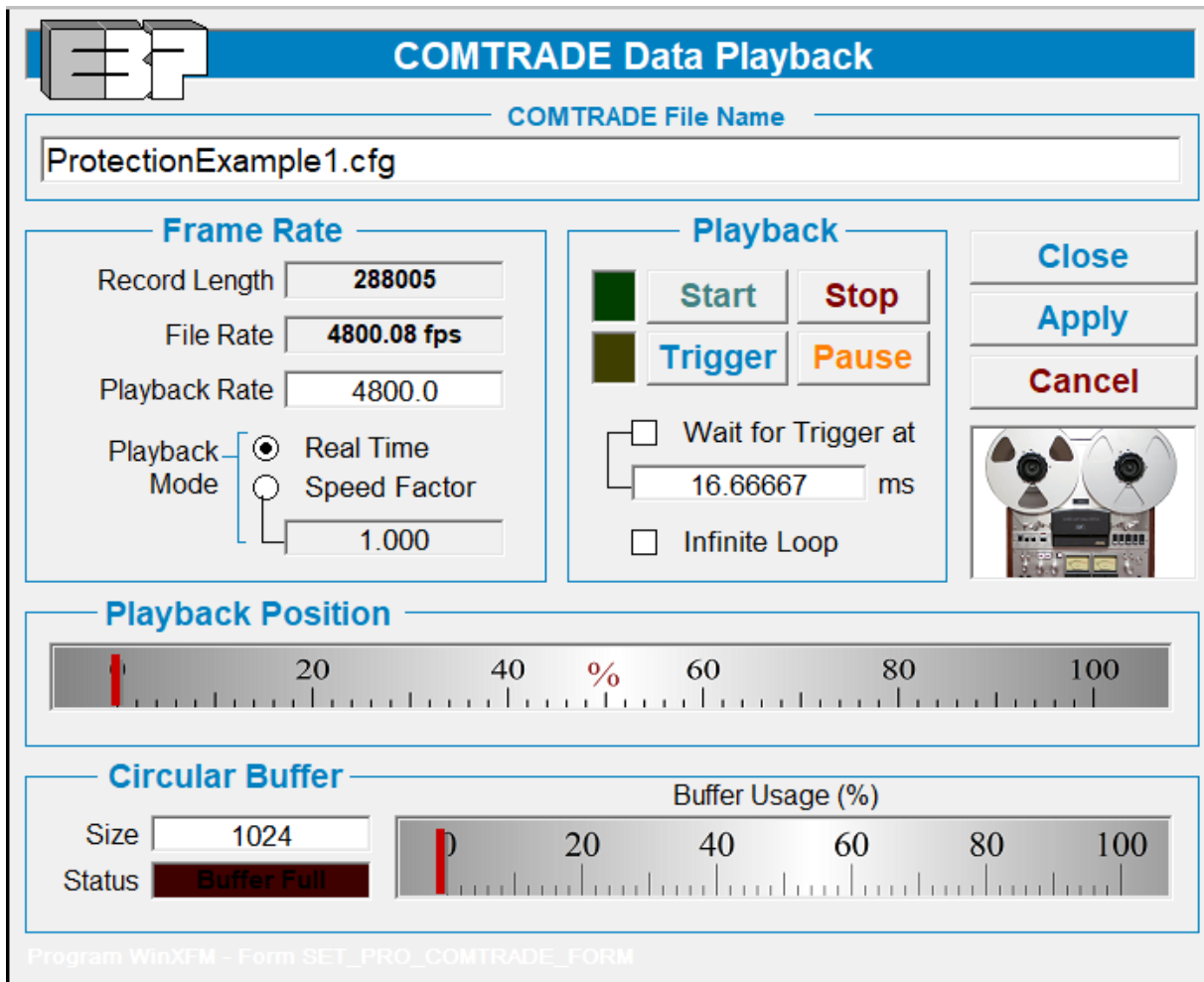
Figure 3.3: Settings of the EBP Relay, Single Component Protection Case

Step 6: Input Data

Next, two exclusive alternatives of data inputs are introduced in **Step 6a (using COMTRADE files, simulation) and Step 6b (using merging units, real time)**. Step 6a is to use existing COMTRADE files for EBP, while Step 6b is to use the actual data obtained from the merging units for EBP. Note that here two demonstrative examples are also provided for two possible selections of data source.

Step 6a: Input Data from Existing Comtrade Data Files

Click the 'Setup' button in the 'COMTRADE Data' block. The pop-up window is shown in Figure 3.4. After that, click 'COMTRADE File Name' to select the COMTRADE file corresponding to this event. (with '.cfg'). Also, the playback rate is selected as 'real time' and the circular buffer size is selected as 20000. The COMTRADE file names are "ProtectionExample1.cfg" and "ProtectionExample1.dat".

Figure 3.4: Input Data from Existing COMTRADE Files, Single Component Protection Case

Step 6b: Input Data from Merging Units

Click the 'Setup' button inside the 'MU Data Concentrator' block. The pop-up window is shown in Figure 3.5. The selections are shown inside the figure. Also, the merging units setup, measurements setup, and the reference clock setup are shown in Figures 3.6, 3.7 and 3.8, respectively.

Figure 3.5: Input Data from Merging Units, Single Component Protection Case

Figure 3.6: Set Up the List of Merging Units, Single Component Protection Case

Figure 3.7: Set Up the List of Measurements, Single Component Protection Case

	Name	Phase	Type	Scale	Offset	Instrument Transformer	MU Order	Mu ID
1	Voltage_Primary_AN	AN	Voltage	0.01000	0	1.0 kV / 69.0 V	5	SIEMENSMU0101
2	Voltage_Secondary_AN	AN	Voltage	0.01000	0	1.0 kV / 69.0 V	6	SIEMENSMU0101
3	Current_Primary_A	A	Current	0.001000	0	5.0 A / 4.0 A	1	SIEMENSMU0101
4	Current_Secondary_A	A	Current	0.001000	0	5.0 A / 4.0 A	2	SIEMENSMU0101

Figure 3.8: Set Up the Reference Clock, Single Component Protection Case

Step 7: Run the EBP Relay

The final step is to run the EBP relay. First, select the algorithm of the EBP relay to be 'SCAQCF' and 'Estimates', as shown in Figure 3.9. Next, click the 'Start' button inside either the 'COMTRADE Data' block (with existing COMTRADE files, Step 6a) or the 'MU Data Concentrator' (with merging units, Step 6b). Afterwards, click the 'Start' button inside the 'EBP relay block'. The 'Target' will be 'Asserted' if the program detects a continuous low confidence level, and the 'Breaker' will be 'Open' if the relay trips the transformer under protection.
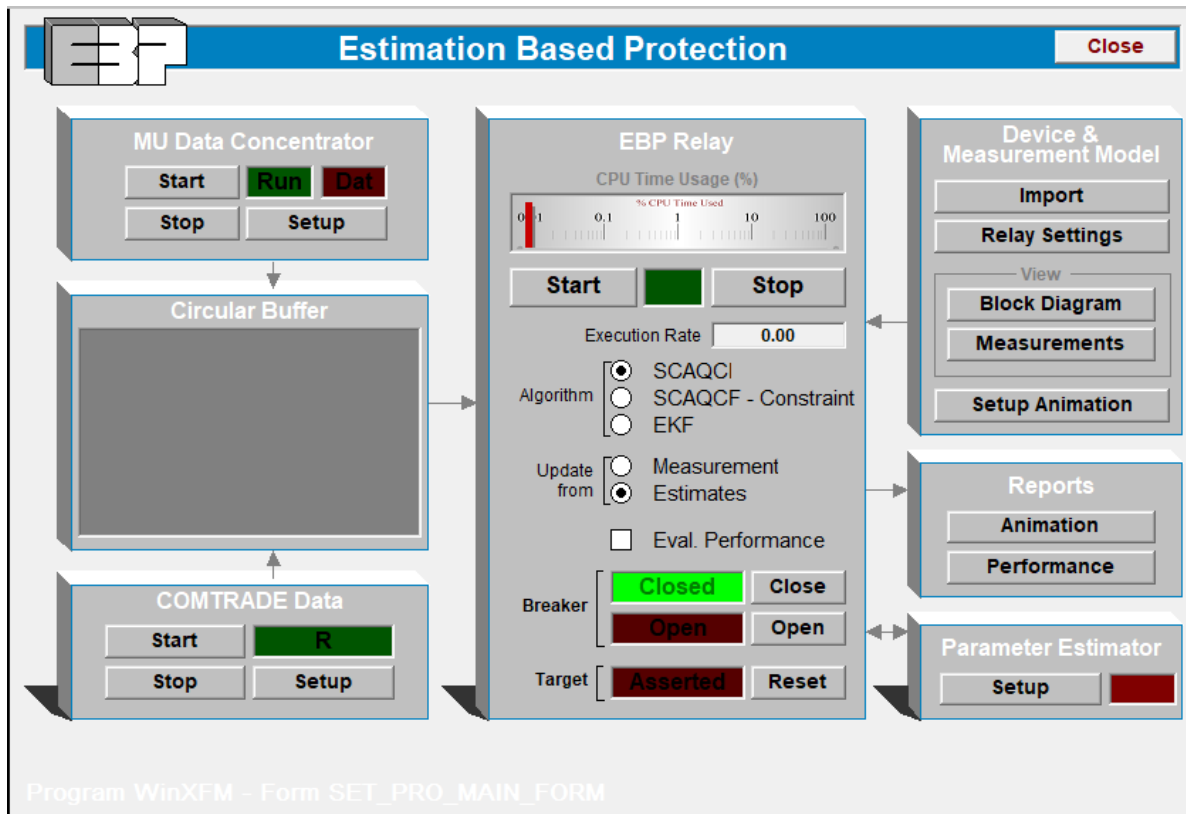
Figure 3.9: EBP Relay Algorithm Selection, Single Component Protection Case

Next, the performance of the EBP relay is shown with the following event. An internal coil fault occurs at time 19.78 sec with the fault impedance being 10 Ω. The simulation results are shown in Figure 3.10 for the period 19.50 sec to 20.00 sec.
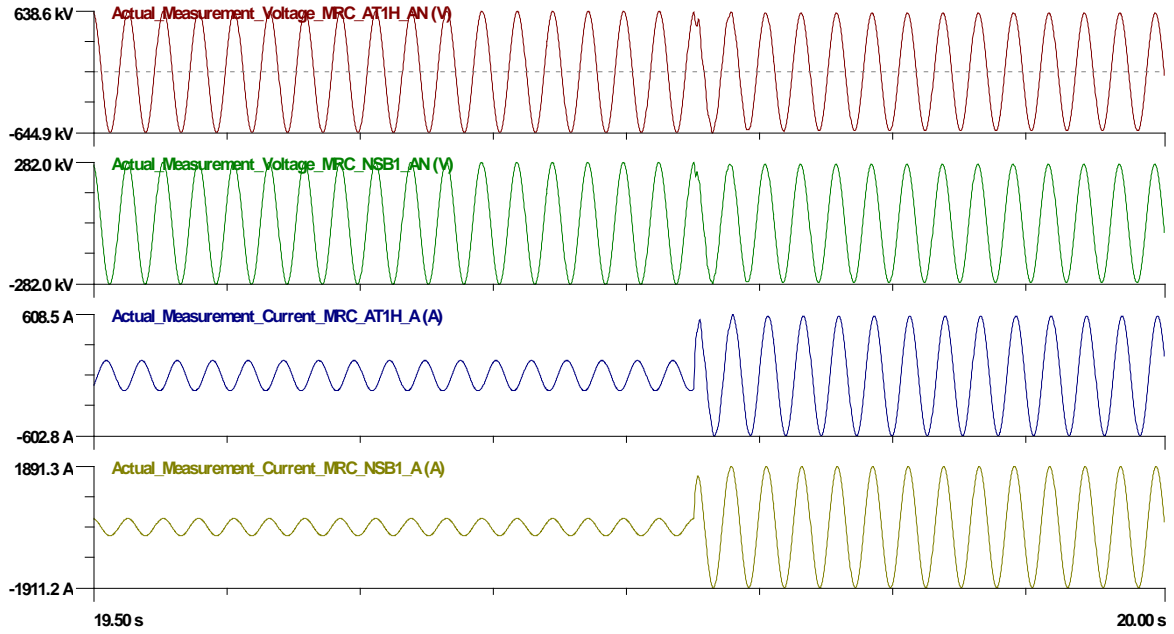
Figure 3.10: Voltage and Current Measurements of an Internal Coil Fault, Single Component Protection Case

The results of the EBP relay are depicted in Figure 3.11. The actual and estimated values of the phase A currents at bus MRC_AT1H are shown in the first two channels. The residuals, i.e. the differences between the actual and estimated values, are shown in the third channel. The chi-square test results, confidence level and trip decision are provided in the last three channels. The confidence level drops to zero after one sampling period from the fault initiation at 19.7802 sec and stays zero during fault. This means that the relay detects the fault at time 19.7802 sec and it will trip this fault at 19.8002 sec. Since the fault was initiated at 19.78 sec, this means that the EBP relay detects the fault in 0.0002 sec.
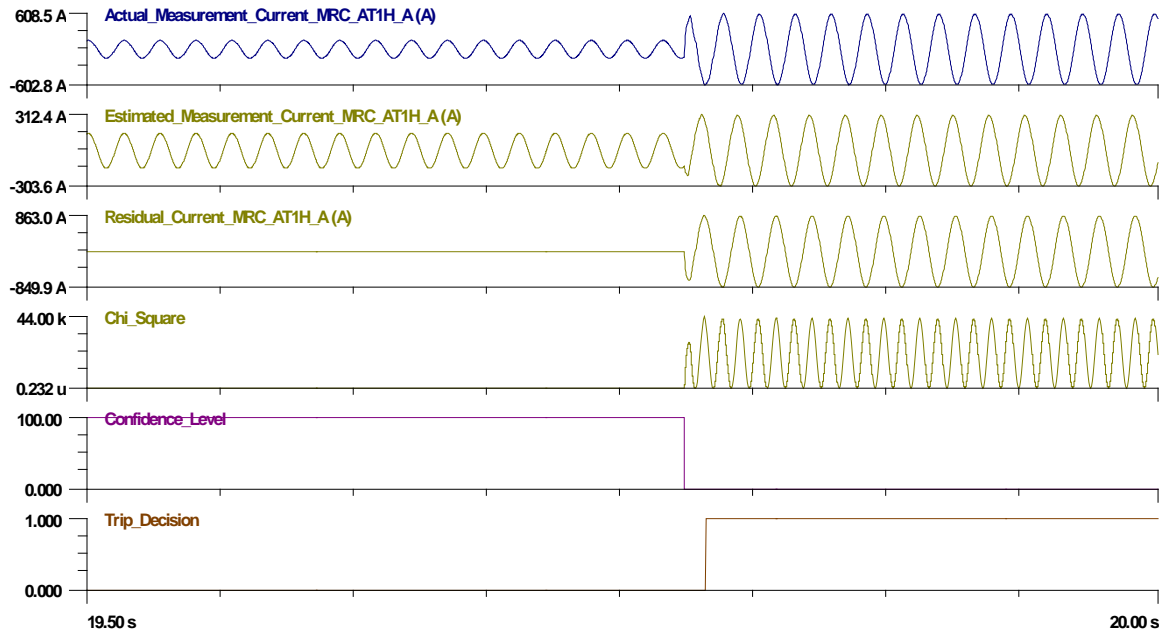
Figure 3.11: EBP Relay Results of an Internal Coil Fault, Single Component Protection Case

3.2   Multi-Component Protection Zone - Unit Protection

The protection of a unit (or network) consisting of several devices is similar to the single component protection. The protection zone in this example is a unit zone consisting of a transformer and a UD cable.

