Integration of Protection and Control Systems in Dynamic Security Assessment Methods

Final Project Report

S-105

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

Integration of Protection and Control Systems in Dynamic Security Assessment Methods

Final Project Report

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Power Systems Engineering Research Center

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The report has two parts. Part I is the ASU contribution. Part II is the Georgia Tech contribution.

Executive Summary

Part I: Arizona State University

The growing integration of inverter-based resources (IBRs) into modern power systems poses new challenges for ensuring transient stability and secure operation, particularly during and after faulted conditions. One of primary objectives of this work is to develop a real-time Artificial Intelligent (AI)-based Dynamic Security Assessment (DSA) framework, which is developed and examined using IEEE 39-bus system during this project. Another objective of this project is to prepare and extend this tool for the Western Electricity Coordinating Council (WECC) system model. Achieving this goal requires access to historical WECC event data, as well as a comprehensive system model to generate accurate datasets for training online AI-based DSA tools. To meet this requirement, the WECC network is modeled in DIgSILENT PowerFactory, chosen for its ability to support root mean square (RMS)- electromagnetic transients (EMT) co-simulation and incorporating manufacturer-validated relay models.

This report describes the process of representing the WECC system in DIgSILENT, including data migration, discrepancy resolution, and the integration of detailed protection systems. In addition, the IEEE 39-bus system is modeled in DIgSILENT and modified to include IBRs. This modified test system is used to generate datasets via RMS–EMT co-simulation for evaluating the performance of AI-based DSA tool.

The generated data are used to train Random Forest (RF) and Convolutional Neural Network (CNN) models to predict distance relay operation during and after fault events, using impedance trajectories obtained from phasor measurement unit (PMU) locations. The results show that the proposed AI-based DSA tool achieves high prediction accuracy with rapid inference capability, enabling timely decision support for system operators. This work establishes a scalable, protection-aware foundation for integrating real-time DSA into operational practices, enhancing reliability in IBR-rich power systems.

Part II: Georgia Institute of Technology

This project is focused on identifying operational security vulnerabilities in T&D assets of an electric power system dominated by IBRs. It focuses on the performance of protection and control systems and the implications of this performance on the dynamic security of the system. Georgia Tech effort for this project has been focused on the following three parts of the study. (1) Proper representation of inverter-based resources in dynamic studies by developing a co-model of the power system, the IBRs, and the protection and control system, (2) Investigation of protection response including normal performance of protection and control as well as failures of protection and control systems, and (3) developing the framework for dynamic security assessment of an IBR dominated electric power system.

This report aims to understand the causes of disturbances and contingencies when Inverter-Based Resources (IBR) are connected or suddenly disconnected from the grid or when a fault occurs in the system and there is interaction between the power system and protection response and the controllers of IBRs. It explores the extent to which follow up responses are expected to occur and examines the implications for existing legacy protection schemes using real-life test cases. The report begins by introducing the problem statement and providing examples of real-life incidents

that occurred in the US and around the world due to IBR triggered disturbances and other transients. The report provides explanations why this work is crucial for determining the optimal design and positioning of new IBR projects to minimize disturbances in the grid.

Chapter 2 of the report is devoted to the development of a co-model of power system, IBRs and protection and control. The integrated co-model consists of (a) a breaker-oriented, physically-based three-phase electric power system model, including IBRs, (b) the P&C system with links to the physical power system, and (c) automated procedures to extract the positive sequence and EMT co-model from (a) and (b). The co-model is symbolically shown in Fig. 2.1 comprising power components, relays, merging units and the interconnection between the power components and the protection devices. The co-model enables co-simulation of the power and P&C systems during any disturbance, i.e. a fault event, etc., to determine the response of the system, i.e., whether the disturbance will be properly cleared and there will be no follow-up events or whether there will be follow-up events, such as a common mode outage, cascading outages and possibly instability. It is important to note that it is possible that the response of the P&C system to cause all of the above-mentioned follow-up events, even if the P&C system would have performed as designed, i.e., no failures within the P&C system. There is a certain probability that failures within the P&C can occur, such as breaker failure, hidden failures in instrumentation and devices as well as P&C changes due to cyber-attacks. We use a probabilistic model of breaker failure, hidden failures and/or cyber-attacks of the P&C system. The probabilistic models enable the co-simulation to capture the consequences of failures in the P&C system.

We also propose the development of an automated procedure to convert part of the power system co-model into a positive sequence (per-phase equivalent) bus-oriented model. This co-model will enable faster simulation of the system when all faults have been cleared and will facilitate efficient application of other analysis methods such as the energy function method and time domain simulation of the un-faulted system. For demonstration purposes we converted the IEEE 24 bus reliability system, which is based on symmetrical component modeling and bus-oriented model, into a **24-substation**, three-phase, physically-based, breaker-oriented, P&C system inclusive model. Each substation is modeled with variable breaker arrangements, for example ring-bus, breaker and a half, double breaker, etc.

Chapter 3 of the report uses the co-model to characterize the response of the system to faults and disturbances and how this response shapes the contingencies that the system will experience. The overall objective of this task is to identify events which may result in major system disturbance by triggering common mode outages, follow-up outages and/or cascading outages. For this purpose, the co-model is utilized to perform co-simulation to answer the following questions: (a) how long of a co-simulation is needed to capture all the effects of a fault event, and (b) can part of co-simulation switch to single phase (positive sequence) co-simulation once faults have been cleared so that the co-simulation can proceed with the much more efficient analysis of positive sequence based models, and (c) can and at what point in the time domain co-simulation one can switch to other direct DSA methods to determine whether the system is stable.

P&C failures have been integrated into the co-simulation using a Monte Carlo type approach. We investigated the feasibility of developing selection of critical P&C failures via sensitivity methods, which are expected to be more efficient. We determined that a time simulation period of four

cycles after the last protective relaying response, i.e. after the fault(s) have been cleared to establish the post fault level of disturbance of the system, is enough to take the system to a point where the simulation can continue with a simplified model. The post fault(s) conditions of the system are used to assess dynamic security with more efficient methods. We introduced the Energy Method to assess the stability of the system.

Chapter 4 provides a framework for performing dynamic security assessment in an IBR dominated power system, using the co-model. The objective of this task is to determine the long-term dynamics after the fault(s) have been cleared and whether the post fault dynamics will result in more relay actions such as tripping of an unstable generator. First, dynamic security assessment is conducted in RMS-EMT co-simulation. Second, we use energy function methods for faster DSA as follows: continue the time domain co-simulation of the co-model for four cycles after the last fault has been cleared. At that time, we switch to an energy function method using the approach described in [9]. Specifically, the manifold of the center of oscillations is computed from the time domain co-simulation data using estimation methods. The center of oscillations manifold is identified as points in the system for which the frequency varies linearly with time (does not oscillate). Knowledge of the center of oscillations enables the computation of the total energy of each generator, i.e. kinetic and potential energy, as well as the potential barrier of each generator. The kinetic energy of each generator is directly computed. The potential energy requires the manifold of the center of oscillation and the present state of the generator. Note that the manifold of the center of oscillations may be slowly moving with time. Once the total energy is computed, a direct comparison to the total energy of a generator to the potential energy barrier will determine the stability or instability of the specific generator.

Chapter 5 presents a summary of the work and how the work at Georgia Tech is integrated with the work at ASU. It also provides an assessment of how this work contributes to the needs for assessing the dynamic security of an IBR dominated power system, considering the response of protection and control systems. While this project made important developments for dynamic security assessment of IBR dominated power systems integrated with protection and control systems, the topic is very broad and complex and more research will be needed to bring these developments to practical use.

The report also includes two Appendices. Appendix A presents the co-model of the IEEE 24 Substation RTS. Specifically, the co-model is based on the IEEE 24-bus Reliability Test System which has been converted into a 24-substation test system with integrated protection and control (co-model) and the ability to easily change synchronous generators into IBRs. Appendix B presents multiple events conducted on the IEEE 24 Substation RTS and the response of the protection and control to these events.

Project Publications:

[1] Reza Cheshomi, Amir Esmaeili-Nezhad and Mojdeh Khorsand, “Online Machine Learning-Based Dynamic Security Assessment With Protection Modeling Trained on RMS-EMT Co-Simulation Data,” *North American Power Symposium 2025*.

Student Theses:

[1] Reza Cheshomi, *Hybrid RMS-EMT Co-Simulation and Machine Learning-Based Dynamic Security Assessment for Inverter-Based-Resource-Dominant Power Systems, PhD Dissertation, Expected May 2027.*

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1. Introduction

1.1 Background

Modern power systems are experiencing a paradigm shift due to the widespread integration of IBRs, increased system dynamics, and extensive wide-area interconnections. This transformation introduces significant challenges for ensuring the transient stability and dynamic security of the grid. Transient stability, defined as the ability of synchronous generators to maintain synchronism following significant disturbances, remains one of the critical aspects of system security [1 ,2]. Events such as short-circuit faults, high-resistance faults, and sudden disconnection of generators or transmission lines can trigger rotor angle instability and cascading outages [3].

Dynamic Security Assessment (DSA) is a critical function for evaluating the ability of a power system to withstand disturbances and maintain stable operation under a wide range of operating conditions and contingencies. Traditional DSA methods rely on extensive time-domain simulations using detailed mathematical models of system components. While these approaches provide high accuracy, they face practical challenges in large interconnected grids due to high computational costs and the need to account for a vast uncertainty space arising from variable operating points, renewable generation variability, and stochastic fault events. To address these limitations, recent research has explored the use of data-driven and hybrid methods that combine measurement-based features, often extracted from PMU data, with advanced machine learning (ML) and deep learning (DL) algorithms to predict system stability in real time. These techniques have demonstrated the ability to reduce computational requirements while maintaining, and in some cases improving, prediction accuracy. However, the effectiveness of such models is highly dependent on the quality and representativeness of the training data, as well as the inclusion of realistic system dynamics, protection actions, and control responses.

Despite recent advances in data-driven DSA techniques, a critical limitation in most existing frameworks is the lack of explicit modeling of protection and control (P&C) systems. Protective relays, particularly distance relays, are vital for fault detection, isolation, and dynamic network reconfiguration. Including their behavior has been shown to improve the accuracy of transient stability assessments, especially under fault-induced topological changes [4, 5]. The growing integration of IBRs amplifies the importance of modeling P&C systems, as the characteristics of fault currents in IBR-dominated grids differ substantially from those in traditional systems. While synchronous machines contribute high-magnitude fault currents with significant negative- and zero-sequence components, IBRs inject low-magnitude, rapidly decaying fault currents with reduced sequence content [6]. Conventional protection schemes, which rely on these legacy characteristics, may therefore misoperate in modern power systems, leading to delayed fault clearance or even incorrect relay operation. These vulnerabilities have manifested in real-world events, where typical transients in legacy networks triggered disproportionate responses from protection systems interacting with IBRs, resulting in widespread photovoltaic (PV) disconnections [7]. Such events underscore the need for a realistic evaluation of P&C system behavior under evolving grid conditions and highlight that excluding detailed protection logic from DSA frameworks, particularly ML- and DL-based models, undermines their ability to capture critical system dynamics. Accurately modeling these interactions is challenging, as traditional RMS domain simulations often fail to represent the fast control dynamics and switching behavior

inherent to IBRs. While EMT simulations offer the necessary granularity to capture such dynamics, their computational demands make them impractical for large-scale systems. RMS-EMT hybrid co-simulation presents a practical and scalable solution by allowing selective modeling of sensitive sub-networks, such as those with high IBR penetration, in the EMT domain, while representing the remainder of the system in the RMS domain. This approach enables both fidelity and scalability, making it a suitable foundation for realistic and comprehensive DSA of modern power systems.

1.2 Literature Survey

The increasing complexity of modern power systems, driven by the widespread integration of IBRs, advanced control schemes, and evolving operational requirements, has intensified the need for accurate and efficient stability and protection studies. A wide range of research efforts has focused on enhancing dynamic security assessment, adapting protection systems to new operating conditions, and developing advanced simulation frameworks capable of capturing both electromagnetic and electromechanical dynamics. This section reviews key contributions in these areas, providing context for the methodologies and tools adopted in this work.