Figure 3.12 shows the transmission system used for the simulations. As shown in Figure 3.13, the unit zone consisting of a transformer and a UD cable. The transformer under protection is the 3-phase 3 winding transformer 1 (225 kV/ 93 kV/ 10.5 kV, 100 MVA). The UD cable under protection is the cable 1 (90 kV, 250 feet, 142.84 A rated current), from bus CABLE1~90 to bus XFM1~93.
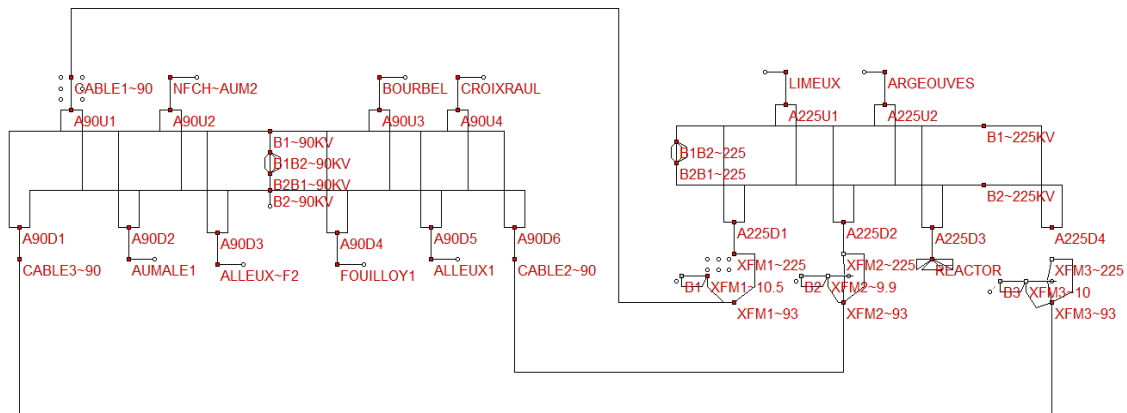
Figure 3.12: The Unit Zone EBP Simulation System

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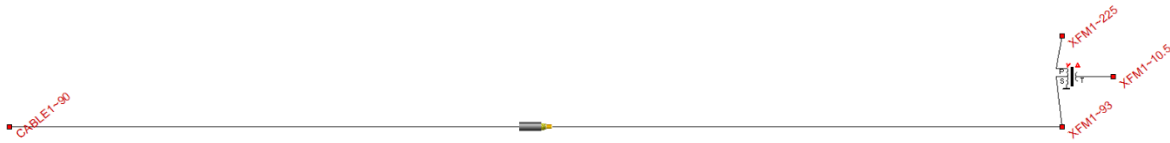
Figure 3.13: The Unit Protection Zone (Including a Cable and a Transformer)

The steps of preparing the model data, the measurement definition data, loading this information to the setting-less protective relay (EBP relay) are as follows.

Step 1: Prepare Device Model Files

Open the .NMT file (ProtectionUnitExample2.NMT) of the transmission system. Click the 'IGS->XFM' button and select the line under protection. Next, click the 'Export' button to export the device SCQDM/SCAQCF models of the unit zone under protection. The details are given in Appendix C. The file name that contains these models is "ProtectionUnitExample2.TDSCAQCF".

Step 2: Prepare Measurement Model Files

Open the .NMT file (ProtectionUnitExample2.NMT) of the transmission system. Click the 'IGS->XFM' button and select the IEDs that summarize the measurements of the unit zone under protection. Next, click the 'Export' button to export the measurement models of the line under protection. The details are given in Appendix D. The file name that contains the measurement models is "ProtectionUnitExample2.TDMDEF".

Step 3: Import Device Model Files

Click the 'Import' button on the 'Estimation Based Protection' interface, 'Device & Measurement Model' block. An example pop-up window is shown in Figure 3.14. After that, check the device model file format (i.e., .TDCSAQCF), click 'Device & Measurement Model Files', select files, and click 'Import'. Typically the measurement model files are imported at the same time, as long as we also check the measurement model file format, '.TDMDEF', before we click 'Device & Measurement Model Files', select files, and click 'Import' (the measurement model file should have the same name as the device model file expect the extension). Finally, check the 'active' box inside the 'Select Protected Device' block to activate the devices under protection.
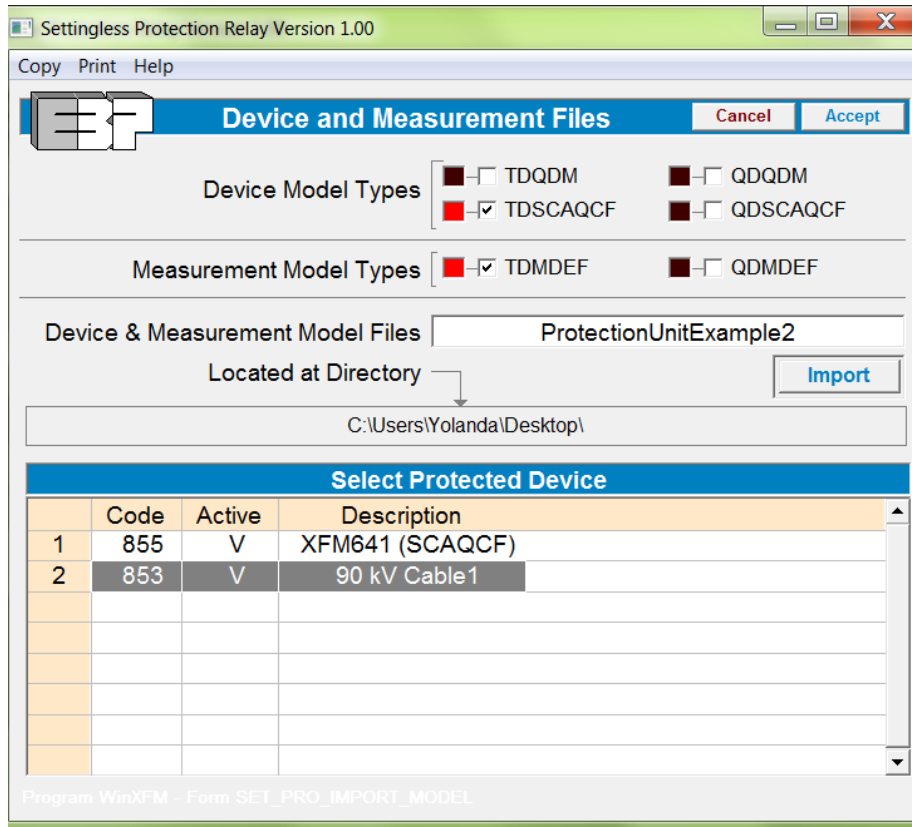
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Figure 3.14: Importing Device and Measurement Files, Unit Protection Case

Step 4: Import Measurement Model Files

Click the 'Import' button on the 'Estimation Based Protection' interface, 'Device & Measurement Model' block. An example pop-up window is shown in Figure 5.14. After that, check the measurement model file format (i.e., .TDMDEF), click 'Device & Measurement Model Files', select files, and click 'Import'. Typically, the device model files are imported at the same time, as long as we also check the device model file format, i.e., '.TDSCAQCF', before we click 'Device & Measurement Model Files', select files, and click 'Import' (the device model file should have the same name as the measurement model file expect the extension). Finally, check the 'active' box inside the 'Select Protected Device' block to activate the devices under protection.

Step 5: Provide Settings for the EBP Relay

Click the 'Relay Settings' button inside the 'Device & Measurement Model' block. The pop-up window is shown in Figure 3.15. Here the two settings are 50 ms for the reset time (T_r) and 20 ms for the delay time (T_d). Also, the number N is selected to be 2.

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Figure 3.15: Settings of the EBP Relay, Unit Protection Case

Step 6: Input Data

Next, two exclusive alternatives of data inputs are introduced in **Step 6a (using COMTRADE files, simulation) and Step 6b (using merging units, real time)**. Step 6a is to use existing COMTRADE files for EBP, while Step 6b is to use the actual data obtained from the merging units for EBP. Note that here two demonstrative examples are also provided for two possible selections of data source.

Step 6a: Input Data from Existing Comtrade Data Files

Click the 'Setup' button in the 'COMTRADE Data' block. The pop-up window is shown in Figure 3.16. After that, click 'COMTRADE File Name' to select the COMTRADE file corresponding to this event. (with '.cfg'). Also, the playback rate is selected as 'real time' and the circular buffer size is selected as 20000.

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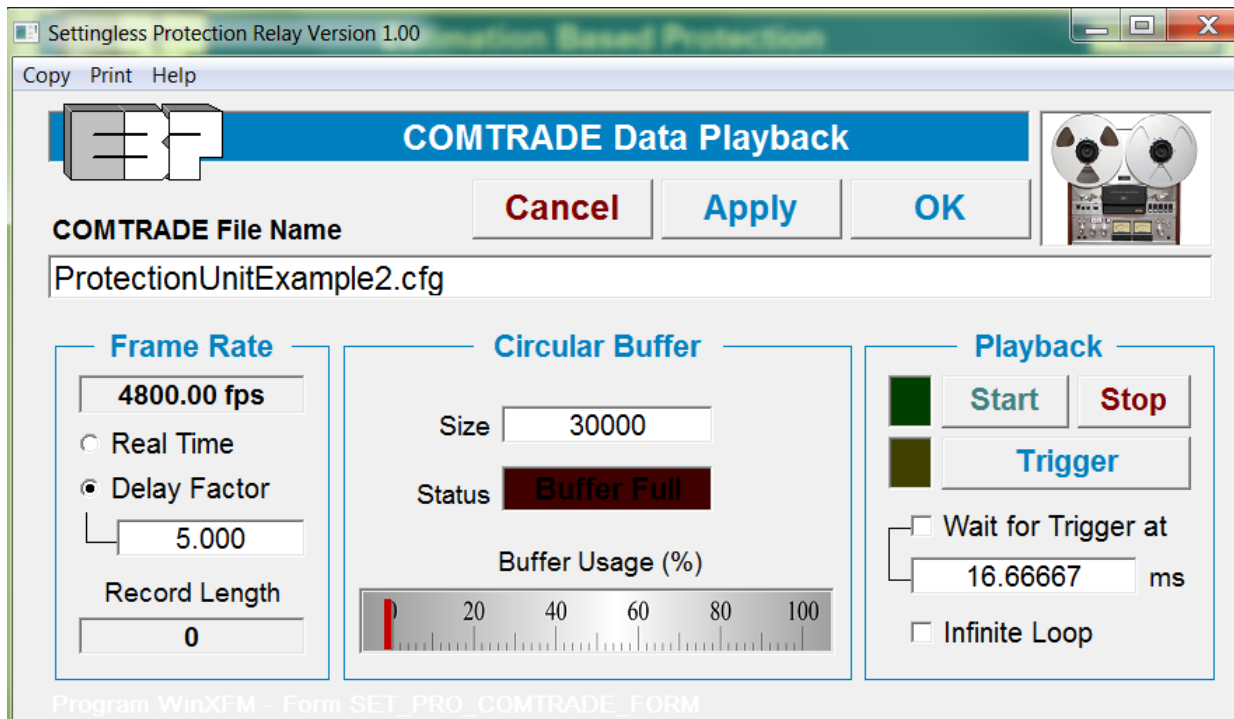
Figure 3.16: Importing COMTRADE Data Files, Unit Zone Case

Step 6b: Input Data from Merging Units

 (After testing the unit zone protection case in the hardware, we will update the results here)

Step 7: Run the EBP Relay

The final step is to run the EBP relay. First, select the algorithm of the EBP relay to be 'SCAQCF' and 'Estimates', as shown in Figure 3.17. Next, click the 'Start' button inside either the 'COMTRADE Data' block (with existing COMTRADE files, Step 6a) or the 'MU Data Concentrator' (with merging units, Step 6b). Afterwards, click the 'Start' button inside the 'EBP relay block'. The 'Target' will be 'Asserted' if the program detects a continuous low confidence level, and the 'Breaker' will be 'Open' if the relay trips the line under protection.
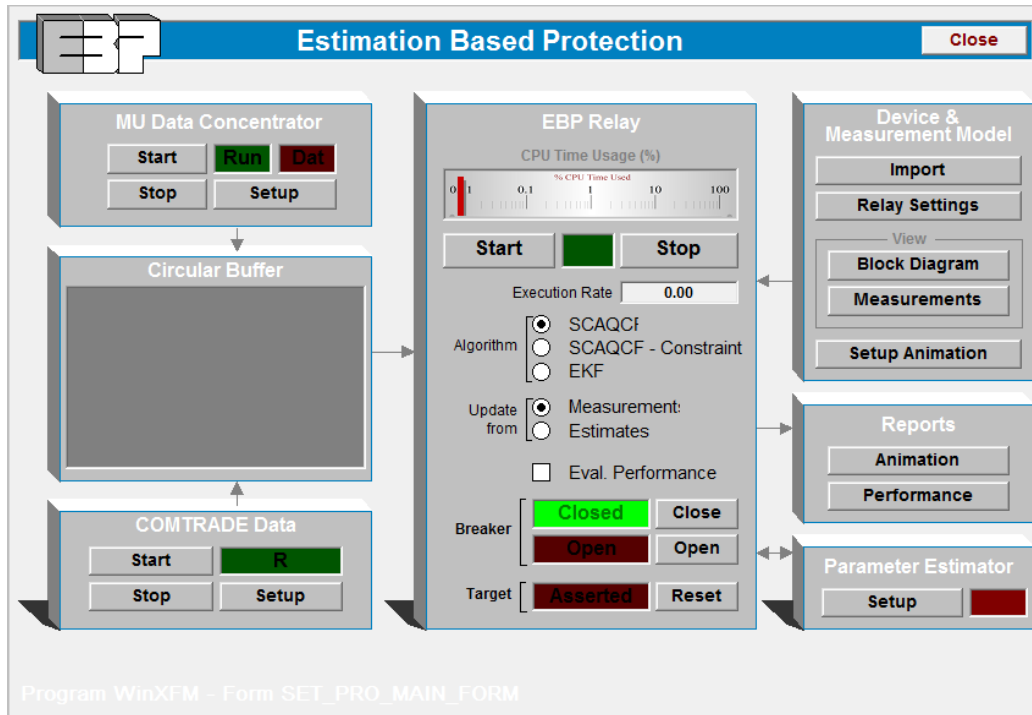
Figure 3.17: EBP Relay Algorithm Selection, Unit Protection Case

Next, the performance of the EBP relay is shown with the following event. A phase A to neutral internal fault with 0.01 Ω impedance occurs on cable 1 at 125 feet from bus Cable 1~90 kV at t=10.00 s and it clears at t=10.18 s. The simulation results are shown in Figure 3.18 for the period [9.925 sec to 10.21 sec].
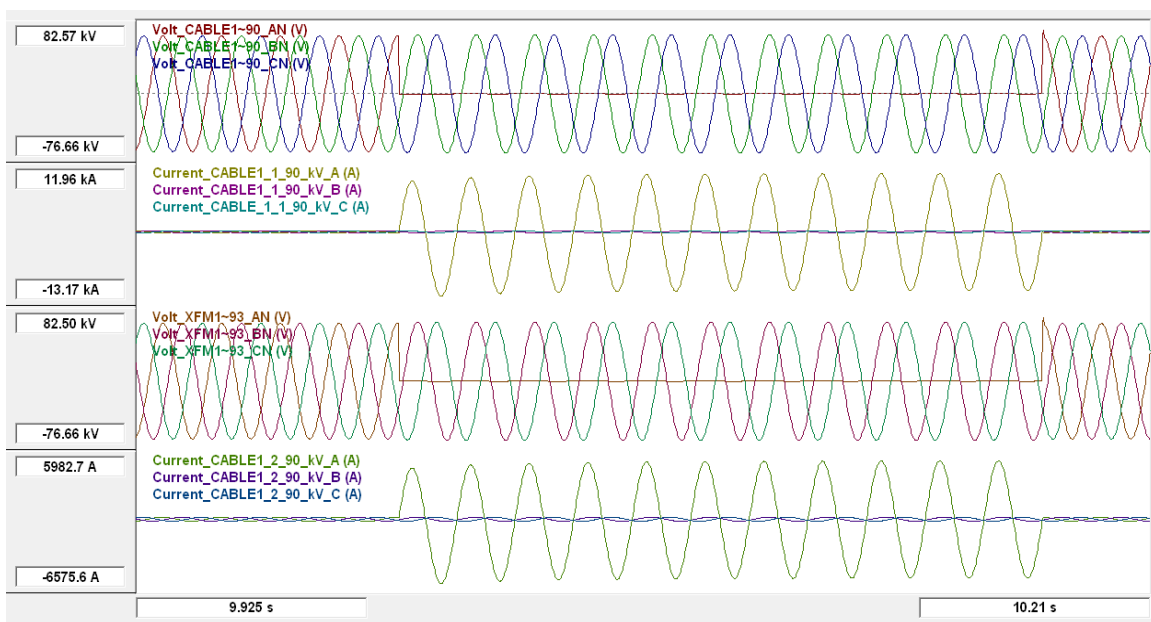
Figure 3.18: Current and Voltage Measurements of a Phase A to N Bolted Internal Fault

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4. Laboratory Implementation and Testing

4.1   Introduction

Laboratory testing enables the testing of the setting-less relay with hardware in the loop. For this purpose simulated data are streaming into a bank of digital to analog converters, the output of the converters are next fed into a bank of amplifiers to bring the analog signal to typical levels encountered in an actual system. These signals are connected to merging units and the merging units are connected to the setting-less protective relay.

This section describes the experiment set-up and provides example results. It is organized as follow: Section 4.2 describes the laboratory circuitry that enables experiments with hardware in the loop; Section 4.3 describes the simulated events and the associated data used for these experiments; Section 4.4 explains the detailed setup for how to send simulation data to the merging units; Section 4.5 describes the data received from merging unit; Section 4.6 combines the simulation data (input) and merging unit data (output) and calculates their differences; Section 4.7 analyzes the differences between input and output.

4.2   Experiment Circuit Description

The connection diagram between various equipment is illustrated in Figure 4.1. Basically, the experiment consists of three parts: 1) simulator; 2) process bus; 3) setting-less protection relay.
In the simulator part, the user interface generates digital streaming waveforms representing the terminal voltages and currents of the protection zone (power system component) to the NI 32 channel DC/AC converter. It is emphasized here that the source for the digital streaming waveforms can be simulated voltages and currents of the power system component, or field collected measurements from the CTs/PTs in the COMTRADE format. Omicron amplifiers receive the analog signals from the NI DC/AC converter and amplify these signals to a range which is very similar to real output of electronic CTs/PTs (for voltages around 50V and for currents around 5A). In this manner, the electrical output (voltages and currents) of the Omicron amplifiers are treated as the secondary electrical quantities from the CTs/PTs in this lab implementation.

In the process bus part, two merging units from Reason and GE are connected to the output terminals of the Omicron amplifier, and a cross connect panel or Ethernet hub routes the data from the output of merging units.

The Setting-less protection relay, which is implemented as another user interface, receives the data sampled by each merging unit and feed the data to dynamic state estimator.

As a summary, the simulator sends COMTRADE file to the experiment circuit (called input COMTRADE file), and the relay receives streamlined data from the experiment circuit, the relay has the option to feed the data directly into the protection algorithm, or simply store all data into COMTRADE file (called output COMTRADE file) for future use.
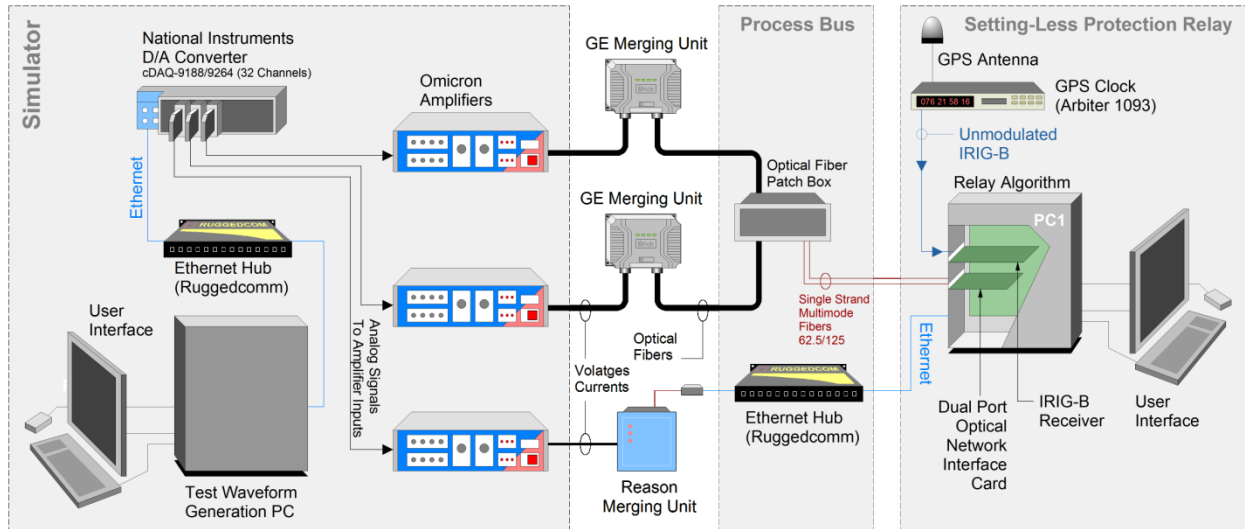
Figure 4.1: Experiment Setup – Connection Diagram

In this document, only the data from REASON merging unit is used. A detailed wiring diagram between the amplifier and the REASON merging unit is illustrated in Figure 4.2. The CMS 156 amplifier has three phase voltage channels and one neutral voltage channel, three phase current channels and one neutral current channel. All the outputs are connected to the inputs of the REASON MU via a panel where banana type plugs are used. The wiring cable from amplifier to the panel is AWG #10, and the wiring cable from the panel to the MU is AWG #16. The amplifier has 1V/50V amplification over voltage channels, and 1V/5A amplification over current channels.
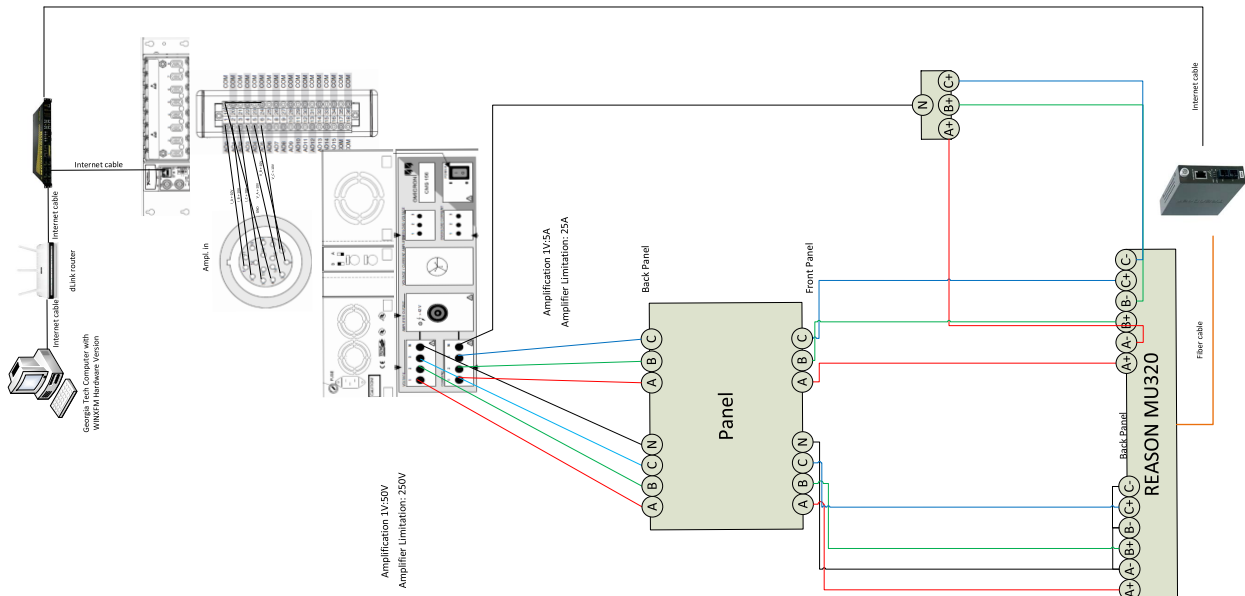
Figure 4.2: Wiring Diagram between Amplifier and Reason MU

4.3   Simulation Events

The test system that WINXFM uses to generate simulation data to the amplifier is illustrated in Figure 4.3. The transmission line framed by the blue dashed line, from node YJLINE1 to node YJLINE2, is under protection. The loading current on the line is around 420A. There are three voltage meters and three current meters on node YJLINE1 and another three voltage meters and three current meters on node YJLINE2. However, since the merging unit can only sample dataset from one amplifier, the voltage and current measurements on node YJLINE1 is chosen.

The simulation time is 2 seconds, where the transmission line works in normal operation. No external/internal events simulated.
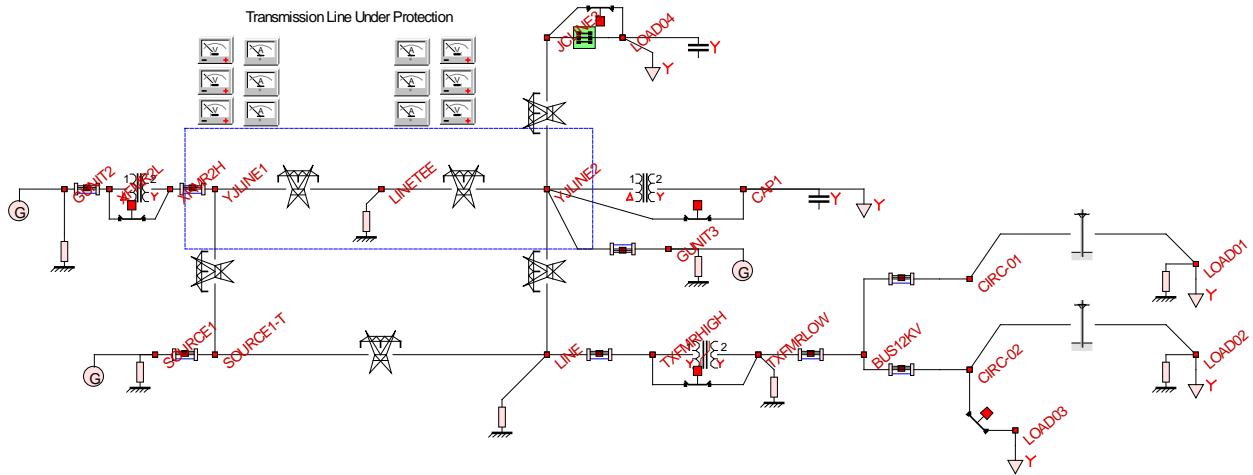
Figure 4.3: Test System for Generating Simulation Data

A snapshot of the voltage and current measurements on node YJLINE1 is in the Figure 4.4. Here, Voltage_A_SIM stands for simulated phase A to neutral voltage on node YJLINE1.
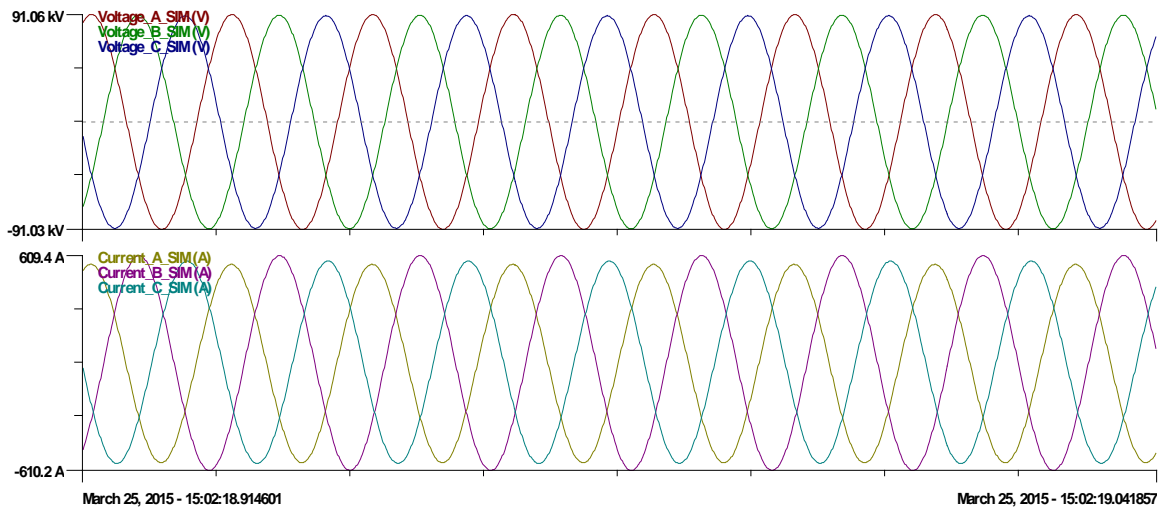
Figure 4.4: Test System Simulation Results

Experiment Setup

To run the experiment, the user needs to setup two user interfaces.

The first user interface sets up the transformation ratio of the amplifier. Since PT/CT are not available at this moment, the amplifiers transform the simulation data which are in primary electrical level to a range which is very similar to real output of electronic CTs/PTs (for voltages around 50V and for currents around 5A). In this manner, the electrical output (voltages and currents) of the Omicron amplifiers are treated as the secondary electrical quantities from the CTs/PTs in this lab implementation. Figure 4.5 to Figure 4.10 shows the setup for each channel. In Figure 4.5, the source peak is 569A for phase A current, and set the transformation ratio to 500:1, so that the amplifier output peak is 1.138A. Note that 5A peak is usually used but for the sake of safety we set the peak around 1A. The same ratio is set for phase B and C current in Figure 4.6 and Figure 4.7. In Figure 4.8, the source peak is 91kV for phase A voltage, and set the transformation ratio to 100kV:66.7V, so that the amplifier output peak is 60V. The same ratio is set for phase B and C voltage in Figure 4.9 and Figure 4.10. Figure 4.11 is used to check all the amplifier channels. Only 6 channels are active at this moment. The data are played back repeatedly so that a discontinuity happens every 2 seconds.

Figure 4.5: Amplifier Setup for Transformation on Phase A Current
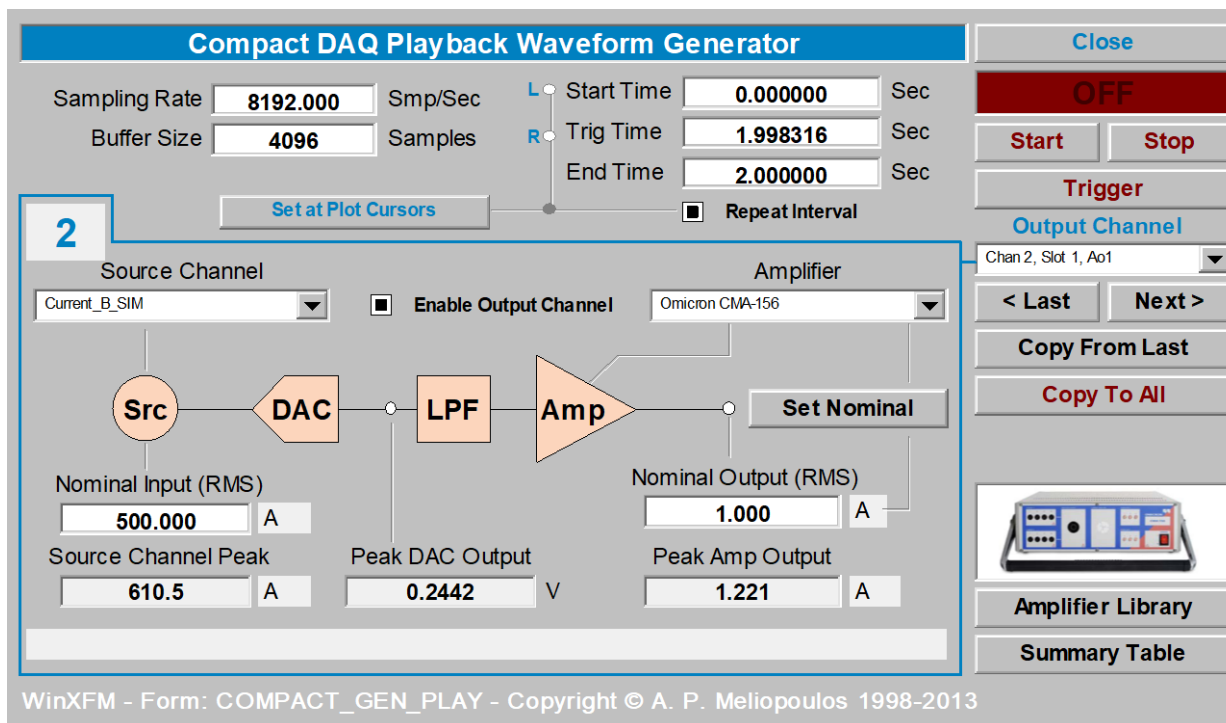
Figure 4.6: Amplifier Setup for Transformation on Phase B Current

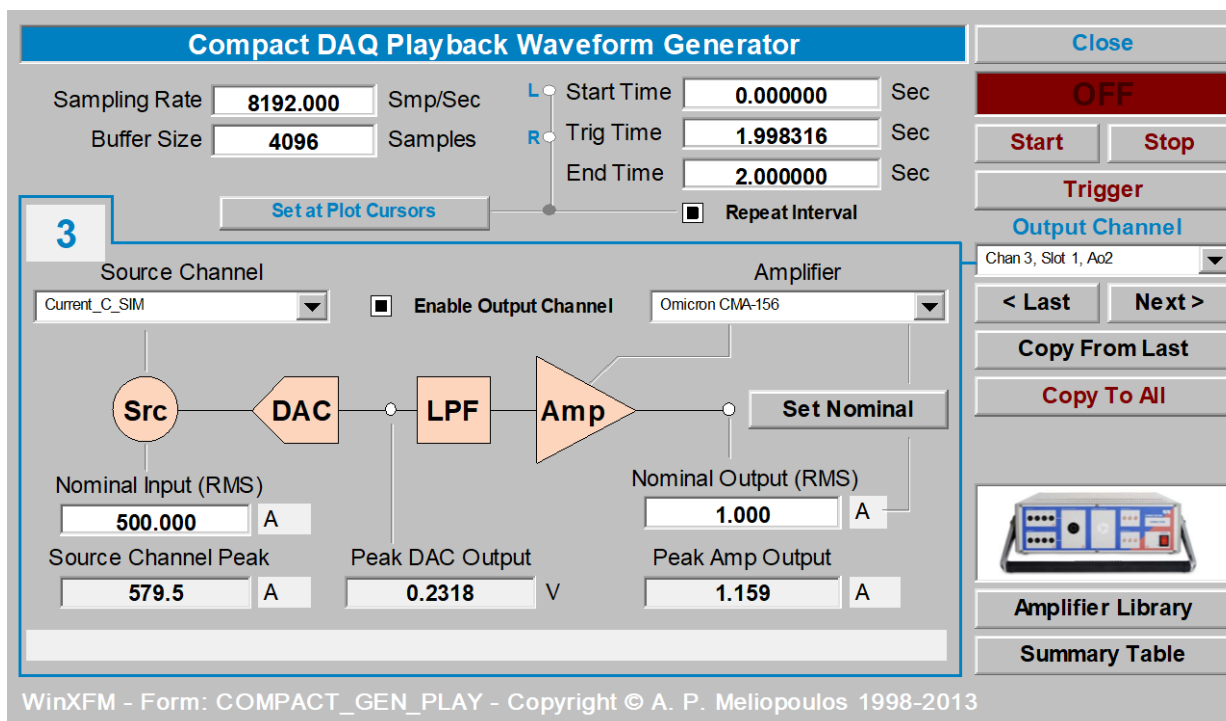Figure 4.7: Amplifier Setup for Transformation on Phase C Current