1.2.1 State-of-the-Art Approaches to Dynamic Security Assessment

DSA tools play a crucial role in evaluating system stability under various contingencies. Traditional DSA relies on time-domain simulations with deterministic models, which, although accurate, suffer from limitations including high computational cost, lack of scalability to large uncertainty spaces, and challenges in real-time operation. To address these limitations, recent developments have introduced data-driven and hybrid approaches leveraging ML and DL techniques for DSA. A broad spectrum of ML models, including decision trees, support vector machines (SVMs) [8], artificial neural networks (ANNs), and ensemble methods such as RF [9], have been successfully applied to DSA tasks.

RF models are especially valued for their interpretability, robustness, and fast inference speed. An enhanced online RF algorithm was proposed to address frequent updates in model parameters and demonstrated its application in online voltage stability assessment using PMU data [10]. In addition, combining feature selection with iterated RF has proven effective for real-time DSA applications [11].

Various deep learning architectures have also been explored for enhancing DSA performance. Cascaded CNNs have been proposed to enable efficient offline screening of large-scale contingencies, significantly reducing average simulation times by enabling early termination of time-domain simulations without compromising accuracy [12]. Other CNN-based frameworks have been developed for real-time classification of transient and oscillatory system states using PMU voltage phasor data, providing high accuracy and robustness against measurement noise, while maintaining scalability to larger power systems [13]. A convolutional neural network and gated recurrent unit (CNN-GRU) based model has been proposed to enhance the capability of capturing complex patterns and dynamic behaviors in power system signals for improved stability monitoring [14]. These techniques and algorithms form a foundation expected to be further improved, adapted, or adopted as core components of the next-generation smart grid [15], as they

demonstrate the effectiveness of deep learning approaches, particularly CNNs, in enabling rapid and noise-tolerant stability monitoring for complex power systems.

Recurrent neural networks such as Long Short-Term Memory (LSTM) models have also been employed to process raw synchrophasor data and produce adaptive predictions based on available post-fault measurements, enabling dynamic trade-offs between early response and classification reliability. This approach reduces the overall model complexity and training time compared to ensemble methods, while leveraging the LSTM's ability to capture temporal dependencies in time-series data [1]. Combining CNNs and LSTMs has further improved prediction speed and early fault detection capabilities [16].

In summary, the evolution of DSA methodologies from traditional time-domain simulations to advanced ML and DL frameworks reflects a clear shift toward achieving real-time, scalable, and noise-tolerant stability assessment. These emerging approaches leverage high-resolution measurement data and advanced feature extraction techniques to improve predictive accuracy while reducing computational burden. As power systems continue to integrate higher levels of inverter-based resources and operate closer to stability limits, the development of hybrid data-driven DSA tools that combine the proven strengths of classical methods with the adaptability of modern learning algorithms will be critical for enhancing operational reliability.

1.2.2 Importance of Modeling Protection Systems in Transient Stability Studies

Reliable simulation of power system dynamics under fault conditions depends not only on accurate modeling of generators, loads, and control devices, but also on the inclusion of protective relay behavior. Recent studies have shown that the interaction between IBRs and conventional protection schemes can lead to undesirable effects such as delayed or incorrect relay operation, which in turn can increase the risk of instability or prevent important events from being detected. These issues become more significant in networks where relay settings are designed based on the behavior of synchronous machines. In such systems, protection devices, particularly distance relays, may misinterpret impedance trajectories due to the distorted waveforms produced by IBRs, increasing the likelihood of misoperation or failure to trip.

Excluding protection systems from transient stability assessments has been shown to result in unrealistic simulation outcomes. For example, system behaviors such as fault-induced topology changes, cascading outages, and post-disturbance instability cannot be captured without explicitly modeling the protection actions that trigger them. Studies such as [4,5] show that not including these elements in the simulation framework often leads to incomplete assessments, limiting the usefulness of the resulting operational strategies.

However, modeling all protection systems in a large-scale grid like the WECC network is computationally demanding and practically difficult due to the need for extensive relay settings and continuous updates. To manage this, selective protection modeling strategies have been proposed that focus on identifying and including only those relays that have the most impact on system behavior.

One notable approach is presented in [5], where a two-stage algorithm is used to identify critical distance relays for inclusion in dynamic simulations. The method evaluates each relay using two

criteria; apparent impedance monitoring and the Minimum Voltage Evaluation (MVE) technique. Relays on lines that experience significant changes in impedance trajectories following a disturbance are identified by the first criterion, while the second identifies relays connected to buses with major voltage drops. Through iterative simulations and threshold-based filtering, the algorithm narrows down a focused set of important relays, enabling accurate modeling while keeping computational demands manageable.

In addition, [4] introduces a data-driven algorithm to evaluate the effect of different protection functions on transient stability results. This method involves running time-domain simulations for a variety of contingencies, both with and without specific protection models enabled. By comparing outcomes such as generator rotor angles, frequency responses, and voltage profiles, the method ranks how much each protection function affects the system. The most influential elements are kept in the model, while less impactful ones are excluded. This reduction makes it possible to simulate complex power systems efficiently without losing critical accuracy.

Moreover, the integration of renewable energy sources, especially those with grid forming inverters, has added new challenges to protection system behavior. These inverters can change current waveforms and introduce responses that do not align with conventional relay settings. As shown in both [4] and [5], neglecting these interactions in transient stability simulations may result in important system dynamics being overlooked, particularly under high IBR penetration conditions.

In conclusion, while modeling every protection device in a large system is not practical, including the most critical relays and protection functions is both achievable and necessary. Algorithmic methods that identify and select key protection schemes help ensure that the simulation results accurately reflect the system's real-world behavior, leading to better assessments and improved system reliability.

1.2.3 Impact of Inverter-Based Resources on Protection Systems

The increasing integration of IBRs, including PV systems and wind turbine generators (WTGs), presents fundamental challenges to conventional protection systems due to the distinct fault current characteristics of these resources. Unlike traditional synchronous generators (SGs), which inject large, uncontrolled fault currents driven by their internal reactance and mechanical inertia, IBRs are interfaced with the grid through power electronic converters that impose strict limitations on fault current magnitude and duration.

This contrast in behavior arises from the design and control of IBRs, particularly Type III (doubly-fed induction generators) and Type IV (full-converter) WTGs, where current injection is actively regulated by fast-switching control systems. These control strategies, often proprietary and manufacturer-specific, are tailored to protect the thermal and structural limits of semiconductor components. As a result, fault currents from IBRs tend to be significantly lower in magnitude, transient in duration, and non-inductive in nature [6].

The discrepancy between expected and actual fault responses has critical implications for legacy protection schemes. Distance relays and overcurrent-based elements, which rely on the magnitude

and direction of fault currents to operate, may fail to detect faults, trip incorrectly, or exhibit delayed operation when exposed to IBR-generated fault conditions.

The inadequacy of conventional protection under these conditions becomes more pronounced as the proportion of IBRs increases within the grid. Misoperations, such as failure to trip during genuine faults or unintended trips during transients, jeopardize system security and highlight the need for revised protection strategies. Among the proposed solutions are adapting relay settings, implementing dynamic reactive current injection aligned with modern grid codes (e.g., VDE-AR-N 4120 in Germany), and incorporating advanced detection logic capable of distinguishing low-magnitude or non-inductive fault currents [6].

Beyond current magnitude, the control structure of grid-forming inverters (GFMs) further complicates the protection landscape. Unlike grid-following IBRs that track the voltage waveform of the grid, GFMs actively regulate voltage and frequency, making them critical in low-inertia, high-renewable systems. However, GFMs are equipped with tightly constrained current limits due to the thermal ratings of their semiconductor switches. To enforce these constraints, GFMs deploy internal control strategies such as reference current saturation, adaptive impedance injection, and virtual impedance emulation [17]. These mechanisms prevent damage but also suppress fault current responses to levels insufficient for conventional protection to operate reliably.

Importantly, the fault response of IBRs is not universal. It is a function of both internal software logic and external network conditions. Many commercially deployed IBRs are configured to limit their current output to 1.1–1.5 times their rated current, typically for only a few milliseconds. These time-limited and low-magnitude responses challenge traditional fault location detection and classification techniques, which were designed based on the expectation of high sustained fault currents from synchronous machines.

In summary, while IBRs, particularly GFMs, are instrumental in facilitating the transition to renewable-based grids, their distinct and constrained fault behavior introduces new vulnerabilities in grid protection. Accurately modeling these behaviors in simulation environments and incorporating them into protection coordination studies is essential. Without such adaptations, the risk of misoperation under high-IBR conditions remains high, potentially undermining the reliability of power system operations [17].

Beyond the general limitations posed by IBRs during fault conditions, specific impacts on individual protection functions have been well-documented. The behavior of IBR fault currents, limited in magnitude, rapidly decaying, and controlled by proprietary algorithms, results in a wide range of operational challenges in conventional protection schemes. A detailed analysis of protection elements under high IBR penetration reveals their vulnerability to either misoperation or complete failure to respond appropriately [5, 18].

For transmission line protection, particularly distance relays, the most critical issues arise from the lower amplitude of fault currents injected by IBRs, reduced supervising phase currents, and the changing impedance seen from the relay location. These conditions can cause both overreach and underreach, potentially resulting in failure to trip or false tripping. Similarly, memory-polarized zero-sequence directional elements may struggle with directionality due to low inertia and phase

shifts introduced by IBRs' fast-reacting controllers, further increasing the risk of protection failure [5, 18-20].

Negative sequence-based schemes, including directional ground fault protection and overcurrent relays, rely heavily on negative sequence current magnitude and angle for correct operation. However, IBRs typically inject weaker and more variable negative sequence currents, which can reduce the effectiveness of both fault detection and directional decision-making, ultimately leading to relay inaction [5, 18].

Pilot protection schemes, especially those utilizing directional comparison blocking (DCB), are affected by the reduction in phase current magnitudes. This weak signal condition may limit the ability of such schemes to detect faults and coordinate protection actions across terminals, resulting in misoperation. Likewise, line current differential (LCD) relays may misclassify internal faults as external due to the differing current patterns of IBRs during faults [5, 18].

Rate of Change of Frequency (ROCOF) protection also could be compromised. With synchronous generators being replaced by low-inertia IBRs, the frequency response of the system becomes steeper during disturbances. This increases the likelihood of unwanted ROCOF relay activation during normal variations, undermining its reliability for islanding detection and stability control [5].

Power swing protection mechanisms, including power swing blocking and out-of-step protection, face notable challenges as well. The reduced inertia and altered impedance trajectories caused by IBRs make it more difficult to differentiate between stable power swings and true faults. The resulting risk includes blocking actual faults or tripping during stable swings. Moreover, the optimal placement and configuration of out-of-step protection become more complex under these evolving conditions [5, 18].

In summary, the operational integrity of traditional protection schemes is severely impacted by the characteristics of IBR-dominated networks. The diverse set of protection functions discussed above demonstrate that existing relay logic and settings require substantial revision to align with the dynamic and non-conventional behaviors introduced by power electronic-based generation. Addressing these vulnerabilities is essential to ensure the resilience, reliability, and security of protection systems in the modern power grid.

1.2.4 Hybrid RMS-EMT Simulation Frameworks for Modern Power Systems

Modern power systems increasingly rely on IBRs, distributed energy technologies, and power electronic devices that introduce fast transients and complex control behaviors. These dynamics cannot be fully captured by traditional phasor-domain RMS simulations, which rely on simplified positive-sequence models. EMT simulations, by contrast, provide high temporal resolution and accurately represent switching operations, control loops, and unbalanced conditions. However, applying EMT simulations across a full-scale power grid is computationally prohibitive. To overcome this challenge, a class of hybrid RMS-EMT simulation frameworks has emerged, enabling selective EMT modeling of critical regions while maintaining RMS simulations for the rest of the system.

This hybrid co-simulation approach achieves a balance between accuracy and computational efficiency by modeling only the regions with dense IBR penetration or sensitive dynamic behavior in the EMT domain. The remainder of the grid is represented using a positive-sequence model and simulated in the RMS domain, providing scalability for large systems without sacrificing fidelity in key sub-networks.

One such advanced methodology is proposed in [21], where a dynamic simulation mode-switching mechanism is integrated into the hybrid platform. This simulator allows switching from a hybrid RMS-EMT model, where selected subsystems are modeled in EMT and the rest in RMS, back to a pure phasor-domain simulation once fast transients subside. This "zoom-in/zoom-out" strategy enables efficient resource allocation, focusing computation on critical periods and relaxing it during steady-state operation. The simulation framework supports multi-layered modeling, including positive-sequence, three-sequence, and three-phase representations. These are coordinated through a Multi-Area Thévenin Equivalent (MATE) algorithm, which partitions the system into subsystems and maintains consistency at virtual boundary buses.

Building on this approach, an open-source hybrid simulation platform designed for transmission and distribution (T&D) co-simulation has been introduced [22]. The platform starts in RMS mode and automatically switches to hybrid RMS-EMT mode when disturbances such as faults or voltage instability are detected. It reverts to RMS mode once the system stabilizes. The transition is managed through a simulation mode switching controller that monitors system metrics like voltage sags and frequency variations. The MATE algorithm is again used for subsystem partitioning and ensuring seamless interaction across domain boundaries.

The effectiveness of RMS-EMT hybrid simulation has been further demonstrated in the context of Fault-Induced Delayed Voltage Recovery (FIDVR) studies, which are especially relevant in systems with high concentrations of single-phase residential A/C units. The residential A/C motors stall under voltage sags, prolonging recovery times and potentially triggering relay misoperations. In another work, RMS-EMT simulation was applied to a test system experiencing a single-line-to-ground (SLG) fault [23]. The hybrid simulation accurately captures the motor stalling dynamics and voltage recovery profiles.

Together, these studies demonstrate the viability and effectiveness of hybrid RMS–EMT simulation frameworks for modern power system analysis through advanced software implementations with dynamic mode switching [21-23]. By combining EMT modeling for critical sub-networks with RMS simulation for the remainder of the grid, hybrid simulation enables accurate representation of critical transients while preserving computational efficiency and scalability. These capabilities are particularly valuable for systems with widespread IBR deployment, where both electromagnetic and electromechanical phenomena must be simultaneously captured.

1.3 Report Organization

The remainder of this report is organized as follows:

- Chapter 2 presents the development of the complete WECC co-simulation model incorporating Protection and Control systems in DIgSILENT PowerFactory. This includes

model conversion, relay implementation, EMT-RMS partitioning, and hybrid simulation setup.

- Chapter 3 introduces an online ML-based DSA framework. This chapter outlines the dataset generation, machine learning model development, and performance evaluation in the context of the co-simulation results.
- Chapter 4 concludes the report with key findings and insights.

2. Development of WECC Co-Simulation with P&C Systems in DIgSILENT

2.1 Chapter Overview

This chapter presents the comprehensive development of a hybrid co-simulation model of the 2028 WECC peak summer planning case implemented in DIgSILENT PowerFactory. The primary objective is to enable DSA studies that integrate realistic P&C behavior, particularly under the influence of IBRs. Starting from a GE PSLF planning case, the WECC model was converted and reconstructed in DIgSILENT. Detailed modeling efforts included mapping of buses, loads, and generation across WECC, followed by the systematic implementation of distance relays and differential protection schemes. Additionally, the chapter details the modeling of various IBRs using DIgSILENT's built-in PV units, IBRs within EMT regions, and the configuration of hybrid RMS-EMT simulation boundaries. Multiple case studies and scenario definitions are provided to validate model behavior, analyze co-simulation speed, and generate datasets for subsequent AI-based DSA model training. This chapter establishes the modeling foundation required for accurate hybrid simulations that capture both electromagnetic and electromechanical dynamics across the WECC system.

2.2 Development of 3-Phase Power Flow Capability in the WECC System Model

The original WECC system model was provided as a GE PSLF file, which supports only positive-sequence analysis. To enable broader simulation capabilities, including 3-phase power flow and RMS (balanced and unbalanced) dynamic simulations, the model was subsequently migrated and developed within DIgSILENT PowerFactory.

To achieve this, a number of modifications and refinements were necessary. One of the most important modifications involved the tuning of negative and zero-sequence impedances of system elements. These adjustments were based on short-circuit data extracted from the original GE PSLF file. Specifically, the zero-sequence impedance of the transmission lines was set to be three times greater than the corresponding positive-sequence impedance. For transformers, the zero-sequence impedance was set equal to the positive-sequence impedance, in alignment with standard assumptions used in the WECC system modeling.

To make the process more manageable, all of the system grids were deactivated except for one. At the boundaries of the active grid and the deactivated grids, 'External Grid' elements (ElmXnet) were used. These elements were configured to inject or absorb the exact amount of active and reactive power observed at their locations in the Balanced (positive-sequence) Power Flow results. With this configuration, a 3-phase power flow was attempted.

If the power flow still failed to converge, one of the 'External Grid' elements could be selected the 'Bus Type' to act as a 'Slack' source. Additionally, the voltage magnitude and angle setpoints of the slack External Grid should be assigned based on the corresponding values from the positive-sequence power flow results.

This process can be repeated for each grid individually to identify problematic areas. Once the 3-phase power flow successfully converges for two neighboring grids separately, the next step is to connect them. This involves activating both grids while deactivating the External Grid elements previously placed between them, and then attempting to run the 3-phase power flow again.

If the power flow fails to converge upon connecting two grids, alternative configurations can be explored. For instance, instead of activating the problematic grid, another neighboring grid can be chosen. By systematically trying different grid combinations and progressively increasing the number of active grids that can successfully converge, the complete WECC system can eventually be assembled in its entirety. These refinements often led to convergence of the 3-phase power flow or at least helped isolate the issue, as the analysis was confined to a smaller, focused portion of the overall WECC system.

Another consideration involves the modeling of switchers. In the original GE PSLF data, switchers were represented as ideal switches. However, during the data conversion process to DIgSILENT PowerFactory, these switchers were modeled as transmission lines with a small amount of positive-sequence impedance. To ensure these artificial impedances do not adversely affect convergence, a very small value of zero sequence impedance was added to them.

It is worth noting that the results of the 3-phase power flow should only be compared to the balanced (positive-sequence) power flow results after all grids have been connected and the 3-phase power flow has been successfully executed on the entire WECC system. Partial comparisons during earlier stages may lead to misinterpretation due to the presence of disconnected boundaries and approximated external injections.

2.2.1 Mitigation of Voltage Unbalance After Power Flow Convergence

In our study, after successfully achieving power flow convergence for the full WECC model in DIgSILENT PowerFactory, we observed a significant level of voltage unbalance at various locations across the system.

For example, in numerous busbars, the voltage magnitude of Phase A remained close to the defined setpoint, while the voltages of Phases B and C were unreasonably low, often around 0.1 per unit. This indicated a structural modeling issue rather than a true system imbalance.

To address this, we began by specifying a load type and assigning its 'technology' to be '3PH PH-E'. This modification significantly reduced voltage unbalance in many areas of the network by explicitly defining the phase grounding and connection configuration of the load.

Nonetheless, some voltage unbalances persisted in specific regions. Upon further inspection, the root cause in these areas was traced to improper transformer vector group settings. During the data conversion from GE PSLF to DIgSILENT, all transformer vector groups were initialized to zero, as PSLF does not contain this information.

In one case, a path consisted of a transformer connected to a series of transmission lines and another transformer at the opposite end. Both transformers had their vector groups set to zero. By changing the vector groups of these two transformers from 0 to 6, the voltage magnitudes across

all three phases became balanced. Importantly, this adjustment maintained the voltage angles within acceptable ranges and preserved the validity of the power flow solution.

Figures 2.1 and 2.2 show the comparison between the voltage magnitudes and angles from the original GE PSLF file and the developed model in DIgSILENT. As illustrated, the two cases exhibit a strong agreement, confirming the validity of the migration and tuning process.

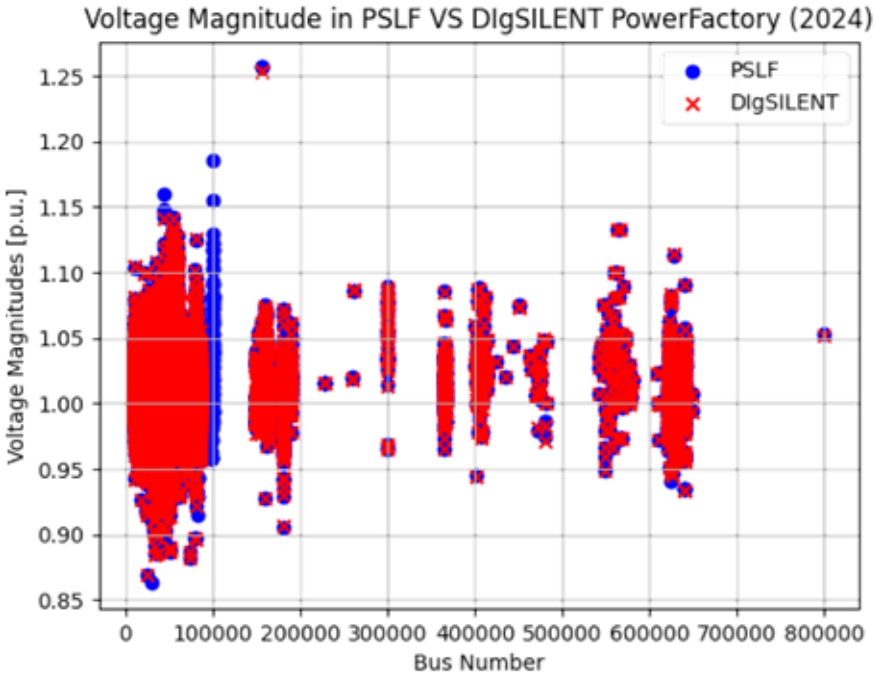


Figure 2.1 Comparison of voltage magnitude between GE PSLF and DIgSILENT models.

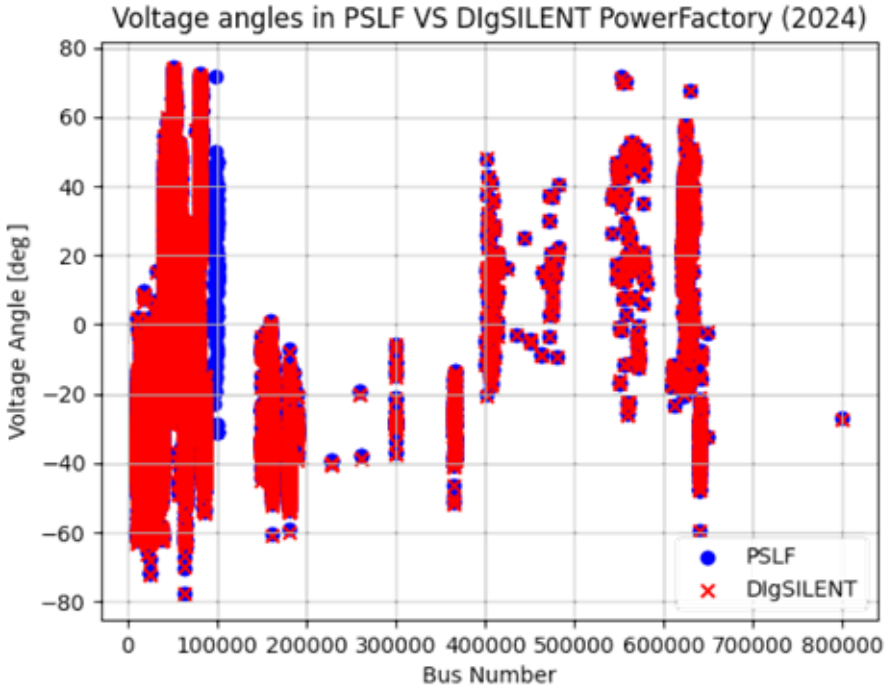


Figure 2.2 Comparison of voltage angle between GE PSLF and DIgSILENT models.

2.3 Development of Unbalanced RMS Simulation Capability

To enable unbalanced RMS simulation of the WECC system, it is first important to understand why the unbalanced RMS simulation is required. Because we want to study various types of faults, including unsymmetrical faults, we cannot use the balanced RMS simulation mode. Therefore, the unbalanced RMS simulation is essential to accurately analyze the effects of such contingencies.

In some cases, certain model signals fail to initialize correctly during unbalanced RMS simulations, even though they perform as expected in balanced RMS simulations. A common example involves parameters within governor or exciter models. An error message such as one or more parameters in the model cannot be initialized may appear during simulation startup.