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Figure 4.8: Amplifier Setup for Transformation on Phase A Voltage

Figure 4.9: Amplifier Setup for Transformation on Phase B Voltage

Figure 4.10: Amplifier Setup for Transformation on Phase C Voltage

	Pin/Slot	Active	Type	Source Chan	Amplifier	Src Nominal	Src Peak	Out Nominal	Out Peak
1	1/0	1	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	1.000 A	1.138 A
2	1/1	1	Current	Current_B_SIM	Omicron CMA-156	500.0 A	610.5 A	1.000 A	1.221 A
3	1/2	1	Current	Current_C_SIM	Omicron CMA-156	500.0 A	579.5 A	1.000 A	1.159 A
4	1/3	1	Voltage	Voltage_A SIM	Omicron CMS-156	100000.0 V	91055.2 V	66.70 V	60.73 V
5	1/4	1	Voltage	Voltage_B SIM	Omicron CMS-156	100000.0 V	90551.6 V	66.70 V	60.40 V
6	1/5	1	Voltage	Voltage_C_SIM	Omicron CMS-156	100000.0 V	90132.6 V	66.70 V	60.12 V
7	1/6	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
8	1/7	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
9	1/8	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
10	1/9	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
11	1/10	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
12	1/11	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
13	1/12	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
14	1/13	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
15	1/14	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
16	1/15	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
17	2/0	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
18	2/1	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
19	2/2	0	Current	Current_A_SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A
20	2/3	0	Current	Current_A SIM	Omicron CMA-156	500.0 A	569.0 A	2.000 A	2.276 A

Figure 4.11: Summary Table of All the Channels Setup in the Amplifier

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The second user interface sets up the data concentrator, which is demonstrated in Figure 4.12. According to IEC 61850-9-2 light, the first four channels are currents and the second four channels are voltages. So that the MU order is 1, 2, 3 for currents, and 4, 5, 6 for voltages. Also, the PT transformation ratio is set to be 100kV/66.7V which is the same as that of the first user interface. The CT transformation ratio is set to be 500A/1A which is the same as that of the first user interface. Here, Voltage_A_MU stands for phase A to neutral voltage captured from merging unit.

Merging Unit Data Concentrator

Close

Measurement Attributes

	Name	Phase	Type	Scale	Offset	Instrument Transformer	MU Order	MU
1	Voltage_A_MU	A	Voltage	0.01000	0	100.0 kV / 66.7 V	5	GATECH-MU320
2	Voltage_B_MU	B	Voltage	0.01000	0	100.0 kV / 66.7 V	6	GATECH-MU320
3	Voltage_C_MU	C	Voltage	0.01000	0	100.0 kV / 66.7 V	7	GATECH-MU320
4	Current_A_MU	A	Current	0.01000	0	500.0 A / 1.0 A	1	GATECH-MU320
5	Current_B_MU	B	Current	0.01000	0	500.0 A / 1.0 A	2	GATECH-MU320
6	Current_C_MU	C	Current	0.01000	0	500.0 A / 1.0 A	3	GATECH-MU320

New | Edit | Delete | Move Up | Move Down | Merging Units

Sampling Parameters

Sampling Rate 4800.00
Base Frequency 60.00
Max Latency 8
Full Buffer Size 1024

Error Counts

Buffer Full 0
Smp Count 0
Late Pkt 0
Missing Pkt 0
Latency 0
Smp Rate 0
Unknown MU 0
Bad Pkt 0

Reset Counts

Streaming

Run **Xmt** **Rcv**

Start

Stop

☑ Plot Raw Data
☐ Packet Reports
☐ Error Reports

Performance

Average Latency (%)   0.00 ms
0   20   40   60   80   100

Buffer Usage (%)
0   20   40   60   80   100

Program WinXFM - Form SET_PRO_MUCOM_FORM

Figure 4.12: Data Concentrator Setup

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4.4   Data from Merging Units

A snapshot of the data captured from merging unit is in Figure 4.13. The data is stored in output COMTRADE file for analysis.

Figure 4.13: Data Captured from Merging Unit

4.5   Combined Results for Input and Output of the Experiment

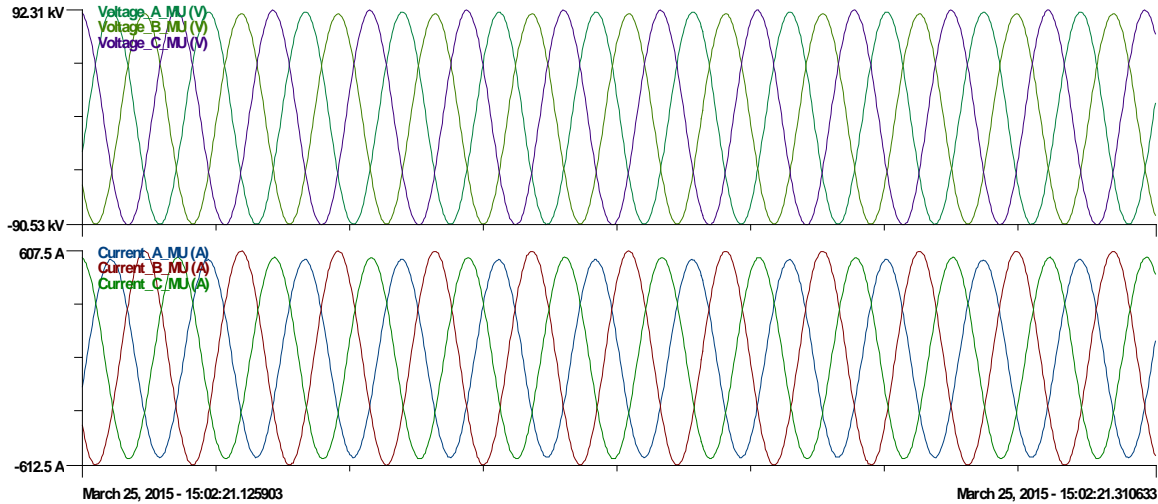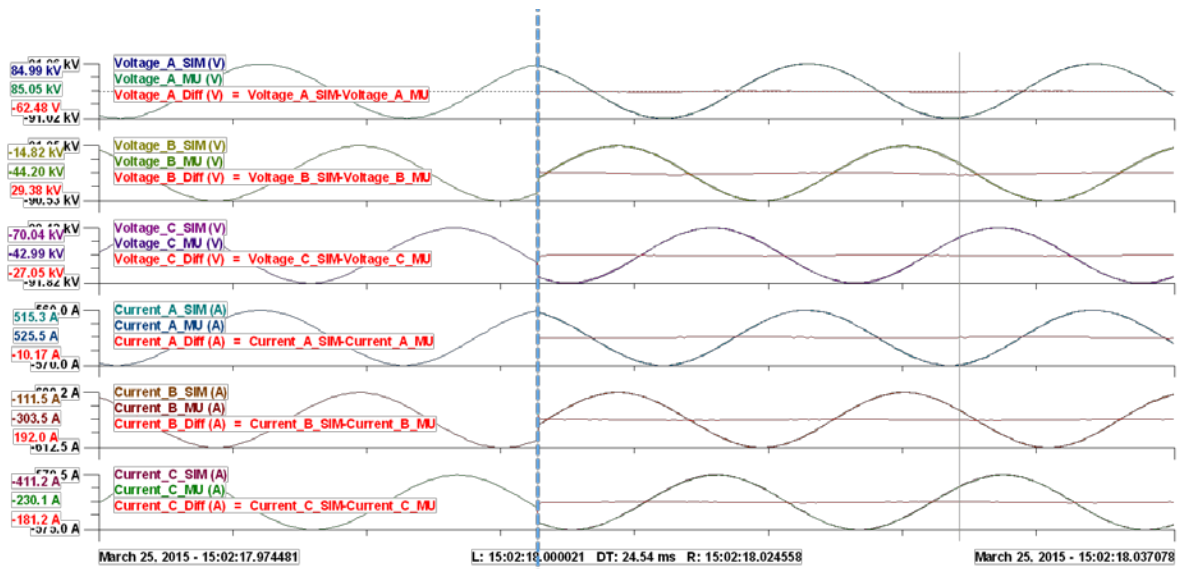As illustrated, the input and output of the experiment are stored in COMTRADE file for analysis. The first study is to compare the input and output, and ideally the two should be identical, however they're not due to channel noises, timing issues, etc.

In order to compare the two, firstly the output needs to be aligned to the input. The reason is that the data are played back repeatedly every playback cycle (one playback cycle is 2 seconds), so that if the merging unit records 10 seconds of data, there would be 5 playback cycles of output, however only 1 cycle of input. The starting point of a single playback cycle of the output needs to be aligned with the starting point of the cycle of the input. Figure 4.14 shows the time alignment point. At the alignment point, one cycle of the playback is finished, and a new cycle is started. It is easy to observe that discontinuity of waveforms exists between two cycles.

Figure 4.14: Alignment Point between Input and Output

The comparison between input and output for a whole playback cycle (2 seconds) is illustrated in Figure 4.15.
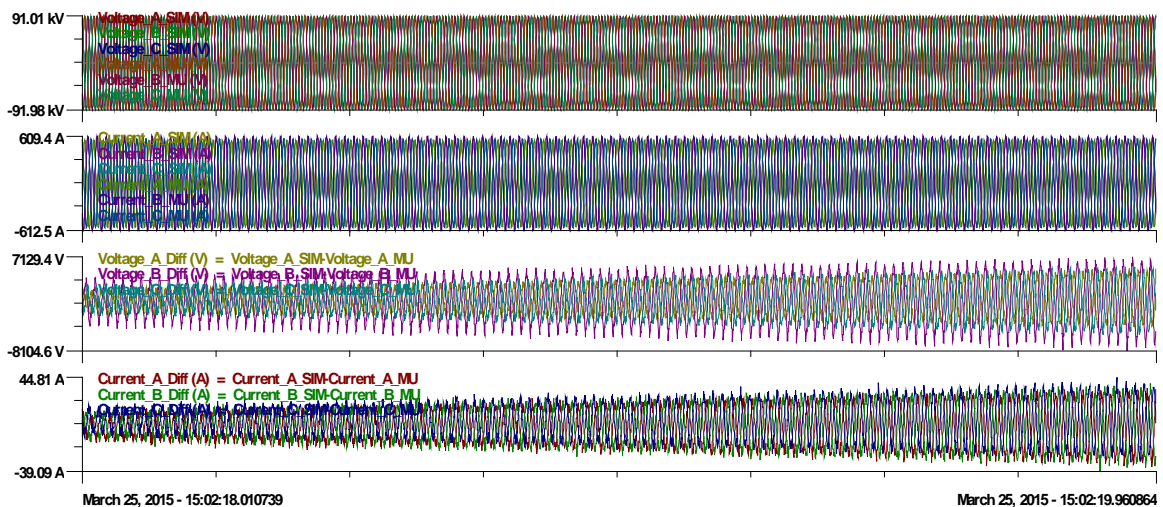

Figure 4.15: Comparison between Input and Output of the Experiment

From Figure 4.15 it is seen that the magnitude of the error increases over time. The detailed analysis would be given in the next Section.

4.6 Analysis of Combined Results

Another six channels are created for analysis purpose:

Voltage_A_Diff: the difference between phase A to neutral voltage from simulation and phase A to neutral voltage from merging unit

Voltage_B_Diff: the difference between phase B to neutral voltage from simulation and phase B to neutral voltage from merging unit

Voltage_C_Diff: the difference between phase C to neutral voltage from simulation and phase C to neutral voltage from merging unit

Current_A_Diff: the difference between phase A current from simulation and phase A current from merging unit

Current_B_Diff: the difference between phase B current from simulation and phase B current from merging unit

Current_C_Diff: the difference between phase C current from simulation and phase C current from merging unit

By observation of the errors, it can be seen that three distinguishing characteristics exist:

The error for each channel is approximately a sinusoidal wave with time varying magnitudes.

Since the input and output are aligned at starting point of one playback cycle, the magnitude of the error is minimum at the alignment point, but it increases over time and reaches maximum at end of the playback cycle.

The sinusoidal error crosses zero value at the same time when the simulation channel reaches peak value; Vice versa, it reaches maximum value when the simulation channel reaches zero value.
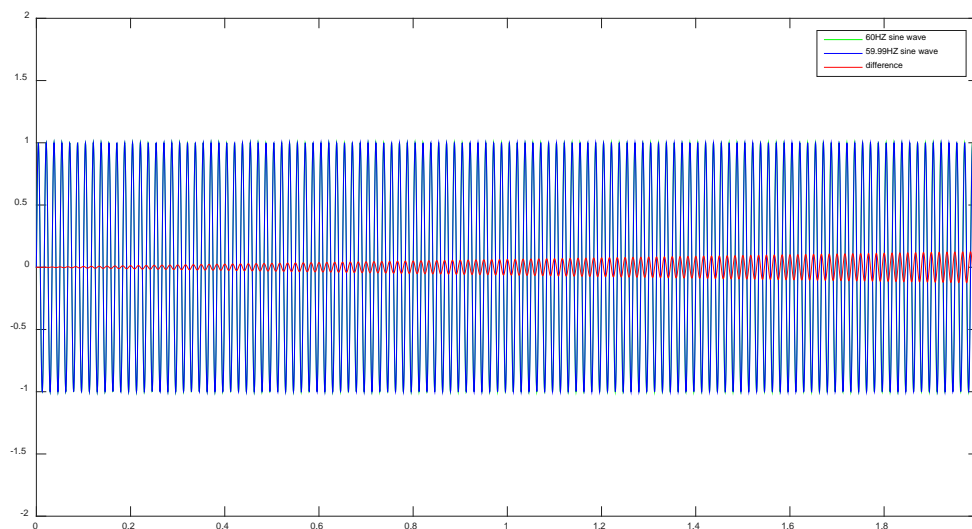

Figure 4.16: Difference between Two Sinusoidal Waves with Slightly Different Frequencies

From the observation, it is suspected that the input and output has slightly different frequencies. The input has a pure 60 Hz frequency while the output might be only 59.99 Hz. The reason is that the difference between two sinusoidal waves with slightly different frequencies is also a sinusoidal wave with increasing magnitude. Figure 4.16 plots three traces: 1) 60 HZ sinusoidal wave; 2) 59.99 HZ sinusoidal wave; 3) difference between the two. It is observed that the difference between the two sinusoidal waves has the three distinguishing characteristics which are also observed in the difference between the simulation data and merging unit data.

5. Field Testing – Use Cases

This document describes a use case for preparing and running the setting-less relay for a specific protection zone.

The protection zone model is a detailed 3-phase capacitor bank defined in the program WinIGS-T. Once the protection zone model has been defined, then it can be exported into a file that is readable by the EBP. The procedure defines the model of the protection zone power components and the placement of the measurements. The file contains the protection zone model in SCPAQCF format and the definition of the measurements.

The file above is read by the EBP software.

Events can be generated independently by the program WinIGS-T and stored in COMTRADE format.

The use case presents the procedure used in EBP to read the model/measurement file and the event in COMTRADE to run the setting-less relay.

The use case described in this report is a three-phase overhead line protection zone. The line is connected to breaker and a half scheme at both ends.

This report presents a few events and their results for this particular use case.

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, 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 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. The procedure for creating the protection zone model and the measurement definition file in program WinIGS-T are presented in Appendices A and B respectively.