Sometimes the root cause lies in time-related model parameters, such as delay constants or time constants, which must align appropriately with the simulation step size. If these parameters are not align relatively to the simulation step size, numerical instabilities may arise.

Another source of error involves model parameters related to limits. For instance, in GE PSLF, a limit parameter might be assigned a value like 999 to signify a practically unbounded maximum. However, in DIgSILENT, such a value might violate model constraints, where the allowable upper bound might be restricted to 99. These discrepancies must be identified and corrected during the tuning process.

Moreover, parameters set to zero in GE PSLF might be interpreted as inactive or ignored by the model. In DIgSILENT, however, a zero value may not imply the same behavior, and could instead be treated as a fixed value, potentially leading to incorrect results.

In cases where parameter mismatches exist between the same model types in GE PSLF and DIgSILENT, it is important to compare the structural block diagrams of the models across both platforms. This comparison helps infer the appropriate value for any ambiguous or undefined parameter in DIgSILENT. If a direct conversion is not possible, applying the default value in DIgSILENT may be a practical starting point for testing.

These practices significantly improve the likelihood of achieving successful initialization and execution of unbalanced RMS simulations for large-scale systems such as the WECC model.

2.3.1 Correction of Invalid Parameters after Data Conversion

During the data conversion process from GE PSLF to DIgSILENT PowerFactory, several inconsistencies and unreasonable parameter values can arise. These anomalies are often not flagged during the import process, as PowerFactory may accept such values silently without generating any warnings or error messages. However, these incorrect parameters can significantly impair the performance and convergence of power flow or dynamic simulations, especially in unbalanced studies.

One critical issue observed involves transformer impedance values. In certain cases, the converted transformer elements exhibited negative impedance values, which are physically unrealistic and technically invalid. These anomalies must be manually reviewed and corrected, as DIgSILENT does not prevent such values from persisting post-conversion.

Another important option available for DSL models is the ‘A-stable integration algorithm (only for RMS Simulation)’. This option considers the models together during the simulation, which can lead to more accurate and stable results. However, it typically increases the simulation running time. In certain cases, such as the one considered in this work, enabling this option improves both stability and simulation speed. Without this option, the results of some models with inaccurate parameters may exhibit instability, causing the computation of their equations to require longer execution times. By selecting this option, some of these problematic DSL models become stable, thereby increasing both the accuracy and the speed of the simulation.

Careful inspection and rectification of these parameters are essential for ensuring a robust and physically meaningful simulation environment in DIgSILENT PowerFactory.

2.3.2 Validation of Unbalanced RMS Simulation in WECC

Figure 2.3 presents the rotor angle trajectories of over 1000 generators within the WECC system during a 15-second unbalanced RMS simulation under no-fault conditions. As observed, the system initializes and maintains a stable operating state throughout the entire simulation period. This confirms that the developed WECC model for unbalanced RMS simulation in DIgSILENT PowerFactory is functionally robust and correctly configured.

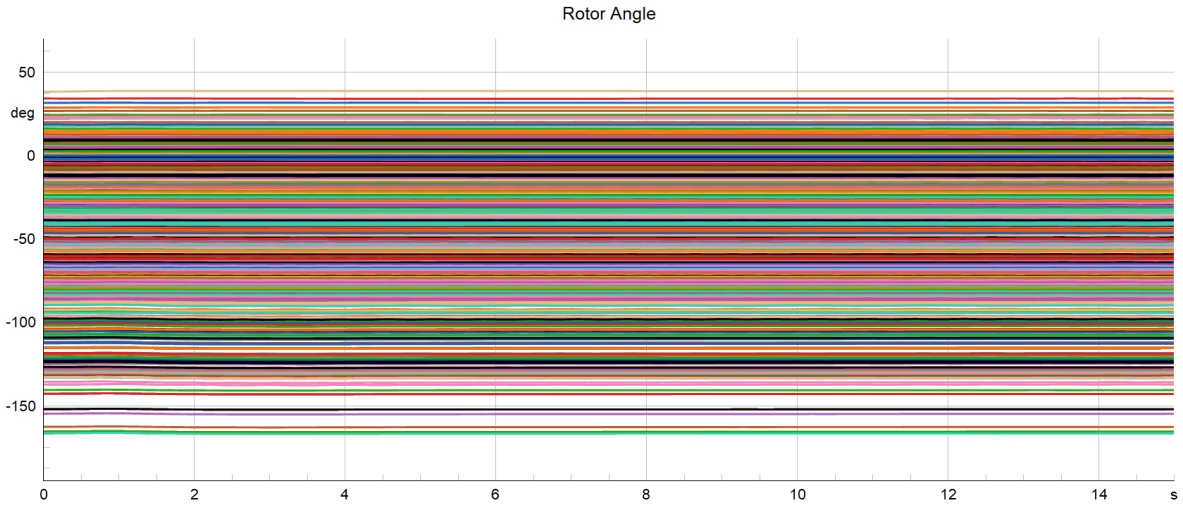


Figure 2.3 Rotor angle response of over 1000 generators during a 15-second unbalanced RMS simulation without any disturbance.

Additionally, the model was subjected to various N-1 contingency scenarios, and the results consistently demonstrated expected system behavior. Further dynamic performance results under faulted conditions will be presented in the subsequent sections.

2.4 Protection System Modeling

The protection system in the developed WECC model was implemented based on the actual protection data corresponding to the region under study. The real-world protection schemes primarily employ distance and differential relays. Accordingly, the model incorporates a combination of these protection types, supplemented with additional differential and distance relays placed at the locations of historical contingencies. In cases where historical fault locations lacked associated protection devices in the original dataset, default settings were used to define suitable relay configurations.

Moreover, several overcurrent and voltage-based (both over-voltage and under-voltage) relays were modeled specifically for the inverter-based resources (IBRs) targeted for placement within the EMT simulation regions. To streamline the logic and prevent unnecessary operations, nonessential subunits of each protective relay were deactivated. For instance, in distance relays, overcurrent and voltage subunits were disabled if they were not required by the protection scheme.

Standard intentional delays were applied to the zone operations of distance relays. Zone 2 relays were configured with a 300 ms intentional delay, while Zone 3 relays had a 600 ms delay. Modeling of the distance relays, as well as the associated current transformers (CTs) and potential transformers (PTs), did not pose significant implementation challenges.

To reflect realistic breaker behavior, a 66 ms delay was introduced for all circuit breakers. This means that once a relay issues a trip signal, the breaker operation occurs 66 ms after receiving this command, simulating actual mechanical actuation time.

It is important to note that in practice, relays receive analog signals from CTs and PTs and internally perform a signal processing algorithm such as Discrete Fourier Transform (DFT) to compute phasor magnitudes and angles for decision-making. This behavior is captured within the EMT domain of DIgSILENT simulations. However, when relays operate in the RMS domain, DIgSILENT appears to bypass this preprocessing step, providing magnitude and angle signals directly to the relays.

After implementing differential relays, a key limitation in DIgSILENT PowerFactory was observed. The software does not support modeling internal faults within transformers such as turn-to-turn faults. Additionally, it is not possible to model a fault at either side of a two-winding transformer that would be recognized by the differential relay as an internal fault.

Figure 2.4 shows a conventional differential relay (R) configuration where current transformers (CTs) are installed at both ends of the transformer. In this structure, applying a fault at the nearest high-voltage (HV) or low-voltage (LV) busbar will be interpreted by the relay as an external fault, and no trip signal will be sent.

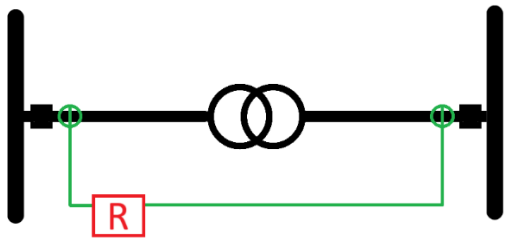


Figure 2.4 Conventional differential relay (R) configuration with CTs on both sides of the transformer. Faults at nearby busbars are identified as external.

To address this limitation, a modified setup was developed, shown in Figure 2.5. In this approach, one additional busbar (ElmTerm) and one circuit breaker (ElmCoup) are added at each side of the transformer. With this configuration, a fault can be modeled at the newly added busbars. In this case, the differential relay will correctly detect the fault as internal and issue the corresponding trip signal.

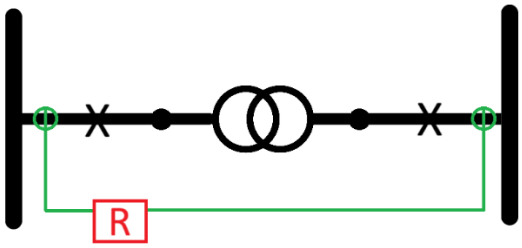


Figure 2.5 Modified configuration with added busbars and circuit breakers. Faults at the inserted busbars are detected as internal by the differential relay.

It should be noted that upon detection of an internal fault, the differential relay sends trip commands to all circuit breakers on each side of the protected transformer. This ensures proper isolation of the faulted component from the rest of the network.

After modeling the differential relays, it was observed that some relays misoperated immediately after the simulation started. The exact cause of this behavior could not be identified, but a practical workaround was implemented to mitigate the issue. Specifically, the vector group of the transformer protected by the misoperating differential relay was changed from group 0 to group 6. The settings of the differential relay were then updated to match this new vector group.

However, directly introducing a phase shift through transformer vector group modification is not permissible in this system, as it would prevent power flow convergence. To overcome this constraint, a dedicated phase-shifting transformer was added immediately downstream of the original transformer. This additional transformer was configured with a vector group 6 to compensate for the phase shift introduced by the modified protected transformer. Its impedance was set to a very small value to ensure that it does not affect the overall network behavior. The windings of the added phase-shifting transformer were configured as YY connection to maintain consistency and avoid introducing further imbalance.

An RMS simulation was conducted in which a Phase A to Phase B fault occurred at 0.5 seconds on one side of a two-winding transformer. This transformer is installed in parallel with another two-winding transformer, and both are protected by differential relays, as shown in Figure 2.6. As seen in Figure 2.7, the differential relay R1 accurately detected the fault as an internal fault and issued a trip signal 3 milliseconds after fault initiation. Conversely, the differential relay R2, which protects the parallel transformer, correctly identified the disturbance as an external fault and did not issue any trip signal.

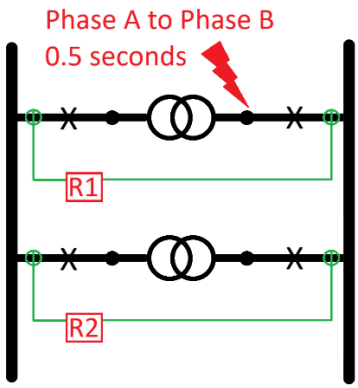


Figure 2.6 Protection scheme where two transformers operate in parallel, each protected by a differential relay, and a Phase A to Phase B fault is applied.

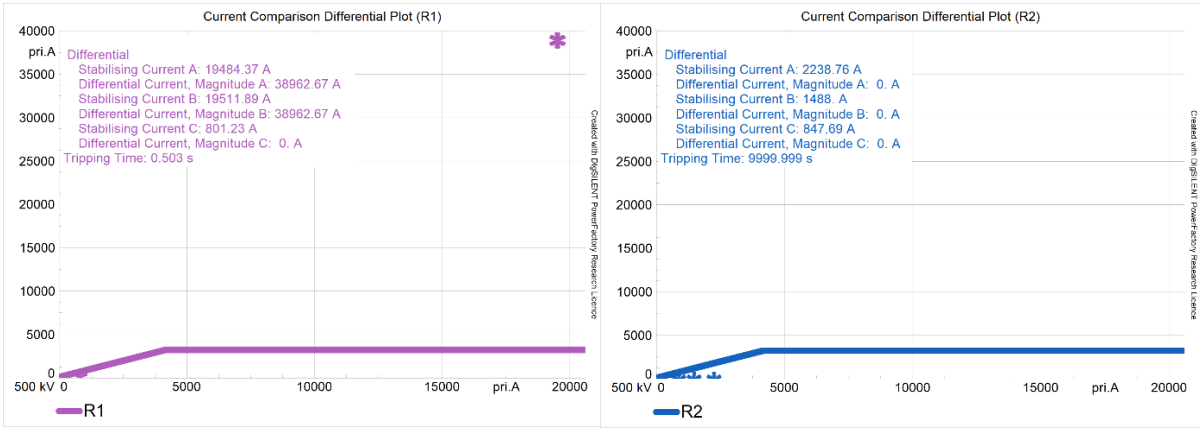


Figure 2.7 R1 detects the fault as internal and operates after 3 ms. R2 identifies the fault as external and does not operate.

Figure 2.8 illustrates a transmission line protected by four distance relays. For some elements within the WECC system, multiple relays are installed to ensure backup protection. In many instances, the primary and backup relays are sourced from different manufacturers. This practice enhances the reliability of the protection system since different relays often exhibit complementary performance characteristics. For example, each relay may have its own blind spots, but when combined, the system benefits from improved protection coverage.

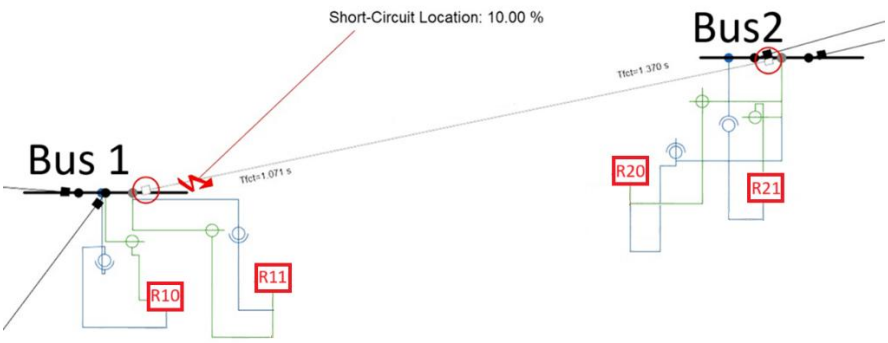


Figure 2.8 Distance relay setup for the line between Bus 1 and Bus 2.

In the illustrated scenario, a three-phase fault occurs at 10 percent of the line segment between Bus 1 and Bus 2 at 1 second during an unbalanced RMS simulation. The primary protection zone (Zone 1) of relays covers approximately 80 percent of the line. As a result, both R10 and R11 detect the fault within their Zone 1 and issue trip signals immediately, leading to the circuit breakers opening 71 milliseconds after the fault occurrence. On the opposite side of the line, relays R20 and R21 detect the fault in their Zone 2, which includes an intentional delay of 300 milliseconds. Consequently, the fault is cleared from the second side 370 milliseconds after the initial disturbance.

Figure 2.9 displays the impedance trajectories confirming the respective zone detections. Figure 2.10 presents the rotor angle trajectories of the generators in the studied portion of the WECC. As illustrated, after the disturbance, rotor angles began oscillating but eventually stabilized once the fault was cleared, indicating system stability was preserved.

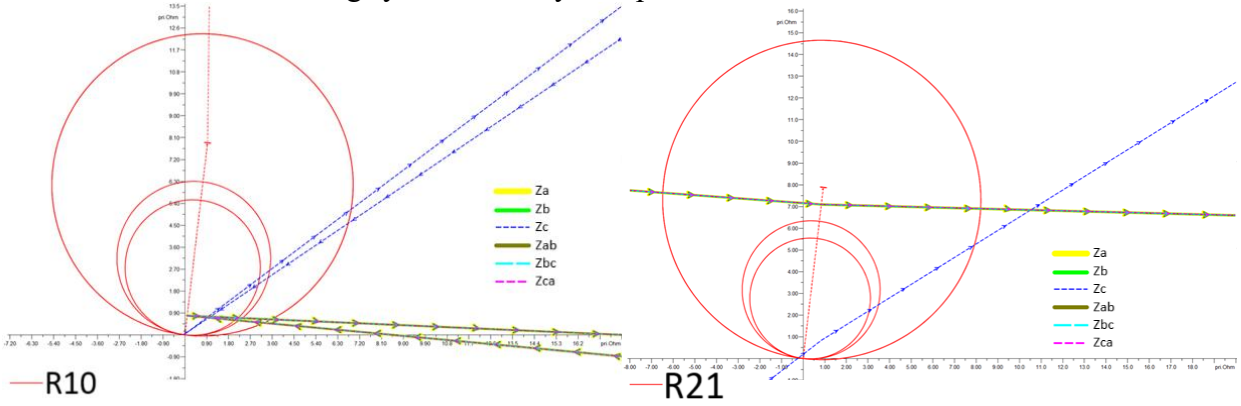


Figure 2.9 Impedance trajectories of R10 and R21 during three-phase fault.

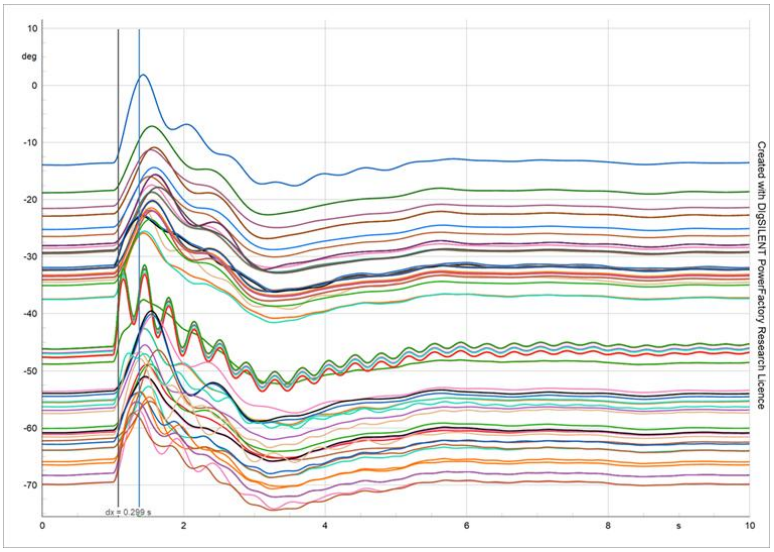


Figure 2.10 Rotor angle response of generators following the three-phase fault.

2.5 RMS-EMT Co-Simulation

Four inverter-based resource (IBR) plants were developed based on black-box models provided in PSCAD format. These IBRs include three hybrid PV and battery energy storage systems (BESS), and one standalone BESS. The modeling and validation of these systems were conducted in DIgSILENT PowerFactory. Each model was tested to ensure its stability and correct performance under various simulation conditions.

Following the successful development and validation of the EMT models, the team integrated them into the WECC network. The integration was configured to facilitate an RMS-EMT co-simulation. Three EMT regions were defined for this purpose. Since two of the developed IBRs are geographically close, they were grouped into a single EMT region. The remaining IBRs were placed in separate EMT regions. The rest of the WECC system was retained in a single unbalanced RMS region.

This partitioning enables a detailed electromagnetic transient simulation of the IBR plants while maintaining computational efficiency by modeling the rest of the system using unbalanced RMS. The co-simulation framework thus allows capturing the fast dynamics of inverter-based resources while preserving the broader system behavior within an acceptable runtime.

2.5.1 RMS-EMT Co-Simulation Configuration in DIgSILENT

The team integrated four IBR plants, modeled using black-box PSCAD files, into the WECC system to enable detailed electromagnetic transient (EMT) analysis. Three of these IBRs are BESS and PV hybrids, and one is a BESS-only plant. These models were validated in DIgSILENT and embedded into the larger network for co-simulation purposes.

The network was partitioned into three EMT regions, with the rest of the WECC system remaining in an unbalanced RMS domain. Since two of the IBR plants are geographically adjacent, they were grouped into one EMT region.

Since we do not have a sufficiently long transmission line located near the IBR plants in the EMT regions, the use of the implicit method for co-simulation is not feasible. Therefore, the team proceeded with the explicit method to carry out the RMS-EMT co-simulation. When using the explicit method, DIgSILENT provides two options to represent the equivalent of remote networks.

2.5.2 Current/Voltage Sources at Boundary Buses Method

As shown in Figure 2.11, let us consider a simplified system where a synchronous generator and a PV plant are interconnected. In this system, the red transmission line is selected as the boundary between EMT and RMS regions.



Figure 2.11 Simplified system example with a boundary line (red) between EMT and RMS regions.

When using the 'Current/Voltage sources' at boundary buses option for co-simulation, DIgSILENT PowerFactory places voltage (ElmVac) or current (ElmIac) sources at the interface buses, as illustrated in Figure 2.12. Suppose the PV plant is placed in the EMT region, while the generator is placed in the RMS region. During the co-simulation initialization process, the voltage or current sources in each region are configured to utilize the voltage or current signals from the corresponding buses in the opposite region.

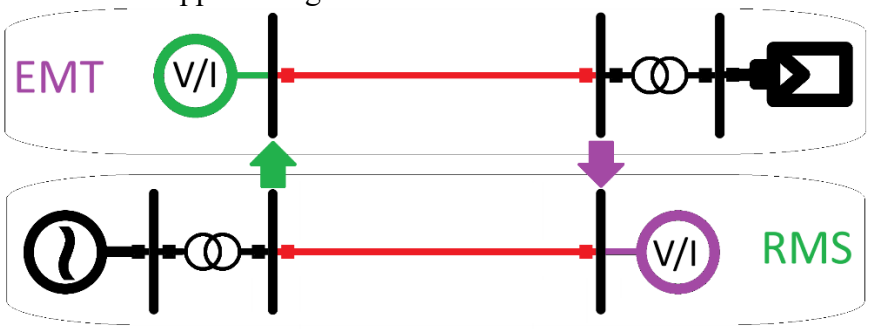


Figure 2.12 Voltage/Current sources interface method for RMS-EMT co-simulation.

Initially, DIgSILENT computes a power flow solution for the entire system to assign the initialization values to these boundary sources. Following that, it performs power flow computations for each region individually. In the figure, the upper part represents the EMT region, which is initialized using boundary values derived from the RMS domain (depicted below). Conversely, the RMS network uses boundary values taken from the EMT side.

It is important to note that, for successful initialization of co-simulation, both the EMT and RMS networks must be capable of being initialized independently. If the initialization fails, DIgSILENT typically does not provide detailed error messages specifying the cause. Therefore, it is recommended to individually initialize both the EMT and RMS domains to diagnose and resolve any issues preventing co-simulation startup.

Furthermore, it is important to note that the boundary element is represented in both the EMT and RMS regions. This configuration allows the monitoring of signals at the boundary from both domains. A practical approach to verify the proper operation of the co-simulation is to observe and compare the dynamic responses of elements located near or at the boundary. The signals recorded in both domains should be closely aligned in their respective simulation domains.

An essential diagnostic signal to evaluate during such verification is the zero-sequence impedance. Experience has shown that discrepancies in this parameter, particularly for elements connected to ground and positioned close to regional boundaries, can lead to numerical mismatches between the regions. Monitoring these signals can help identify sources of numerical instability or inaccuracies in the co-simulation setup.

It is also worth mentioning that the 'Current/Voltage sources' option permits only transmission lines to be defined as regional boundaries. In contrast, the 'Multi-port Thevenin equivalent' method allows both lines and buses to be designated as boundary elements.

Although the DIgSILENT user manual does not explicitly state a requirement concerning the impedance of the boundary line, practical experience shows that inconsistencies in the impedance values across multiple boundary lines can hinder the initialization of co-simulation. Specifically, if the travel times along the boundary lines differ significantly with respect to the co-simulation step sizes and synchronization period, DIgSILENT may be unable to initialize the co-simulation. In such situations, both EMT and RMS single-domain simulations may still initialize correctly, indicating that the problem is specific to the multi-domain configuration.

To resolve this issue, one approach is to select longer transmission lines as the boundaries. Alternatively, for shorter lines, their length can be artificially extended to ensure consistent wave travel times across all boundaries. To maintain the original impedance characteristics, the line parameters should be adjusted such that the total impedance remains unchanged despite the increased physical length.

2.5.3 Multi-port Thevenin Equivalent

If the 'Multi-port Thevenin equivalent' option is selected for explicit RMS-EMT co-simulation, DIgSILENT performs a process similar to the network reduction procedure (ComRed) during initialization. Specifically, the software calculates a Thevenin equivalent representation for each region from its respective boundaries. As a result, this method may yield different results compared to the 'Current/Voltage sources' approach.