5.1   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 test system is shown in Figure 5.1. The protection zone contains a detailed 3-phase capacitor bank and a breaker. A Merging Unit is present to capture the voltages and currents of the capacitor bank at bus CAPB1.
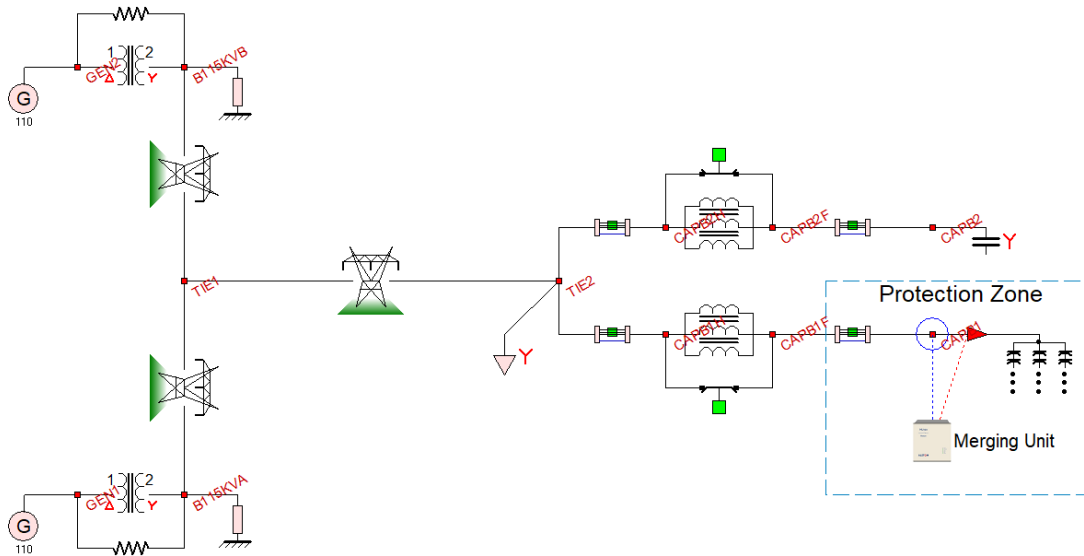

Figure 5.1: Test System for Use Case

The parameters dialog of the capacitor bank is illustrated in Figure 5.2. This dialog can be accessed via left button double clicking on the 3-phase capacitor bank icon. Ensure that the model parameters are correctly set.
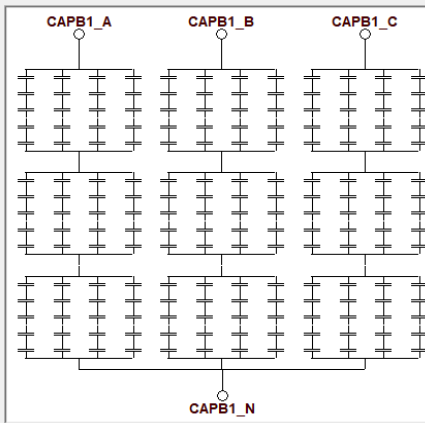

Figure 5.2: Protection Zone Parameters

5.2   Creating Measurement Models for Merging Units

The instrumentation channel and measurement parameters to be used by the EBP relay for the zone protection are modeled in the Merging Unit (see MU icon in Figure 5.1). In this example the EBP relay monitors the phase currents and voltages at the capacitor 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 5.3. Click on the Instrumentation button to open the instrumentation channel list dialog, illustrated in Figure 5.4.

Double-click on each list table entry to inspect the instrumentation channel parameters. Figures 5.5 and 5.6 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).

Figure 5.3: Merging Unit Main Parameter Dialog

Figure 5.4: Merging Unit Instrumentation Channel List Dialog

Figure 5.5: Example of a Voltage Instrumentation Channel Dialog

Figure 5.6: Example of a Current Instrumentation Channel Dialog

Figure 5.7: Instrument Transformer Library Dialog

The instrumentation channel parameters are listed in Table 5.1 with detailed descriptions.

Table 5.1: Instrumentation Channel Parameters – User entry Fields

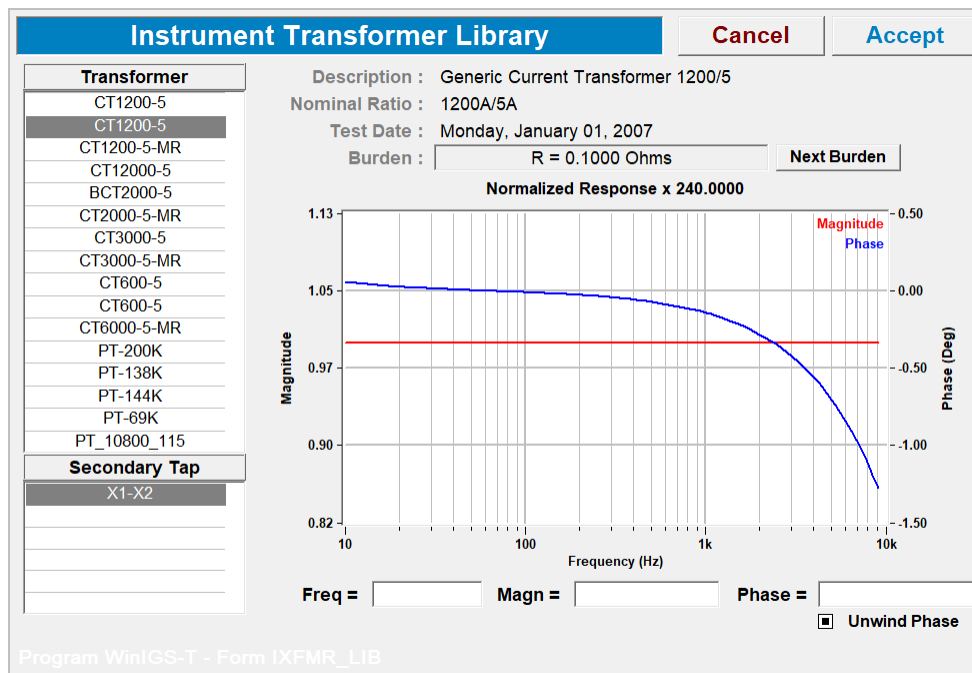| Parameter	Description
Data Type	Specifies the type of the measured quantity. Valid options for merging units are Voltage Time Domain Waveform and Current Time Domain Waveform.
Bus Name	The bus name where the measurement is taken
Power Device	Identifies the power device into which the current is measured (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. 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_PT_AN, if the instrument transformer name is set to PT.
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 5.7)
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 a IED library. This setting retrieved the data acquisition device frequency response for 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 2.2.6. 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.

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 × In)	4A (4 × In)
AC current thermal withstand 1 s (Ith rms)	320A (64 × In)	100A (100x In)
AC current thermal withstand 10 s (Ith rms)	100A (20 × In)	30A (30 × 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 × Vn)
Bandwidth	3 k Hz

Figure 5.8: 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 5.4). 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 5.3). This action opens the Measurement List Dialog illustrated in Figure 5.9.

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

Measurement Channels

	Name	IED Alias	Type	Value	Nominal	Scale	St.Dev	Correction	ale
5	V_CAPB1_AN	Va_1	V-Time		600.0 V	180.0 kV	0.01000 pu	0.996 / -0.086 Deg	0
6	V_CAPB1_BN	Vb_1	V-Time		600.0 V	180.0 kV	0.01000 pu	0.996 / -0.086 Deg	0
7	V_CAPB1_CN	Vc_1	V-Time		600.0 V	180.0 kV	0.01000 pu	0.996 / -0.086 Deg	0
1	C_CAPB1_1_CAPB1_A	Ia_1	I-Time		240.0 A	24.00 kA	0.01000 pu	0.363 / 6.278 Deg	0
2	C_CAPB1_1_CAPB1_B	Ib_1	I-Time		240.0 A	24.00 kA	0.01000 pu	0.363 / 6.278 Deg	0
3	C_CAPB1_1_CAPB1_C	Ic_1	I-Time		240.0 A	24.00 kA	0.01000 pu	0.363 / 6.278 Deg	0

Figure 5.9: Measurement List Dialog

Measurement parameters can be manually created and edited using the **New** and **Edit** buttons of the Measurement List dialog (Figure 5.9), which open the measurement parameter dialog illustrated in Figures 5.10 and 5.11. The fields in this dialog are briefly described in Table 5.2

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Figure 5.10: Voltage Measurement Parameters Dialog

Figure 5.11: 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 CAPB1 is automatically named V_CAPB1_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 capacitor bank connected to bus CAPB1 is named C_ CAPB1_1_ CAPB1_A, where the part CAPB1_1 identifies the power device as circuit 1 connected to the bus CAPB1, and the last part _CAPB1_A identifies the terminal into which the measured current is flowing. Note that the name part 1 is the user specified Circuit Name of the capacitor bank connected at bus CAPB1.
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 values. Default values are 1.0 and 0.0 respectively.

5.3   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:

Select the power devices belonging to the protection zone of interest. In this example select the shunt reactor bank connected to bus CAPB1 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).

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 5.12. (NOTE: to select multiple objects, hold down the CTRL key, and *left-click* on the elements to be selected).

Execute the SCAQCF Export command of the Tools menu, or click on the toolbar icon: (See also Figure 5.12).
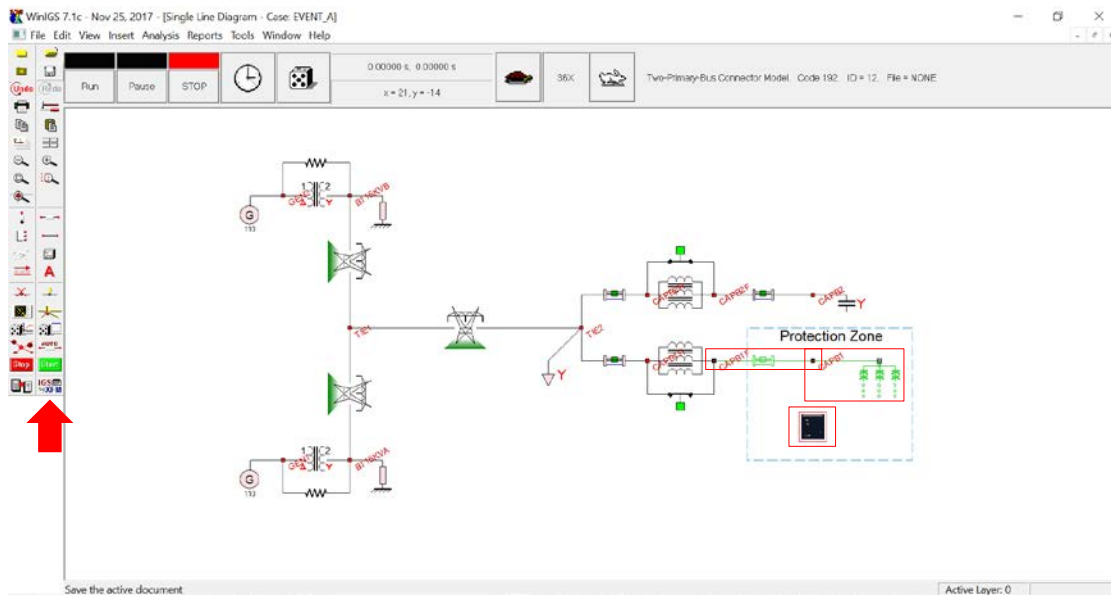

Figure 5.12: Selecting Zone Power Devices and Merging Units

This command/toolbar button opens the dialog window illustrated in Figure 5.13.
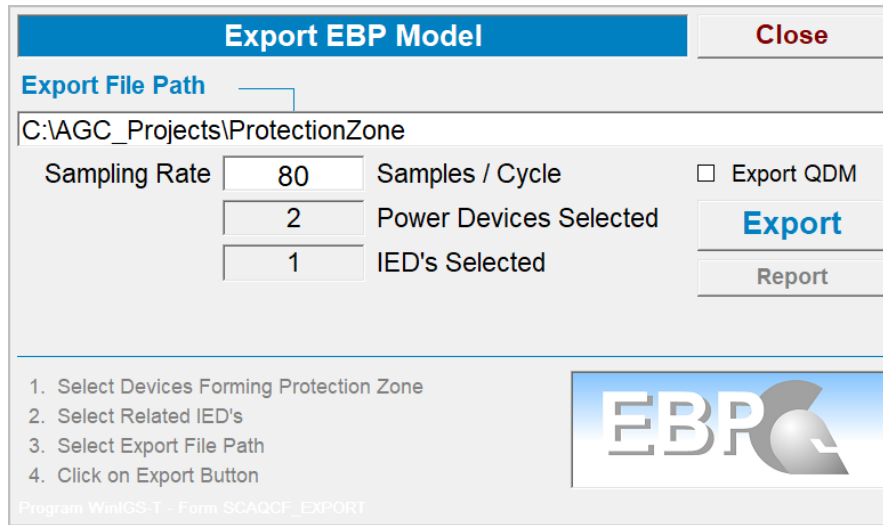
Figure 5.13: EBP Export Dialog

Click on the entry field under the Export File Path label to select the file path of the files to be generated.

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 5.14).
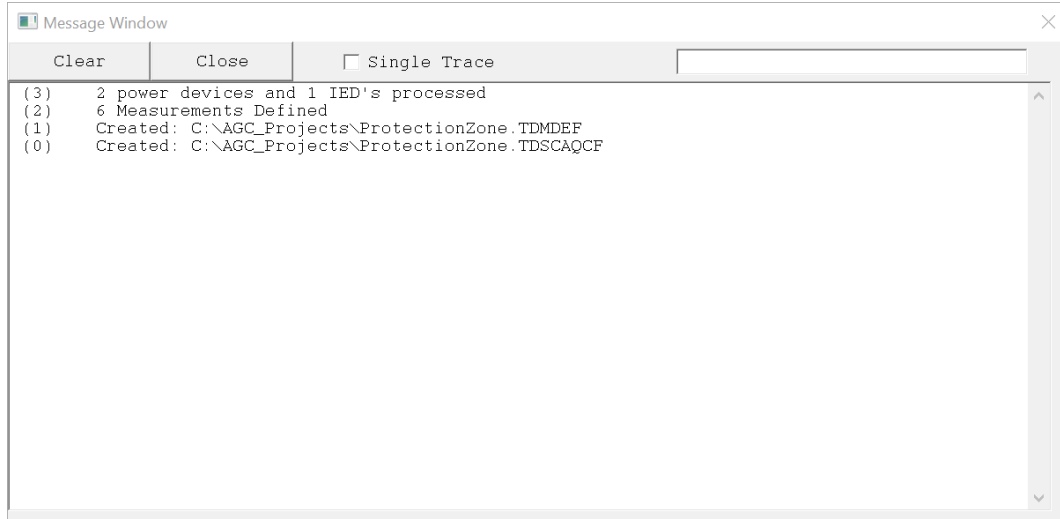

Figure 5.14: Message Window Indicating EBP File Creation Progress & File Paths

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

5.4   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. A few events are described below.

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5.5   Event A: UseCase_02.A

Event A is defined with a Phase A to neutral fault on the TIE1 bus outside the protection zone. Figure 5.15 shows the fault model and fault model parameters dialog. The fault is located 12.35 miles away from the protection zone. It has a fault resistance of 0.01 ohms, starting at 0.98 sec and clearing at 1.02 sec.
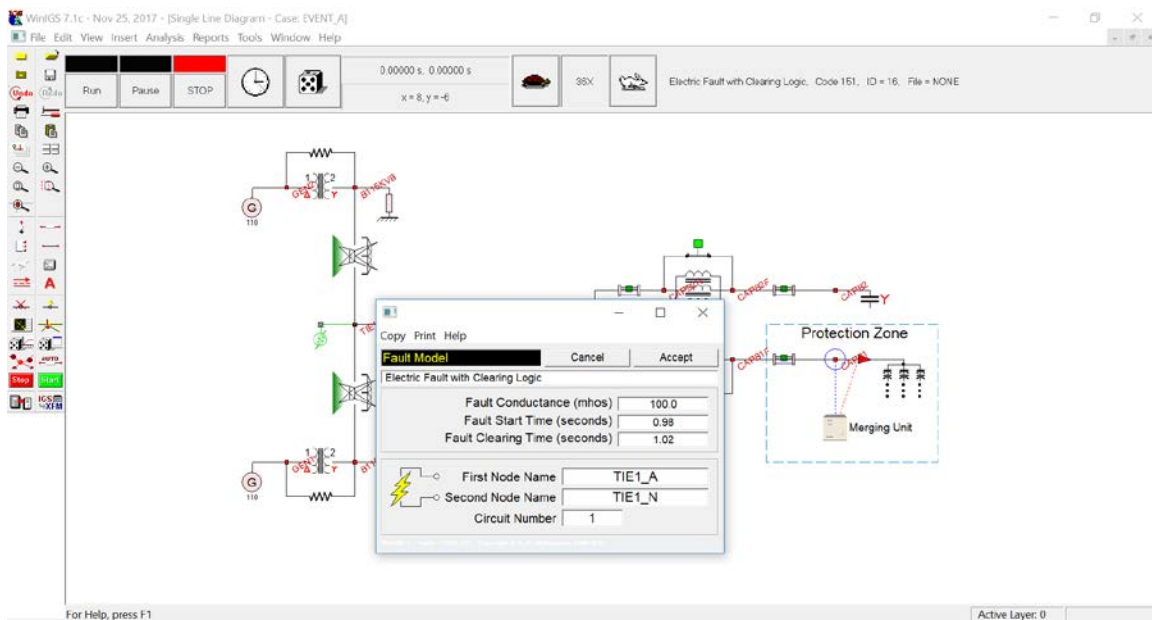

Figure 5.15: Test System with Fault between Phase A and Neutral of TIE1 Bus.