While this technique may lead to more numerically stable simulations in some scenarios, it is generally more computationally intensive and sensitive to modeling inaccuracies. For instance, if

a DSL (DIgSILENT Simulation Language) model includes a term where division by a variable that may become zero or negative occurs during simulation, the co-simulation initialization may fail. Similarly, any occurrence of the square root of a negative number can lead to initialization errors that may not appear in single-domain RMS or EMT simulations.

To mitigate such issues, it is recommended to use protective formulations, such as:
max(0.0001, term)

This ensures that division by zero or negative values and invalid square root operations are avoided during execution.

Although the 'Multi-port Thevenin equivalent' may yield more stable results in certain cases, it is important to recognize that the 'Current/Voltage sources' method is inherently more accurate, as it is the same methodology DIgSILENT employs for implicit co-simulation.

A significant limitation of the Multi-port Thevenin approach, however, is that it supports only a single EMT region. This poses a problem in our case, as the EMT-modeled IBR plants are located at separate geographical points across the WECC system. Attempting to treat all EMT-modeled components as a single region for network reduction is not only impractical but may also result in reduced simulation speed and inaccurate results.

If multiple EMT regions are defined and the user attempts to initialize co-simulation using the Multi-port Thevenin option, DIgSILENT will return a generic 'Initial conditions invalid' error, even though the corresponding single-domain initialization run without issue.

Within the log files, the error message will typically clarify the failure:
'Remote equivalent not supported for EMT to EMT Co-Simulation.'
This means that multiple EMT regions are not supported with the Multi-port Thevenin equivalent method in explicit co-simulation.

2.5.4 Synchronisation Period

The 'Synchronisation period' parameter (dtpar) is defined in the co-simulation initialization settings page under the 'Basic Options' menu in the 'General' tab. This parameter sets the time interval at which the results of each region are synchronized with one another during co-simulation.

It is important to note that DIgSILENT does not allow this value to be smaller than the largest initialization step size defined among all regions. If a user mistakenly sets the synchronisation period to a value smaller than the largest step size, DIgSILENT does not halt the initialization process. Instead, it adjusts the synchronisation period automatically to match the largest step size across all regions and issues a warning message.

This behavior ensures the simulation remains numerically consistent, even though the original setting may have been incompatible. However, users should be aware of this adjustment and ensure

that their co-simulation parameters are explicitly set to maintain desired time resolution and synchronization accuracy.

Figure 2.13 illustrates the interaction between regions during co-simulation under different time resolutions. In this example, the step size of the EMT region is assumed to be half of that of the RMS region. The synchronisation period is selected to be the smallest allowed value which is equal to the RMS region step size.

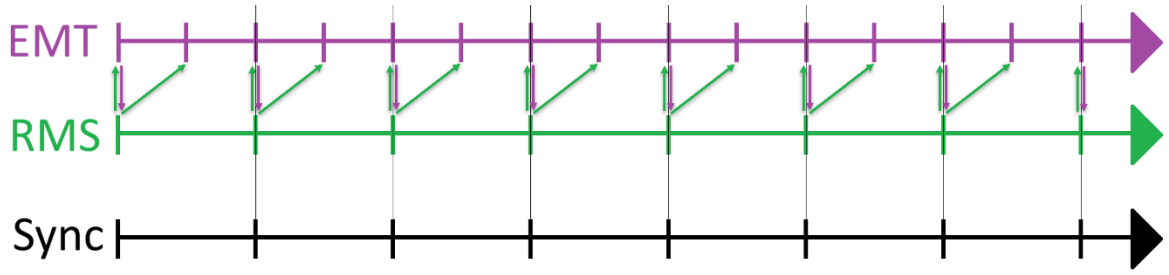


Figure 2.13 Illustration of synchronisation timing between EMT and RMS regions.

As shown, the voltage or current sources at the boundaries in the EMT region are updated based on the results from the same bus location in the RMS region. Since the step sizes are different, DIgSILENT uses the latest available results from the RMS region for synchronization with EMT. This confirms that the co-simulation becomes more accurate if both regions operate at step sizes that are close in value and sufficiently small. Additionally, setting the synchronisation period to its minimum acceptable value helps ensure better accuracy.

Also, the active and reactive power of the IBR starts from zero in all the figures. This occurs because DIgSILENT temporarily disconnects certain elements, such as IBRs and their associated DSL models, during the initialization phase of co-simulation in order to simplify the initialization process. As a result, users may notice that the power flow results shown on the single line diagram do not match expected values. This discrepancy is due to the initialization behavior and should not be interpreted as a modeling error. Therefore, users should avoid relying on the initial steady-state power flow results presented on the diagram. Instead, accurate operating conditions should be confirmed by monitoring key simulation variables, such as the active and reactive power of IBRs, through time-domain plots generated during the co-simulation run.

2.6 AG Fault Scenario in Co-Simulation

To validate the behavior of EMT-modeled inverter-based resources (IBRs) during fault conditions, a co-simulation scenario was conducted involving a single line-to-ground (AG) fault on a transmission line. This line is protected by distance relays and electrically close to one of the IBRs in the EMT region, while remaining electrically distant from the other two EMT regions.

The fault was applied at 80\% of the line length at t=1.5 s, with a fault resistance of 0.1 ohms. The protection system was configured such that the relay on the near side of the fault operated within its Zone 1 settings, resulting in an immediate trip. The relay on the remote side detected the fault in its Zone 2 protection area and issued a trip signal after a deliberate delay of 0.3 s. Including the programmed breaker operation delays, the two ends of the faulted line opened at t=1.581 s and t=1.88 s, respectively.

Figure 2.14 shows the phase currents and power response of the IBR model close to the fault location, which resides in the EMT region. As illustrated, the IBR injects reactive power during the fault interval, as expected. This behavior confirms that the IBR model responds dynamically and contributes to voltage support under faulted conditions.

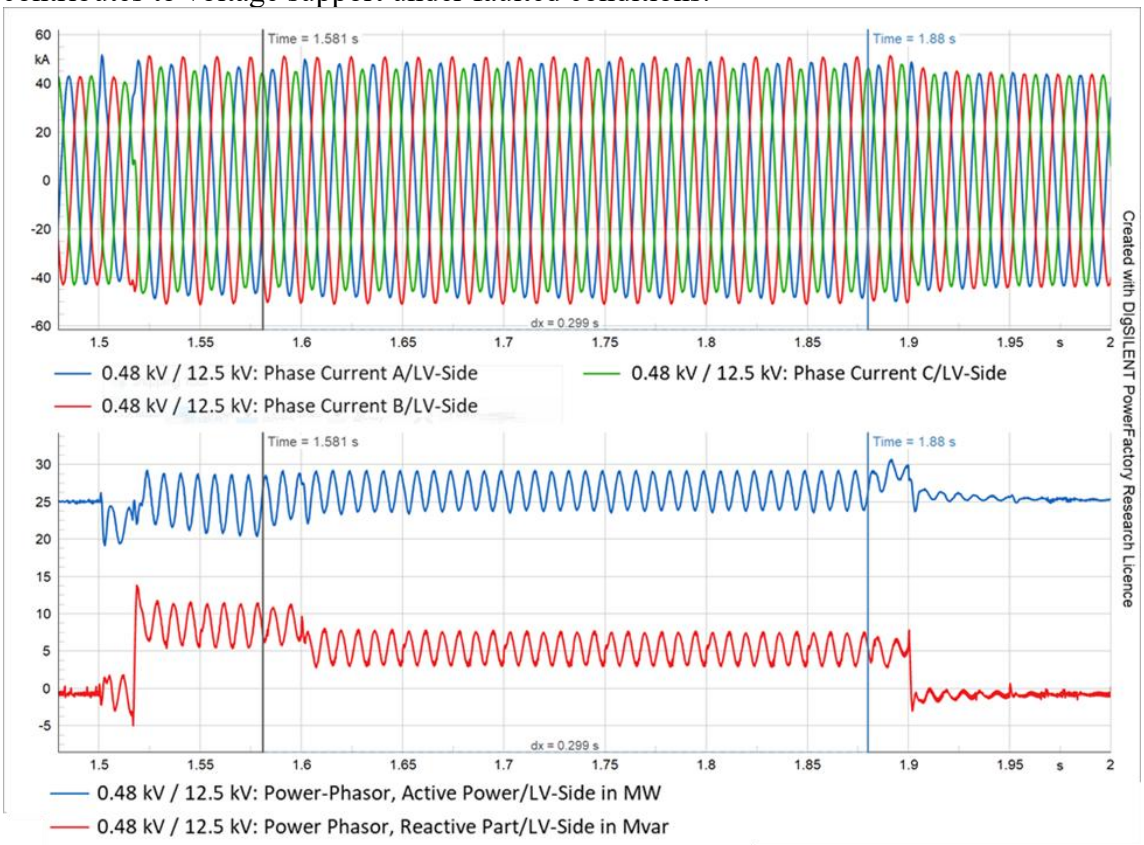


Figure 2.14 Active and reactive power and three-phase current response of the IBR model (EMT domain) during AG fault.

Figure 2.15 presents the impedance trajectories observed by the distance relays at both ends of the faulted line. The left-hand plot corresponds to the relay at the near end of the fault, showing clear entry into the Zone 1 impedance circle, while the right-hand plot corresponds to the remote relay entering Zone 2. These trajectories confirm correct fault detection and discrimination by both relays.

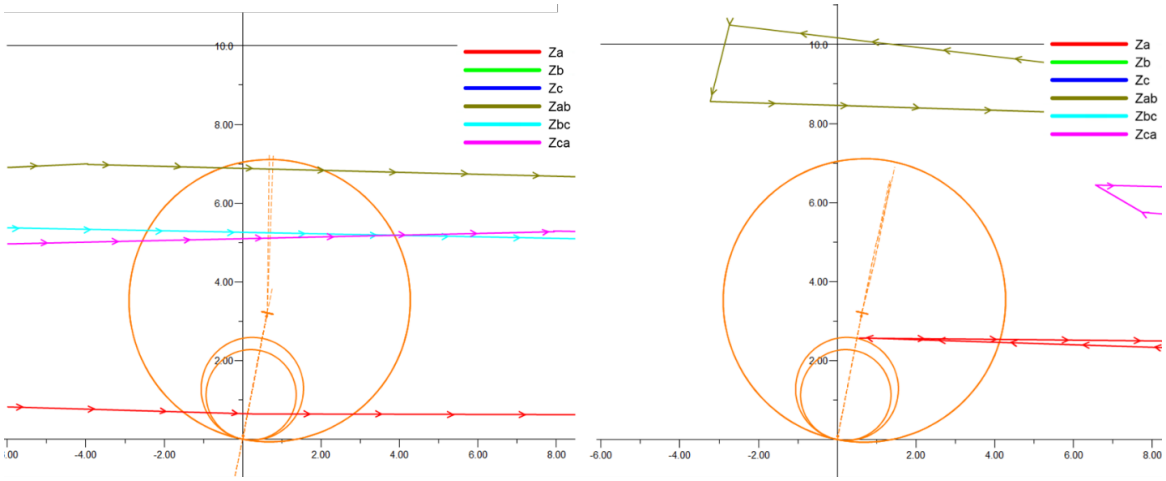


Figure 2.15 Impedance trajectories seen by distance relays at both ends of the faulted line.

To assess system-wide dynamic behavior, rotor angle responses of several synchronous generators in the WECC system are plotted in Figure 2.16. As shown, rotor angles remained largely flat and stable throughout the event window. This implies that the system maintained synchronism and that the AG fault and subsequent relay operations did not provoke significant inter-area oscillations or instability.

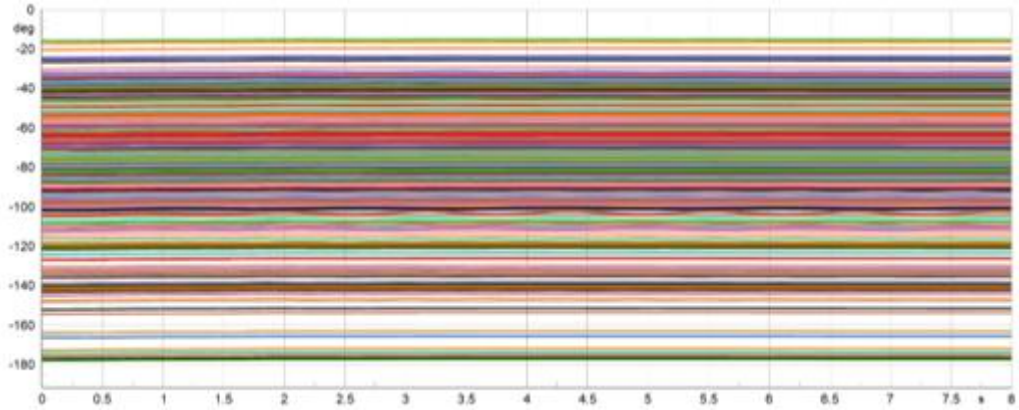


Figure 2.16 Relative rotor angle trajectories of multiple generators in WECC system during AG fault.

It is also important to note that the IBR units located further from the fault showed minimal response deviations. This outcome is consistent with their electrical distance from the disturbance and confirms that the EMT-RMS boundary transformation and simulation topology preserve localization of dynamic effects.

2.7 Scalability Challenge and Investigation into Multi-RMS Region Co-simulation

Despite the accuracy of the co-simulation results demonstrated in various contingency cases, the computational efficiency of running EMT-RMS co-simulation in DIgSILENT PowerFactory for large systems like the WECC is notably low. For instance, simulating 10 seconds of system behavior in the current setup takes approximately 17-18 hours to complete. This issue arises due

to DIgSILENT assigning each co-simulation region to a single processor, limiting the exploitation of parallel computation.

To address this bottleneck, several strategies were explored. One approach involved dividing the monolithic RMS region into multiple RMS subregions, thereby allowing DIgSILENT to utilize more processors concurrently. Three distinct configurations were developed by manually partitioning the RMS region into 37, 21, and 6 separate RMS regions. Figure 2.17 shows the case with six RMS subregions over the WECC network. It is important to note that this partitioning was done manually, as the built-in network partitioning algorithm (butPartition) failed to select technically appropriate locations for region boundaries.

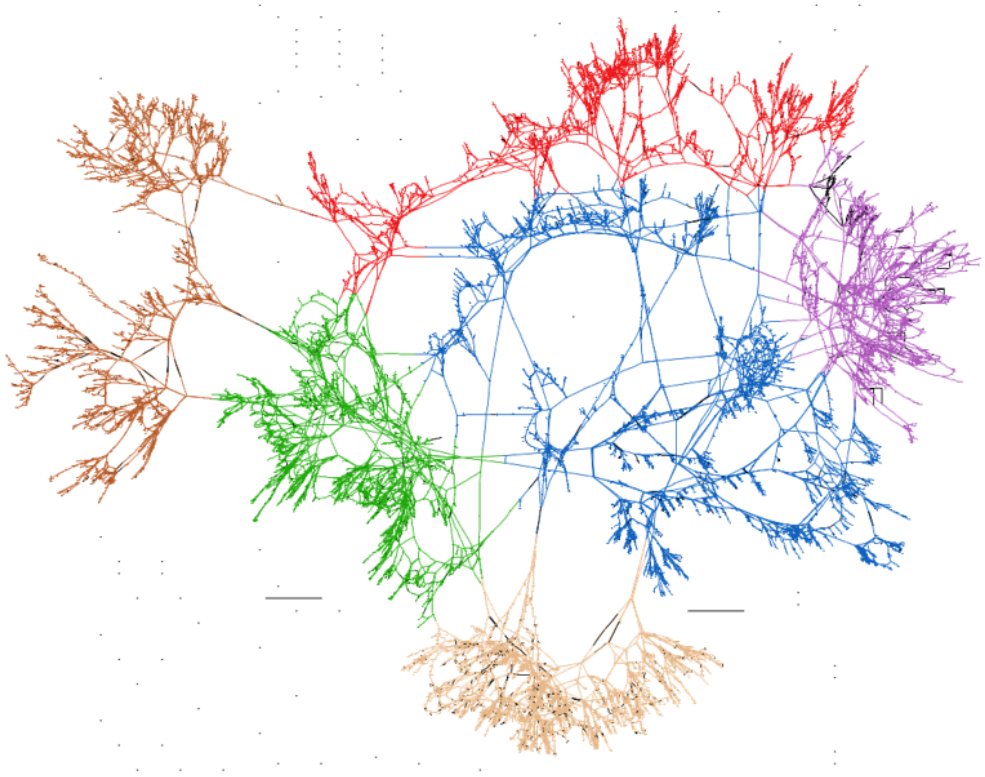


Figure 2.17 WECC network is divided into 6 RMS regions. Each region is shown in a distinct color. Boundaries include multiple transmission lines.

Initially, we employed the Current/Voltage Source interface for co-simulation. However, an unexpected phenomenon was observed; when the co-simulation began, the relative rotor angles of generators exhibited oscillations with frequency of 60 Hz, as depicted in Figure 2.18. This behavior was consistent across cases with multiple RMS regions. The issue was reported to DIgSILENT support, and after reproducing it using the Texas Grid model, they confirmed the anomaly but were unable to identify its root cause. They suggested using the Multiport Thevenin option instead, which suppressed these oscillations.

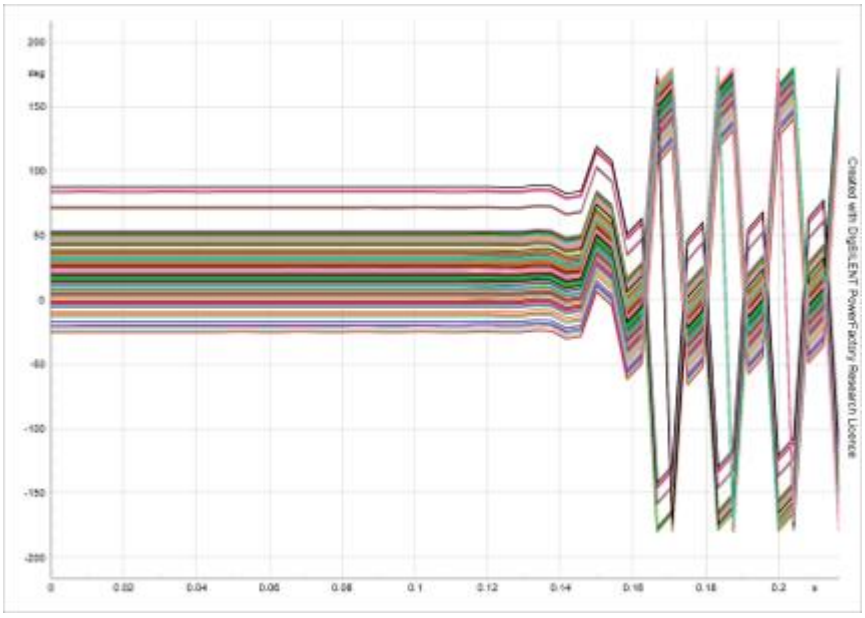


Figure 2.18 Rotor angle oscillations at 60 Hz following the start of co-simulation with multiple RMS regions.

The Multiport Thevenin method comes with a critical limitation which is supporting of only one EMT region. In an attempt to adapt, all IBRs were aggregated into one EMT region. However, this led to serious issues during the network reduction process at initialization. Consequently, a simplified approach was adopted by modeling all but one IBR in the phasor domain, retaining only one IBR model in an EMT region.

With this workaround, the 60 Hz frequency oscillations in rotor angles were eliminated. Nevertheless, another stability issue emerged. Generators in the same RMS region as the power flow reference bus maintained flat rotor angle trajectories during steady-state runs. In contrast, generators in other RMS regions exhibited a gradual decrease in rotor angles over time, even in the absence of disturbances. This discrepancy was shared with DIgSILENT support. Their speculation pointed to reduced inertia in the smaller RMS regions, asserting that the WECC model's components and controls were tuned for a larger, interconnected system. While this may explain some instances, it did not satisfactorily account for our observations.

We hypothesized that reducing the number of RMS regions could mitigate the problem by increasing the inertia within each subregion. Indeed, the fewer the number of RMS regions, the more stable the simulation became. However, the pattern that emerged was that as the number of RMS regions increased, so did the co-simulation speed, but also the rate of rotor angle drift. We concluded that small timing mismatches during boundary data exchange in multi-region RMS setups likely accumulate over time, leading to artificial instability.

Furthermore, it became clear that the structure of the WECC system makes it impractical to identify clear-cut locations for region boundaries. As depicted in Figure 2.17, each boundary spans numerous transmission lines, complicating data exchange.

Additionally, changing the location of the power flow reference bus had a direct impact of placing the reference bus in a different RMS region caused its local generators to exhibit flat rotor angles, while those in other regions continued to drift. This further emphasizes the non-trivial effect of region partitioning.

In conclusion, the effort to improve co-simulation speed by increasing processor usage through RMS region division proved ineffective due to stability issues. These results highlight the challenge of balancing computational efficiency with numerical accuracy in large-scale co-simulation environments like DIgSILENT.

2.8 Reduced Co-Simulation Strategy for Faster Dynamic Analysis

While the EMT regions are efficiently handled by their respective processors, the large-scale RMS region, representing the majority of the WECC footprint, creates a computational bottleneck. As a result, simulating just 10 seconds of dynamic behavior in this configuration requires approximately 18 hours.

To address this performance constraint, an alternative modeling approach was developed that significantly improves computational efficiency without compromising the accuracy of the results. This new method is over seven times faster and achieves comparable outcomes to the full WECC co-simulation case. The core idea behind this method is the strategic reduction of the RMS region by excluding parts of the WECC system not close to the EMT regions. However, simply removing these regions risks neglecting their dynamic influence on the system.

To preserve the impact of the excluded areas, a two-stage simulation strategy was implemented. First, a single-domain unbalanced RMS simulation of the full WECC system was conducted to capture the dynamic behavior of the entire network. Figure 2.19 illustrates the full WECC system modeled in DIgSILENT. In this figure, the black portion represents the majority of the WECC network that is deactivated in the next step, while the purple portion shows the area that remains active for the reduced RMS region in the second simulation step.

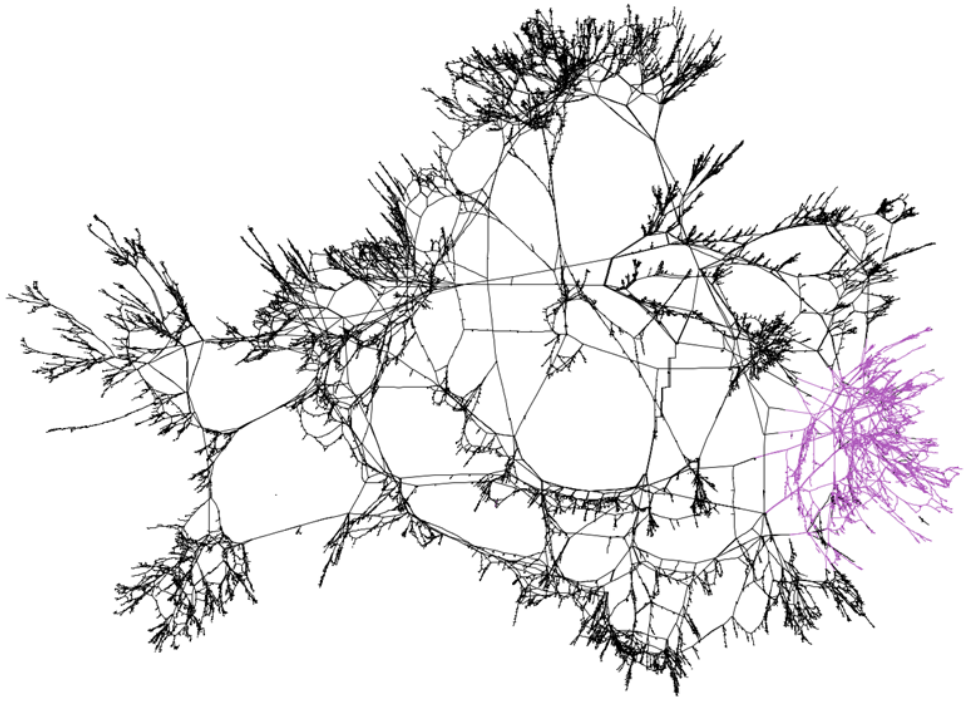


Figure 2.19 Full WECC system modeled in DIgSILENT PowerFactory for the single-domain unbalanced RMS simulation. The black part indicates the portion deactivated in the next step; the purple part remains active in the reduced co-simulation.