The simulation is executed for a period of 2 seconds. The measurements generated during the simulation are stored in a COMTRADE file. Figure 5.16 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 60 Hz system this is achieved by selecting the time step at:

$$\Delta t = 1 / (60 \times 80) = 208 \text{ microseconds.}$$

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

Figure 5.16: Time Domain Simulation Parameters Dialog

5.6   Event B: UseCase_02.B

Event B is defined with a Phase B to Phase C fault on the TIE1 bus outside the protection zone.
Figure 5.17 shows the fault model and fault model parameters dialog. The fault is located 12.35
miles away from the protection zone. It has a fault resistance of 0.01 ohms, starting at 0.98 sec and
clearing at 1.02 sec.

Figure 5.17: Test System with Fault between Phase B and Phase C of TIE1 Bus.

The simulation is executed for a period of 2 seconds. 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 60 Hz system is 208 microseconds (i.e. same as for Event A).

The WinIGS-T case files is named EVENT_B.NMT and is provided with this report. The generated COMTRADE configuration and data files are named EVENT_B_MAIN.cfg and EVENT_B_MAIN.dat respectively.
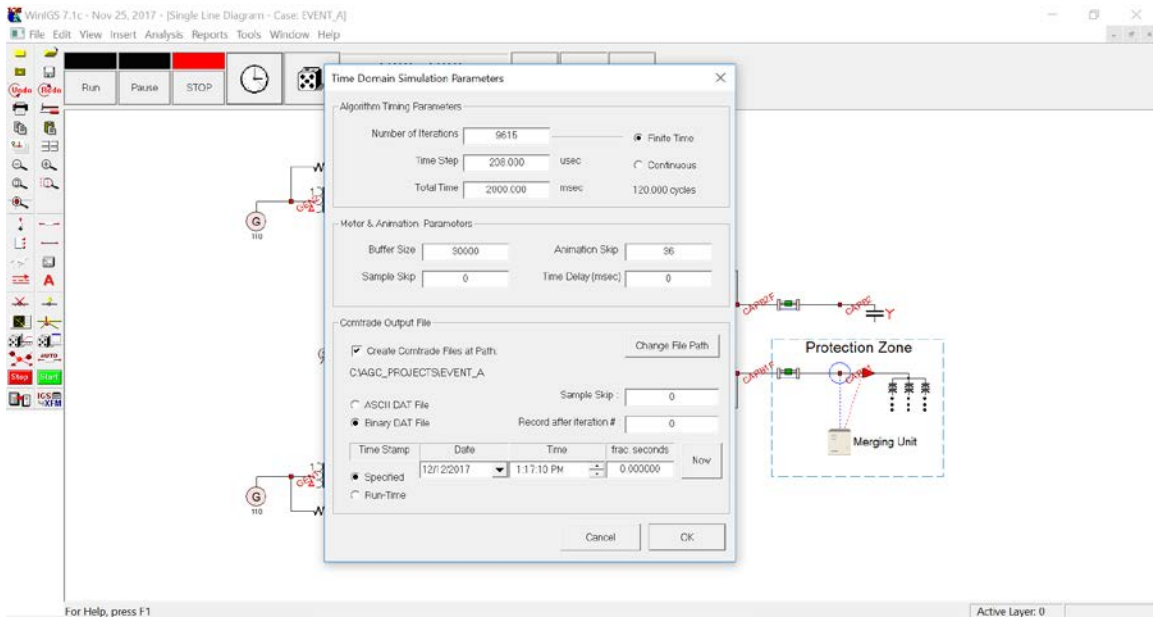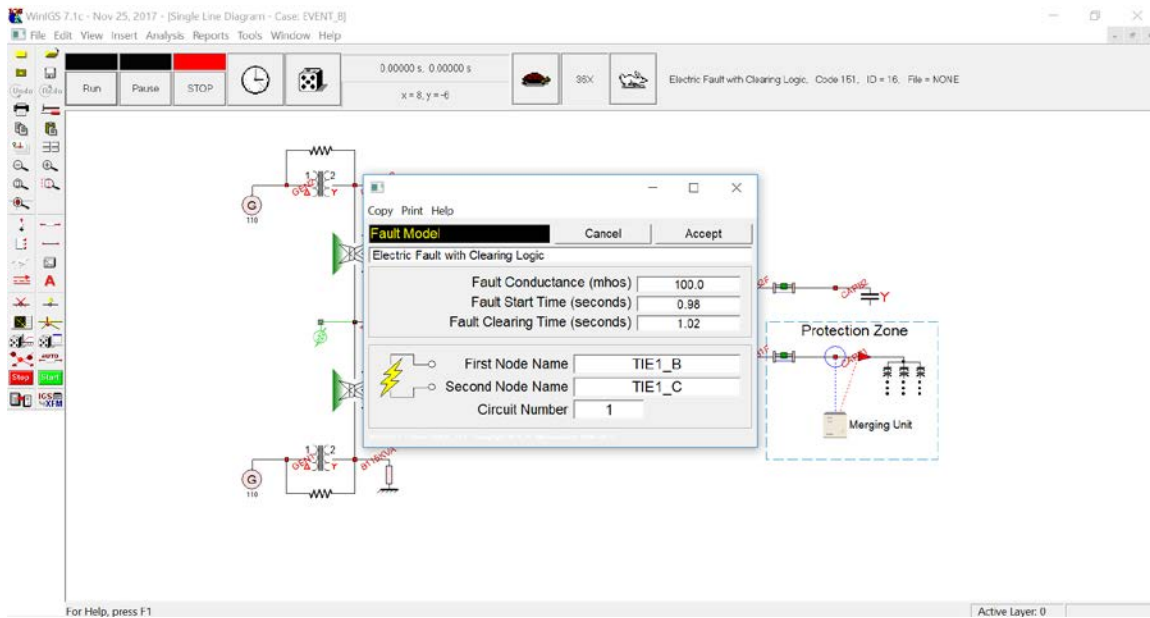
5.7   Event C: UseCase_02.C

Event C is defined with a Phase A to neutral fault on the CAPB1 bus within the protection zone. Figure 5.18 shows the fault model and fault model parameters dialog. This is a fault occurring inside the protection zone, which should be cleared by opening the breaker. It has a fault resistance of 0.01 ohms, starting at 0.98 sec and clearing at 1.02 sec.
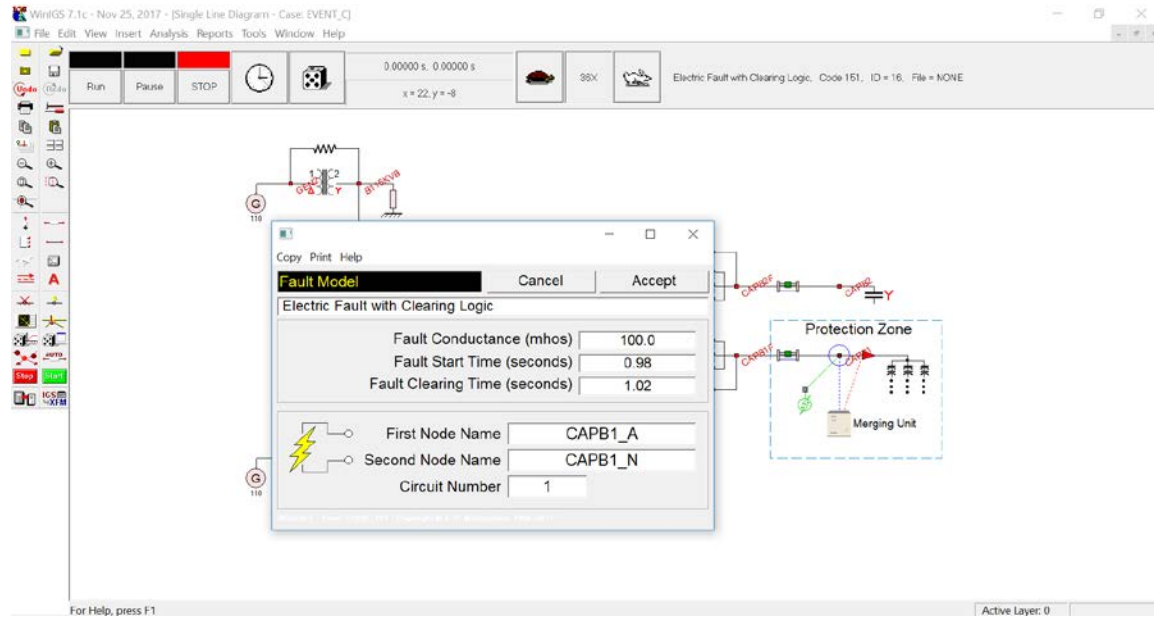
Figure 5.18: Test System with Fault between Phase B and Neutral of CAPB1 Bus.

The simulation is executed for a period of 2 seconds. 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 60 Hz system is 208 microseconds (i.e. same as for Event A).

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

5.8   EBP Results

This section presents the results obtained with the EBP relay for the use case and events described in Section 3. 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 5.19.
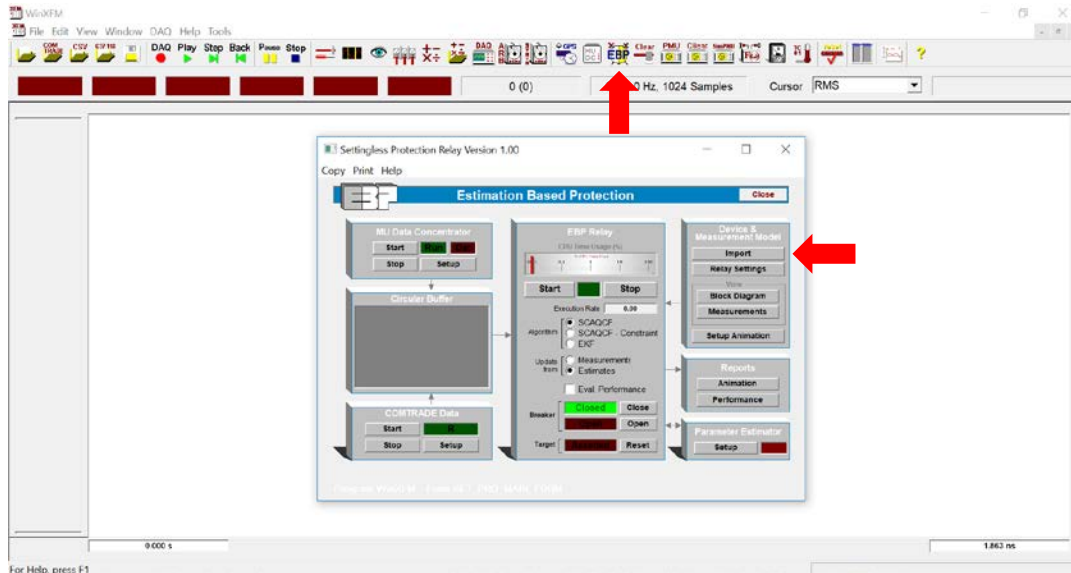

Figure 5.19: Opening the EBP Main Setup Form in the WinXFM Program

5.9   Event A: UseCase_02.A

As described in Section 3, event A is defined as a Phase A to neutral fault on the TIE1 bus. To run the EBP relay using the Event A data, execute the WinXFM program and open the WinXFM file EVENT_A.

Note: this file is provided with this report under the file name 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 5.20. Verify that the Protection Zone 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 5.20. 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:

ProtectionZone.TDMDEF   (Measurement Definition File)
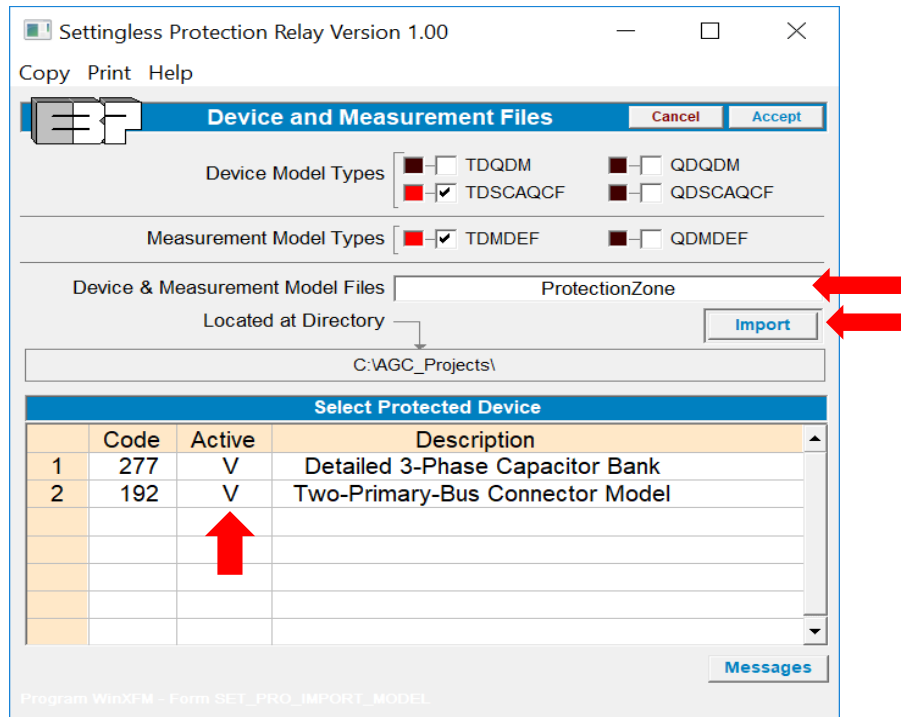ProtectionZone.TDSCAQCF (Device Model File)

Figure 5.20: Importing Protection Zone Device and Measurement Definition Files

The COMTRADE setup dialogue is opened as demonstrated in Figure 5.21 and the window shown in Figure 5.22 pops up. Verify that the **COMTRADE File Name** field indicates that the Event A waveform data has been selected: (file name: EVENT_A_MAIN). Also verify the following:

Playback rate is set at **4800** samples per second for 60 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.

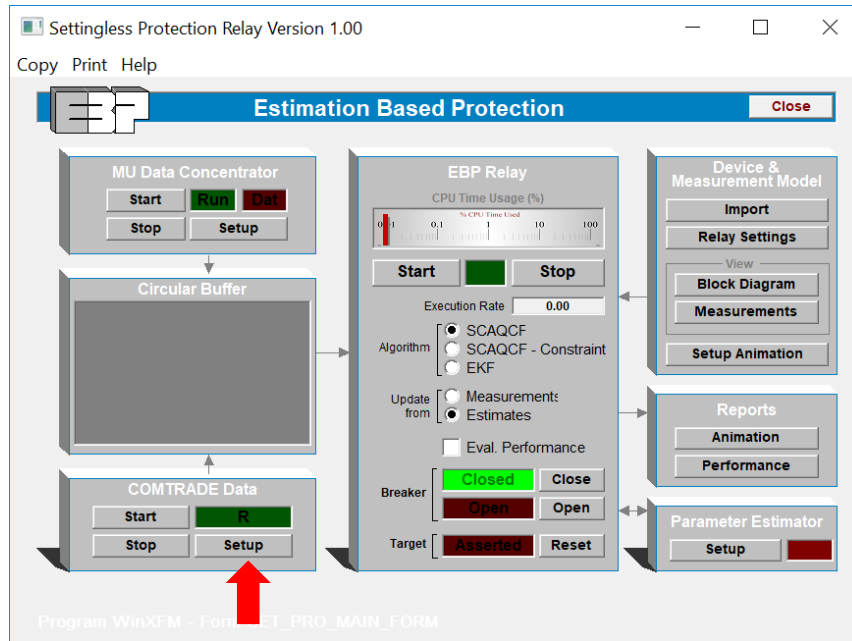Click on the **Close** button to close the COMTRADE Data Playback dialog.

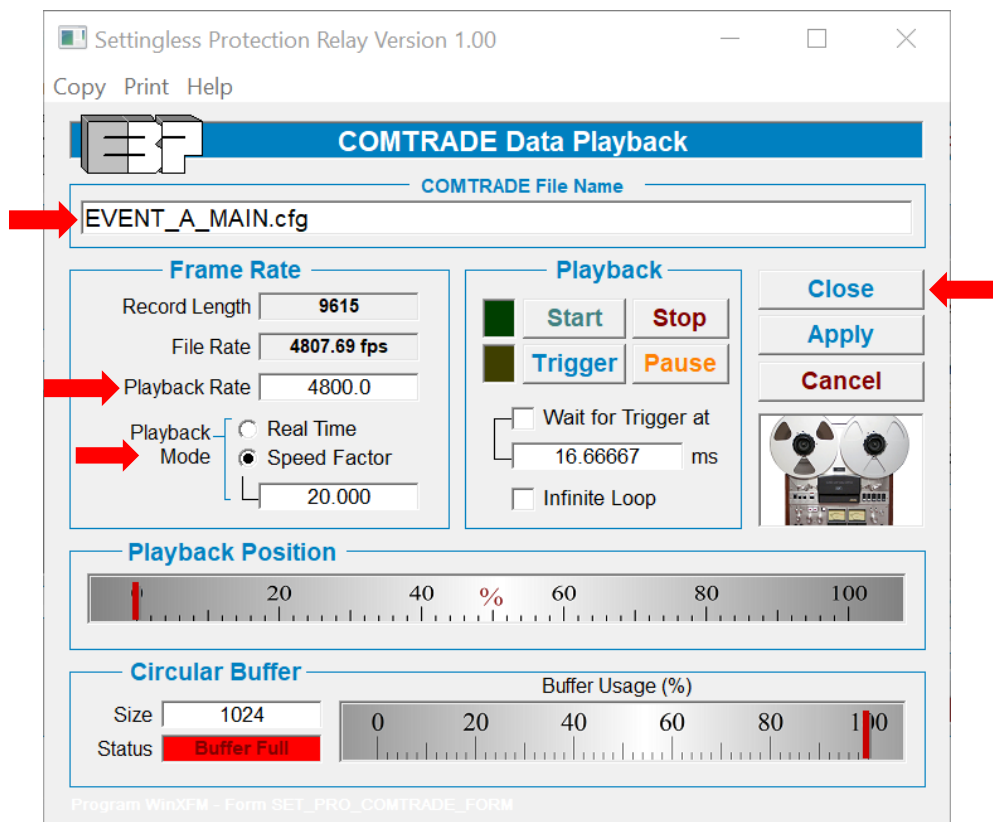Figure 5.21: Opening the COMTRADE Setup Dialog

Figure 5.22: 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 COMTRADE Data block, then on the **Start** button of the EBP Relay block to start the EBP relay. See Figure 5.23 for the location and sequence of these buttons.
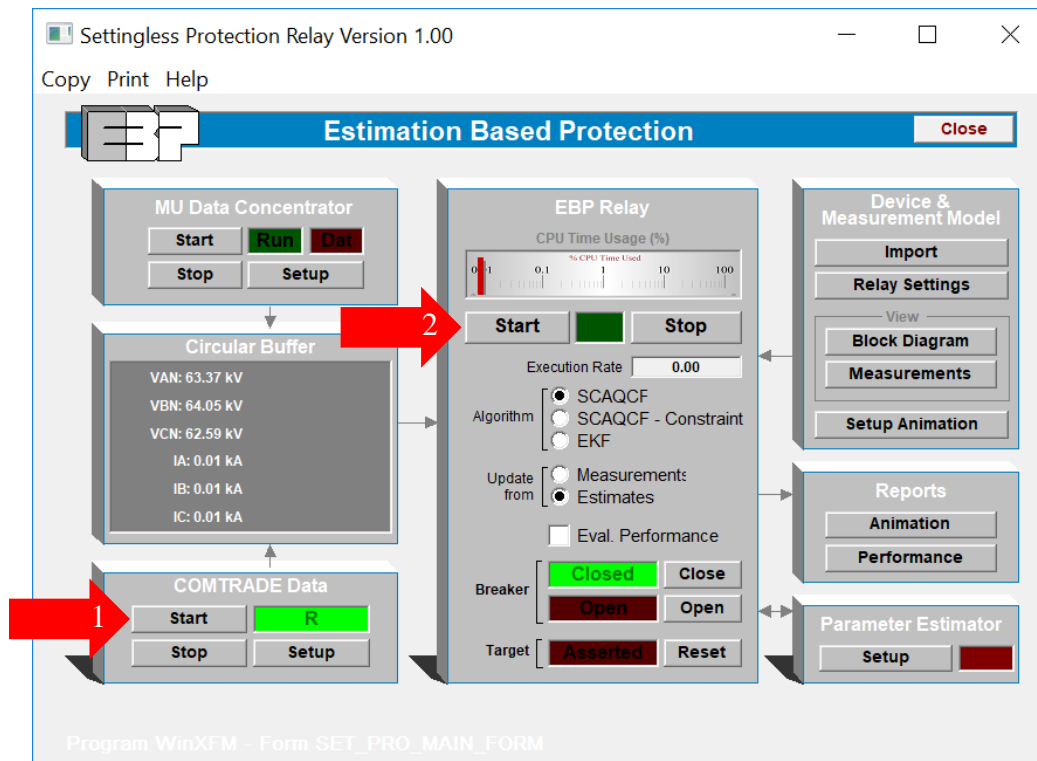
Figure 5.23: Starting the EBP Relay Using Playback Data (COMTRADE)

Once the EBP Relay starts, a number of plots can be viewed on the main WinXFM user interface such as measured and estimated values, trip decision, etc. The actual and estimated measurements of the three-phase capacitor bank are plotted in Figure 5.24, while the waveforms related to trip decision of the relay are given in Figure 5.25.
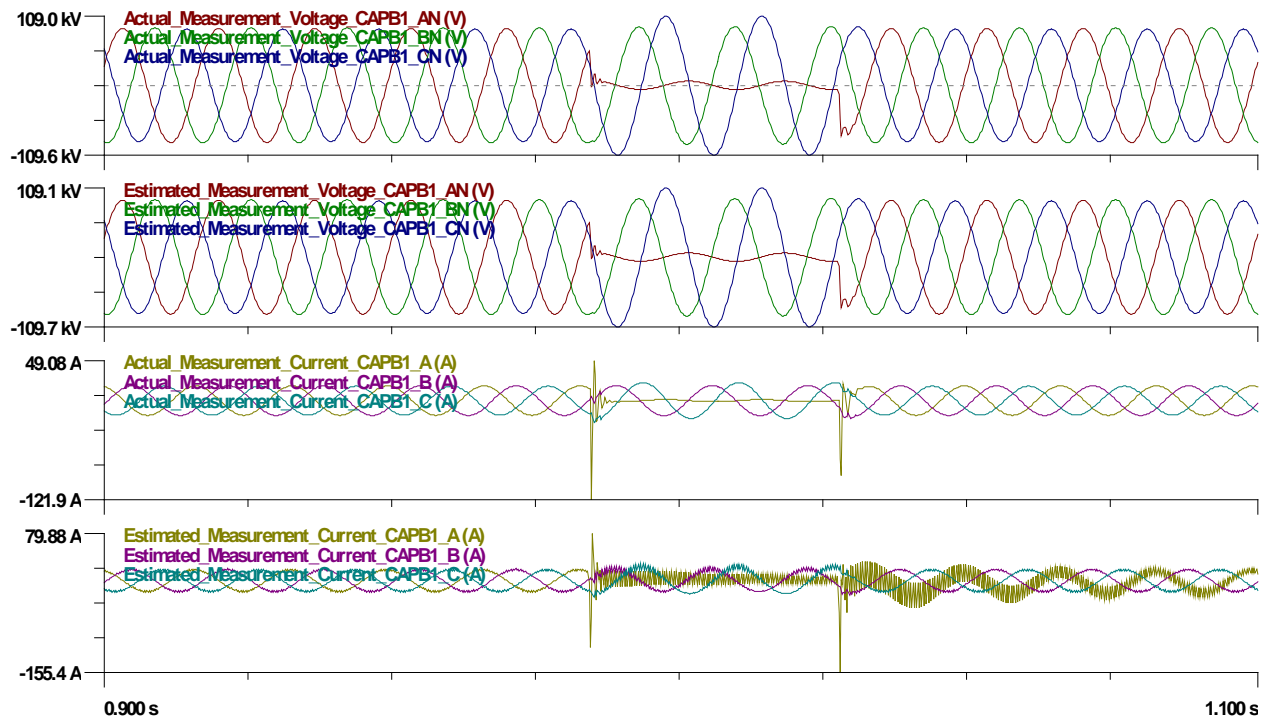
Figure 5.24: Actual and Estimated Measurements of Event A

Figure 5.25: EBP Relay Response of Event A

In Figure 5.24, the estimated values track the actual measurements closely. Abnormalities are seen between the fault, which lasts 0.04 seconds. The residuals of the voltages and current measurements are shown in Figure 5.25, which give the trip decision over time. Notice that at the start and end of the fault, the confidence level slightly drops and goes back to 100% immediately. Hence, the EBP relay detects this external fault correctly and no trip decision is issued.

5.10   Event B: UseCase_02.B

Event B is defined as a Phase B to Phase C fault on bus TIE1. To run the EBP relay using the Event B simulated waveforms, execute the WinXFM program and open the WinXFM file EVENT_B. The procedures of setting up the EBP are the same as those described in Event A, except that all the file names should now be related to Event B.

Once the EBP Relay starts, a number of plots can be viewed on the main WinXFM user interface such as measured and estimated values, trip decision, etc. The actual and estimated measurements of the three-phase capacitor bank are plotted in Figure 5.26, while the waveforms related to trip decision of the relay are given in Figure 5.27.

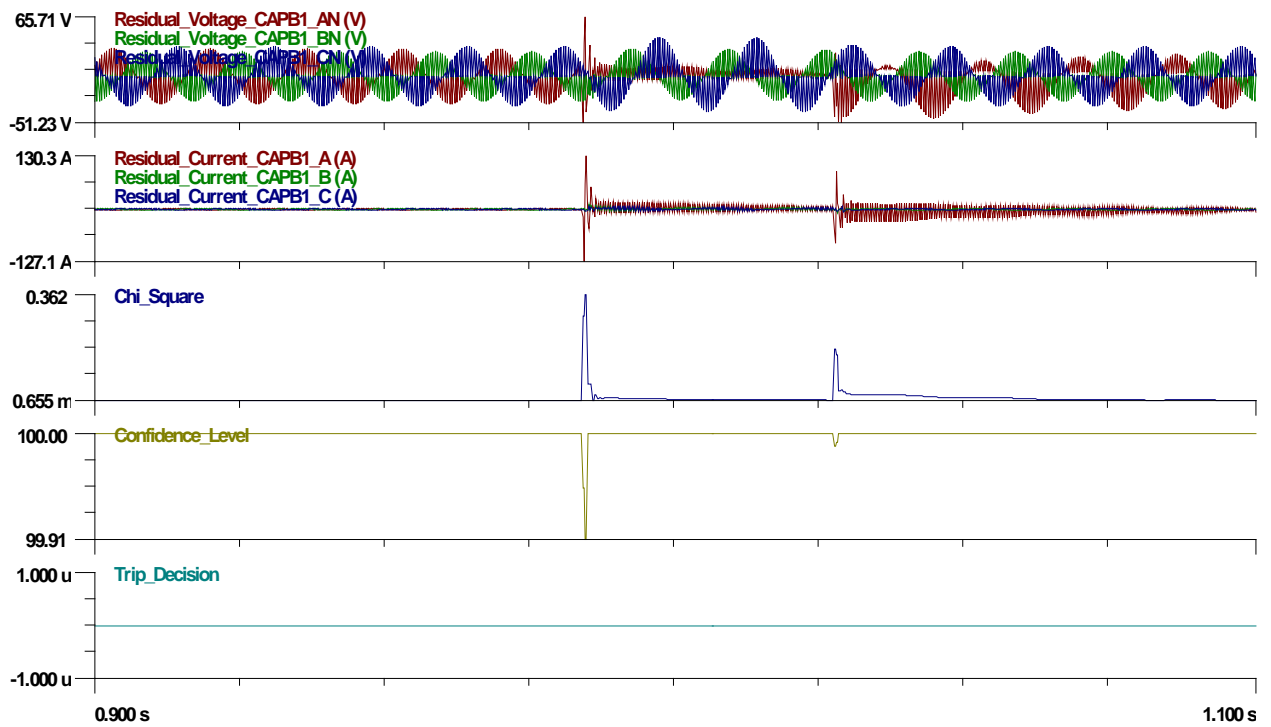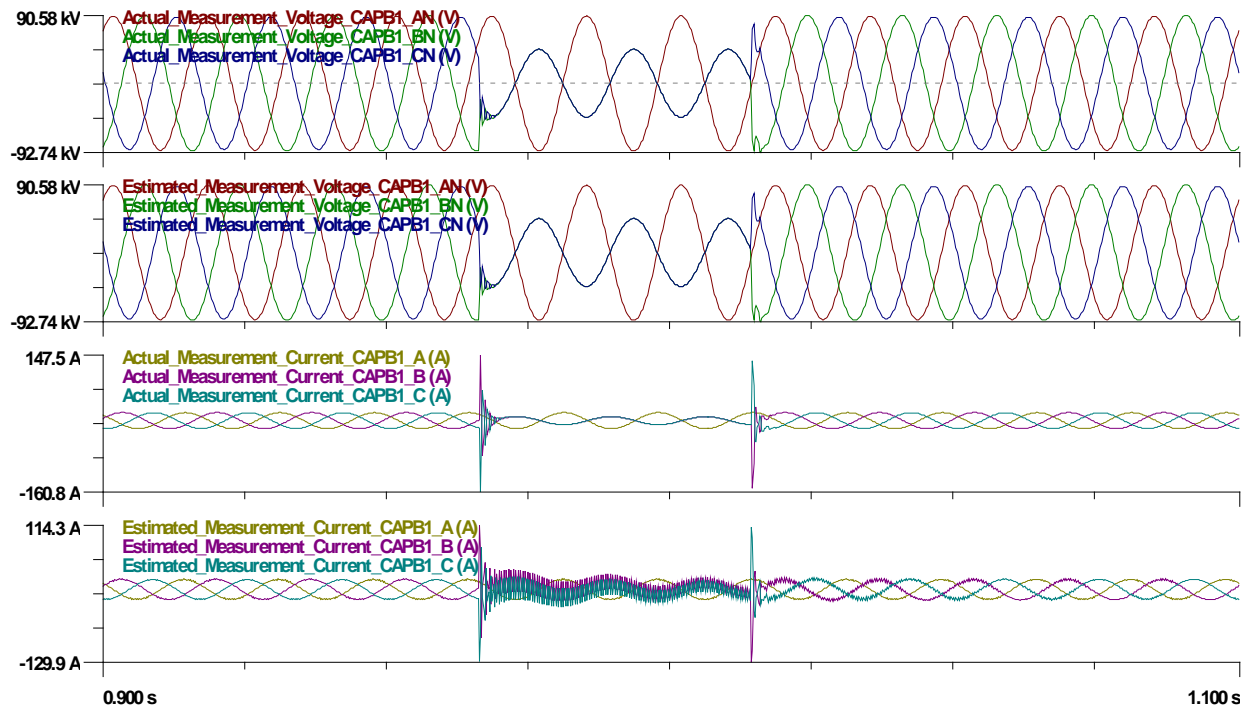Figure 5.26: Actual and Estimated Measurements of Event B

Figure 5.27: EBP Relay Response of Event B

In Figure 5.26, the estimated values track the actual measurements closely. Abnormalities are seen between the fault, which lasts 0.04 seconds. The residuals of the voltages and current measurements are shown in Figure 5.27, which give the trip decision over time. It can be noticed that at the start and end of the fault, the confidence level slightly drops and goes back to 100% immediately. Hence, the EBP relay detects this external phase-to-phase fault correctly and no trip decision is issued.

5.11   Event C: UseCase_02.C

Event C is defined as a Phase A to Neutral fault on bus CAPB1. To run the EBP relay using the Event C simulated waveforms, execute the WinXFM program and open the WinXFM file EVENT_C. The procedures of setting up the EBP are the same as those described in Event A, except that all the file names should now be related to Event C.

Once the EBP Relay starts, a number of plots can be viewed on the main WinXFM user interface such as measured and estimated values, trip decision, etc. The actual and estimated measurements of the three-phase capacitor bank are plotted in Figure 5.28, while the waveforms related to trip decision of the relay are given in Figure 5.29.

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Figure 5.28: Actual and Estimated Measurements of Event C
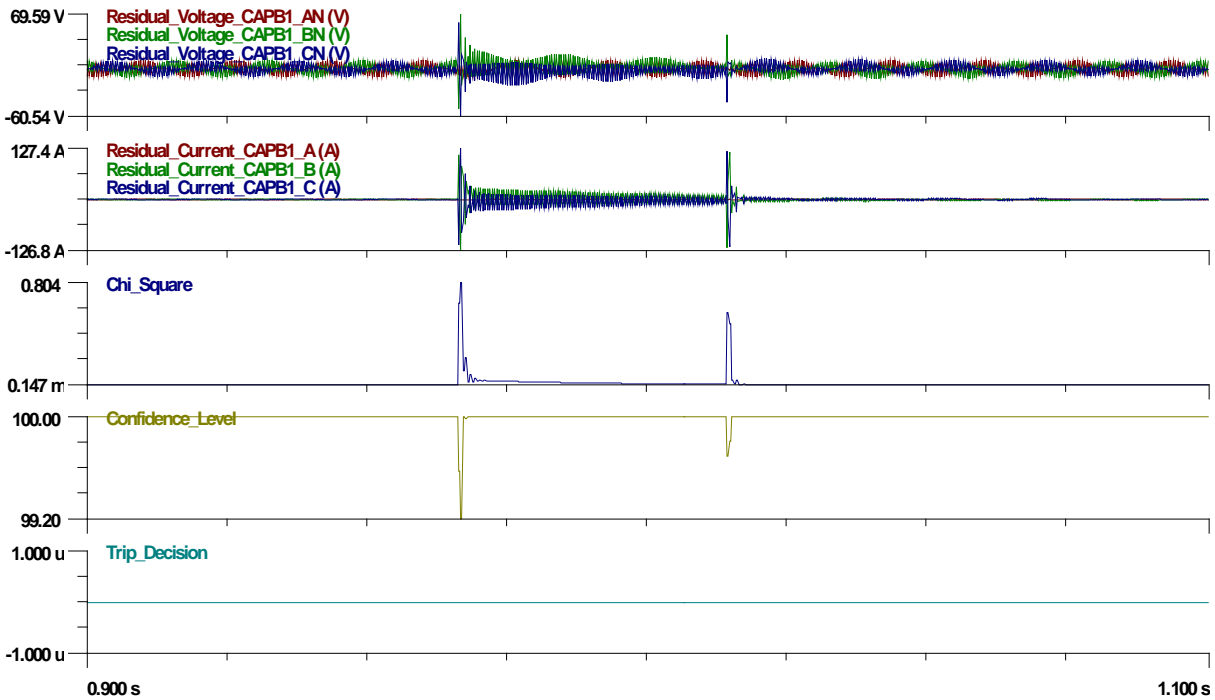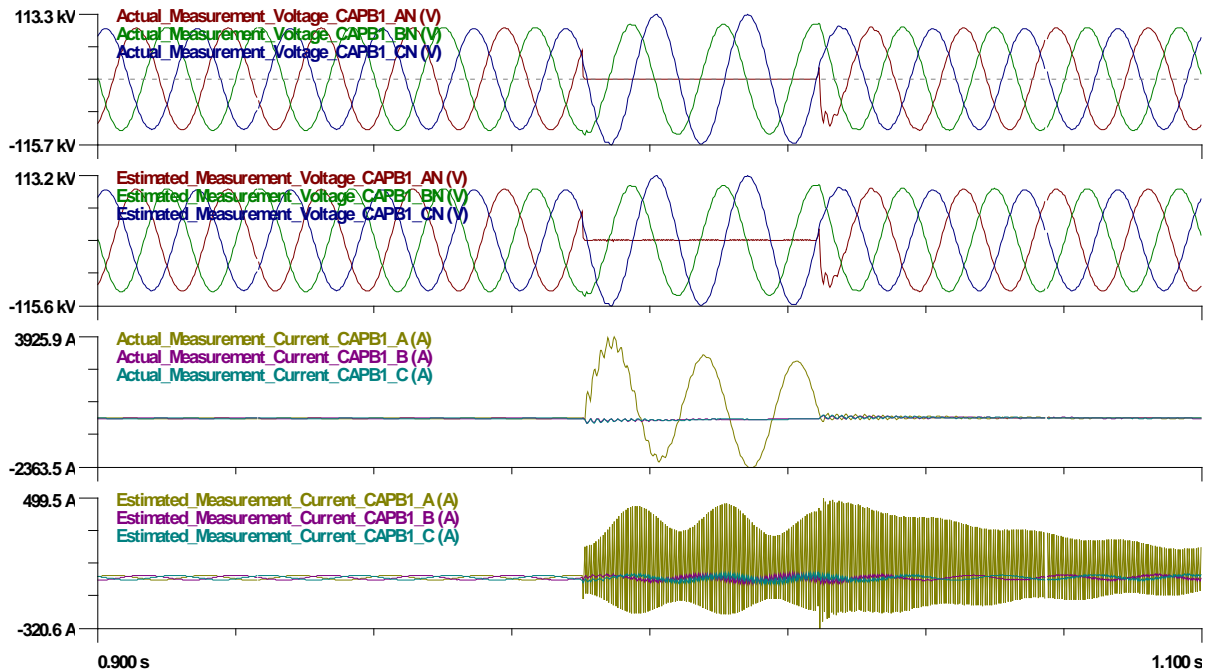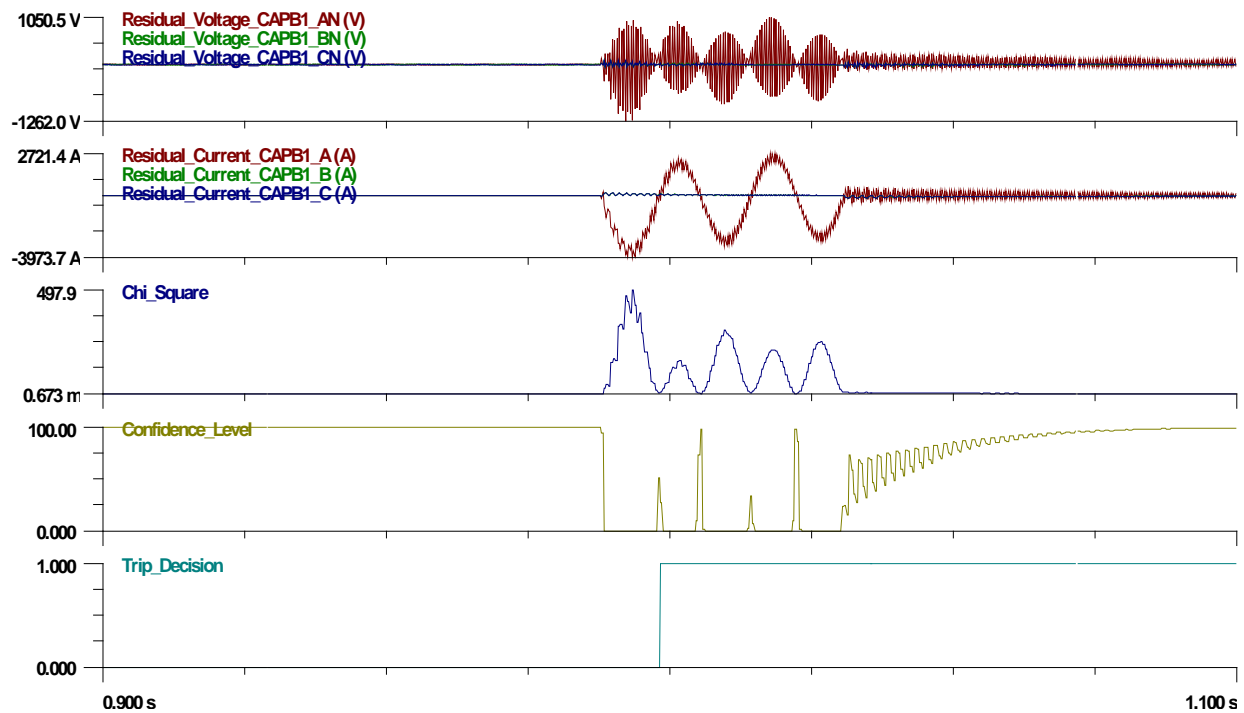

Figure 5.29: EBP Relay Response of Event C

In Figure 5.28, the estimated values track the actual measurements closely. Abnormalities are seen between the fault, which lasts 0.04 seconds. The residuals of the voltages and current measurements are shown in Figure 5.29, which give the trip decision over time. It can be noticed

that at the start of the fault, the confidence level drops from 100% to about 0% immediately. Since its value is kept around 0% for some time, which is a duration set by the user (here is 10 ms), the EBP recognize the fault to be an internal fault within the protection zone. Hence, this internal phase-to-neutral fault is detected correctly and the relay trips after 10 ms of the detection.

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Appendix A: Preparing Device Model Files

This Appendix introduces the way to prepare and import device model files. The steps are as follows.

Step 1: Open the system model file ('.NMT file) in WinIGS-T
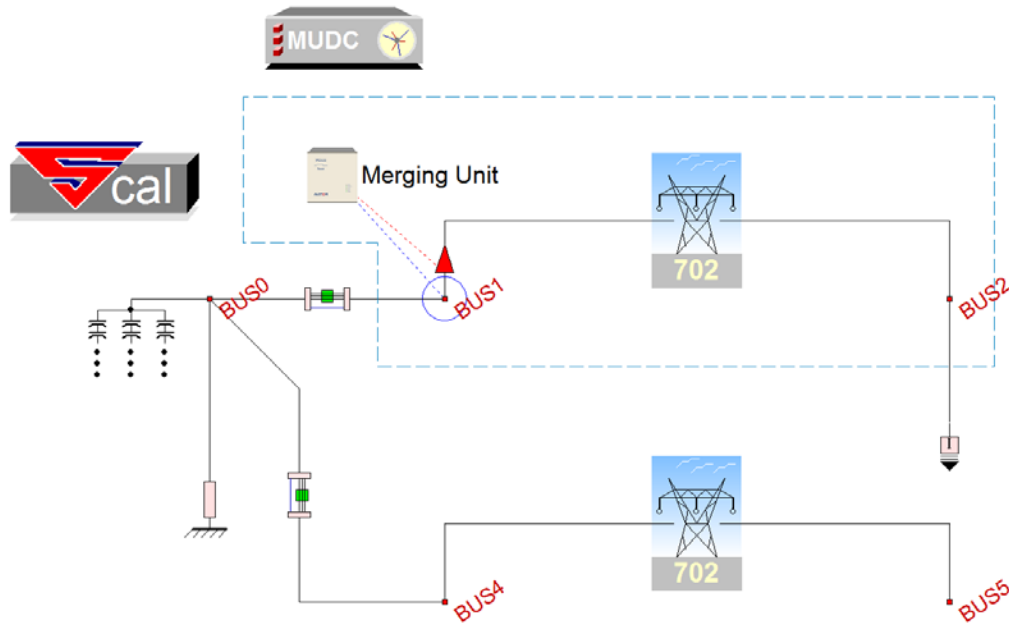Note that this file contains the modeling information of system of interests. An example is shown in Figure A.1.

Figure A.1 System Model File Example

Step 2: Select the devices of interest
Click the button 'IGS->XFM' at the bottom of the left tool bar, IGS XFM to open the 'Estimation Based Protection Model Construction' window.

Next, select the devices of interest. Also, select multiple devices by pressing 'Ctrl' button during selection. The window will display the number of power devices that are selected (the output of device models only works power devices that support SCAQCF standard). This process is shown in Figure A.2. Note that here you can at the same time select the IEDs connecting to the device to output the measurement model, as shown in Appendix B.
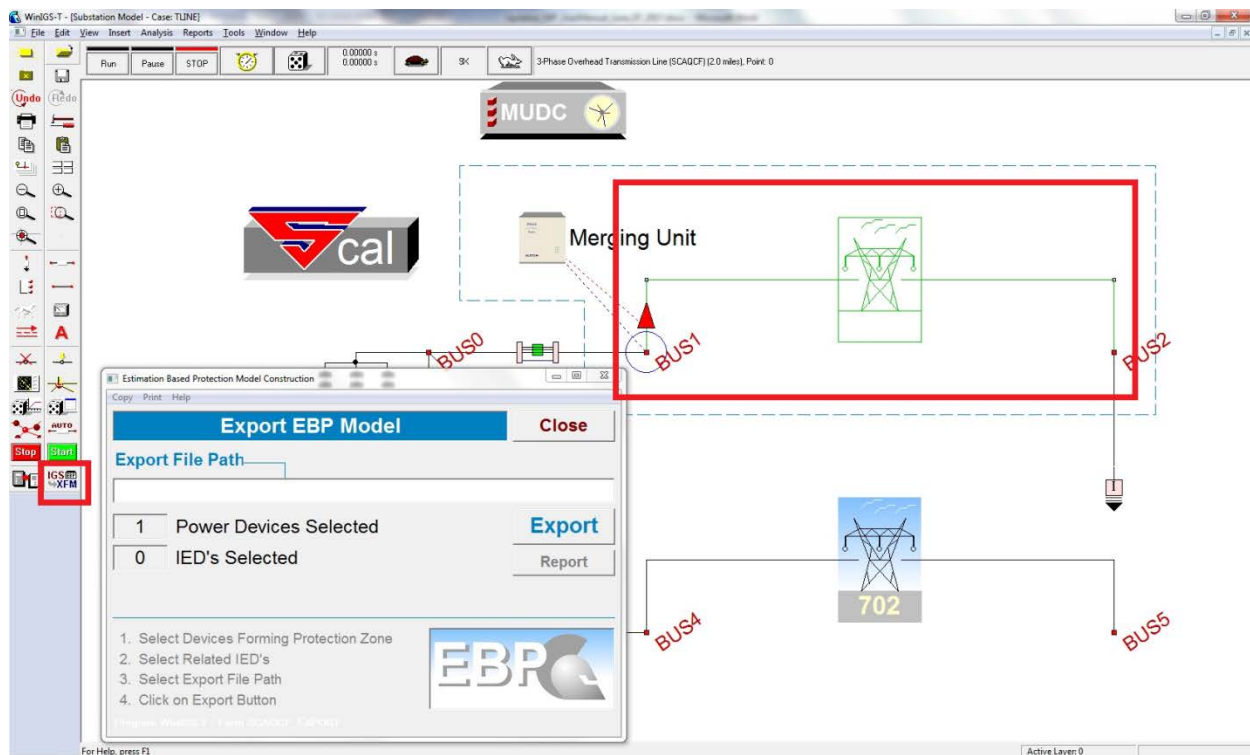
Figure A.2: Select the Device of Interest

Step 3: Output the device models
Click the 'Export File Path' to select the output directory. Next, click the 'Export' button to export the device model file. Note that the device model files are in '.TDSCAQCF' and '.TDSCQDM'. These files are the device model files for EBP. If the IEDs are selected in step 2, the output files will be with measurement definition files as well.

Appendix B: Preparing Measurement Model Files

This Appendix introduces the way to prepare and import measurement model files. The steps are as follows.

Step 1: Open the system model file ('.NMT file) in WinIGS
Note that this file contains the modeling information of system of interests. The example shown in Figure A.1 is used here.

Step 2: Select the IEDs that defines the measurements
Click the button 'IGS->XFM' ![IGS EBP XFM icon] at the bottom of the left tool bar inside the WinIGS-T software, to open the 'Estimation Based Protection Model Construction' window.

Next, select the IEDs that contain the measurement information. Also, select multiple IEDs by pressing 'Ctrl' button during selection. The window will demonstrate the number of IEDs that are selected. Note that here you can at the same time select the device to output the device model, as shown in the Appendix A. This process is shown in Figure B.1.
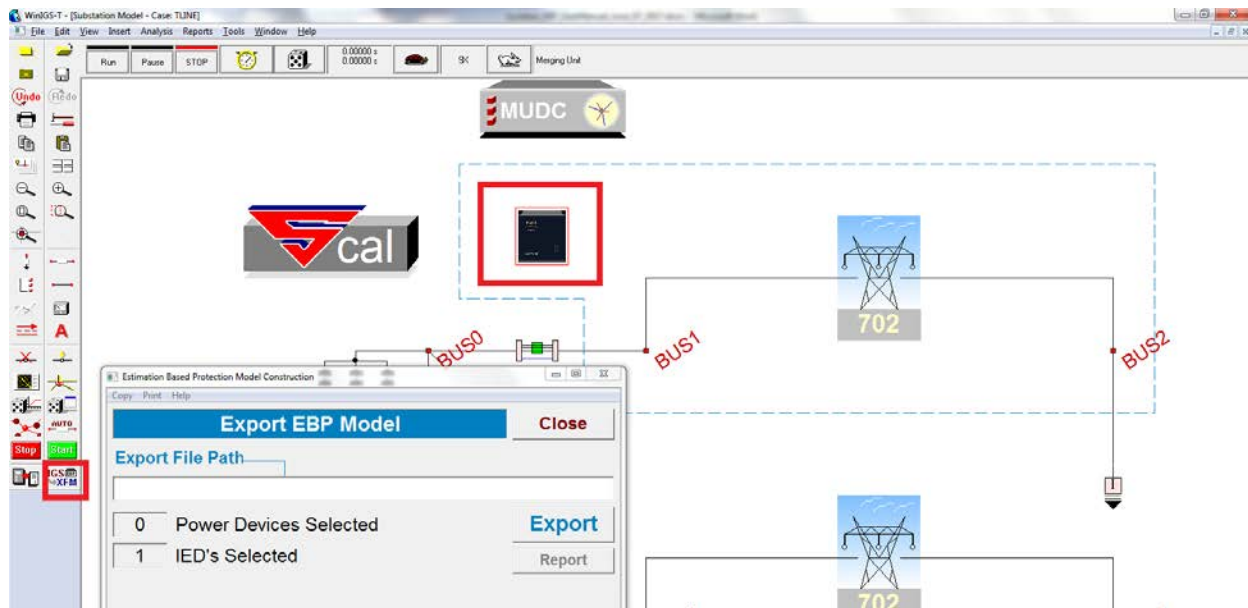

Figure B.1: Select the IEDs with Measurements

Step 3: Output the measurement model
Click the 'Export File Path' to select the output directory. Next, click the 'Export' button to export the measurement model file. Note that the measurement model file is in '.TDMDEF'. These files are the measurement files for EBP. If the devices are selected in step 2, the output files will be with device model files as well.