Next, a reduced co-simulation case was run, where the EMT regions remained unchanged, but the RMS region was limited to include all the grid under study and most parts of the three other grids near the network under study, along with smaller portions of five additional grids. Figure 2.20 displays the whole network used in this reduced co-simulation. The grid under study is black and the other eight networks are in different colors for clarity. The locations of the EMT regions are also indicated.

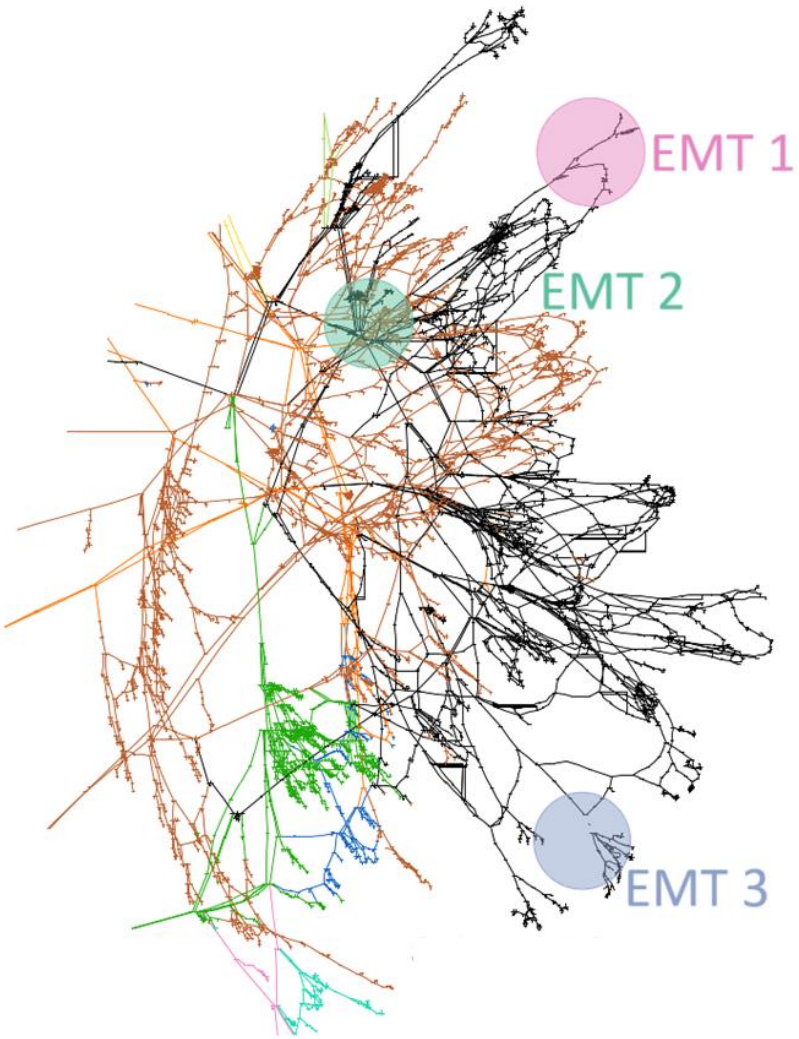


Figure 2.20 Reduced co-simulation network configuration.

In this reduced co-simulation, voltage and current sources were placed at the boundary between the deactivated (black) and active (purple) parts of the WECC. These boundary elements were programmed to read time-series data recorded from the full-system RMS simulation (Step 1) and inject corresponding voltage and current magnitudes during the co-simulation (Step 2). This method ensures that the dynamic behavior of the deactivated regions is effectively included in the reduced co-simulation study. This technique maintains dynamic consistency with the full WECC co-simulation while significantly reducing the computational burden.

Table 2.1 compares the number of busbars in the RMS and EMT regions between the full and reduced co-simulation cases. As shown, the number of RMS buses is significantly reduced in the second approach, enabling faster simulation execution, as the smaller RMS region can be handled more efficiently by a single processor core.

Table 2.1 Comparison of number of busbars in EMT and RMS regions for full and reduced co-simulation cases.

Case	EMT I	EMT II	EMT III	RMS
WECC Co-simulation	10	36	16	26574
Reduced Co-simulation	10	36	16	3836

Figure 2.21 provides a summary of the two-stage simulation strategy in the form of a flowchart. It illustrates the process flow from the initial full RMS simulation to the reduced co-simulation with boundary injection. The figure also includes execution time for each step. The 10-second fault-free scenario takes approximately 15 minutes for the full RMS simulation and about 135 minutes for the reduced co-simulation step, resulting in a total of 2.5 hours compared to 18 hours using the full WECC co-simulation alone. With this new approach, each 10-second dynamic simulation can now be completed in approximately 2.5 hours, more than seven times faster than the original method.

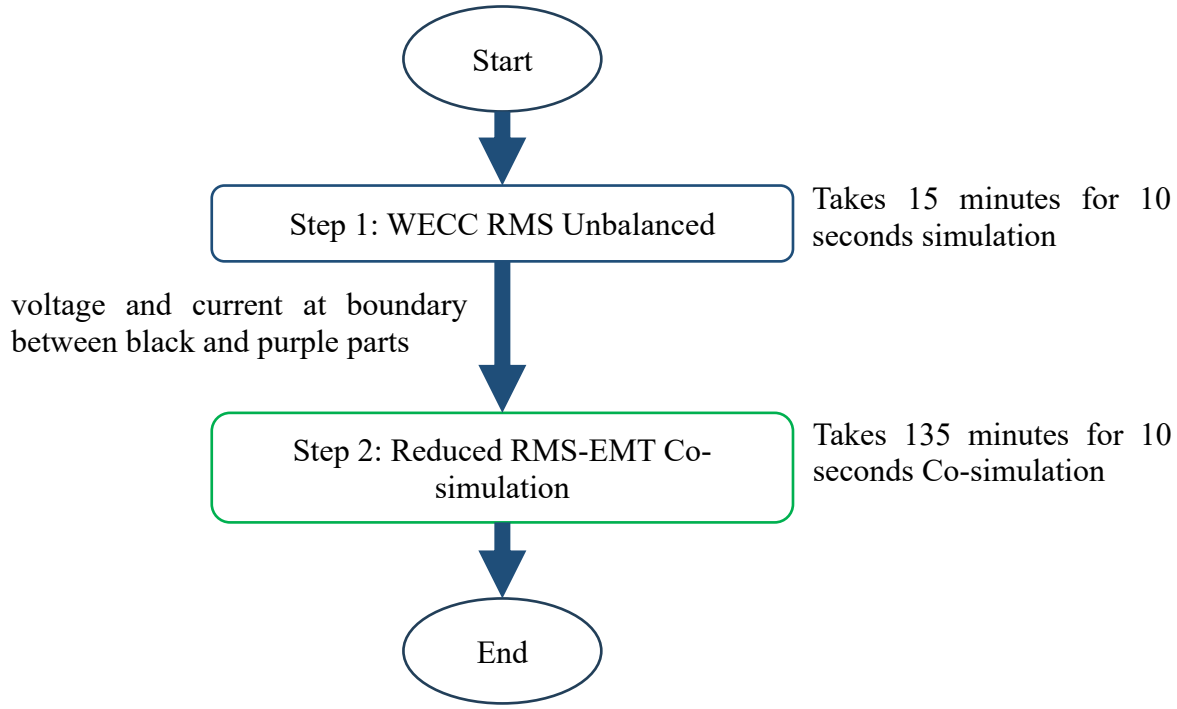


Figure 2.21 Two-stage simulation strategy flowchart.

With this new approach, each 10-second dynamic simulation can now be completed in approximately 2.5 hours, more than seven times faster than the original method. The results between the two approaches are identical, with the only notable difference being the relative rotor angle values due to a change in the reference machine. In the full WECC co-simulation, the reference machine was located in an area that is deactivated in the reduced case. Consequently, the reference machine was moved to the under study area, altering the numerical values of the rotor angles. However, the overall dynamic behavior remains consistent across both cases.

To demonstrate the effectiveness of the proposed two-step reduced co-simulation approach, a representative scenario involving a phase-to-phase (AB) fault was analyzed. This contingency was designed near the EMT regions that include both IBR Plant 1 and IBR Plant 2. The fault was introduced at 1.5 seconds, 40\% along the transmission line, with a fault resistance of 0.1 ohm. In both the reduced co-simulation and the original WECC co-simulation, the protection system operated correctly, and the fault was cleared at 1.571 seconds. The response of IBRs in the Saint and Storey EMT region in the reduced co-simulation matched the behavior observed in the full WECC co-simulation case. Figures 2.22 and 2.23 show the performance of Saint and Storey respectively during this contingency across both simulation approaches. Additionally, while the impact of the fault on IBR plant 3 and 4 regions was minor, their dynamic responses were also consistent with the full co-simulation results.

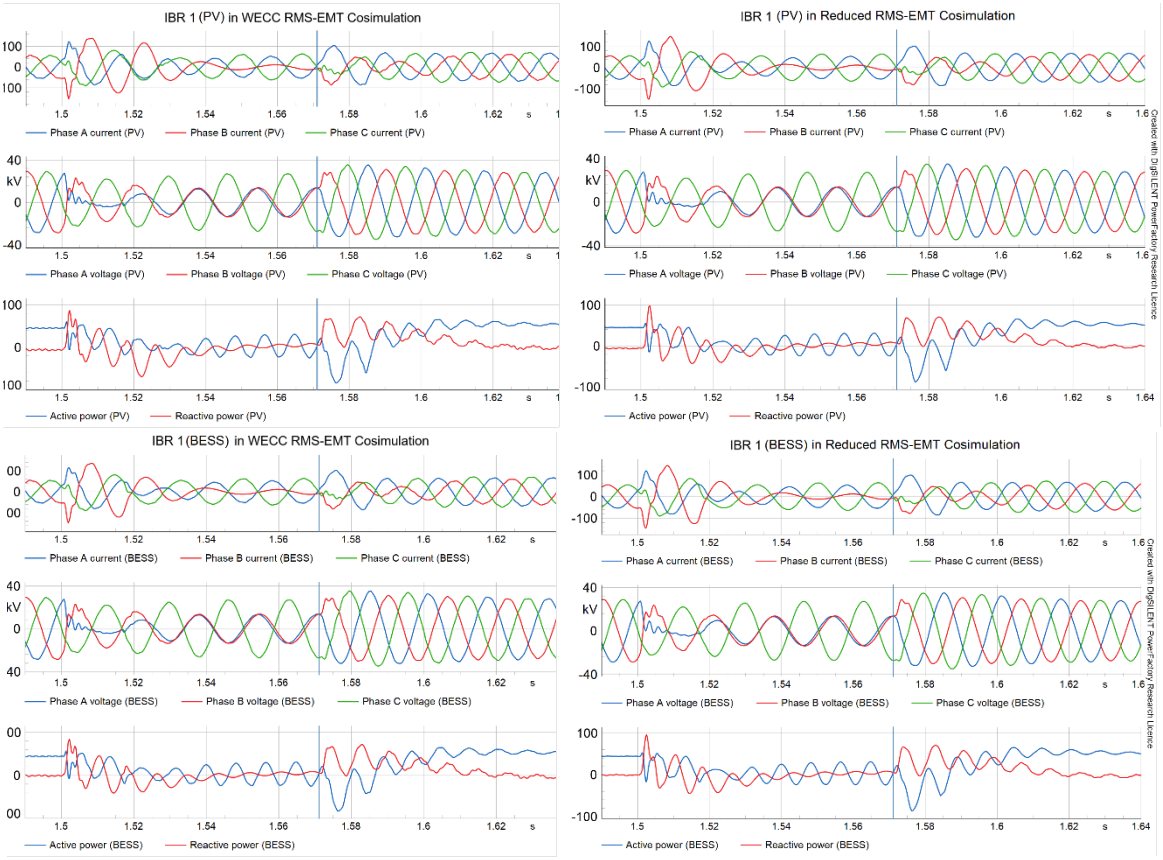


Figure 2.22: comparison of three-phase voltages and currents, active and reactive power output of IBR plant 1 in the reduced co-simulation and full WECC co-simulation.

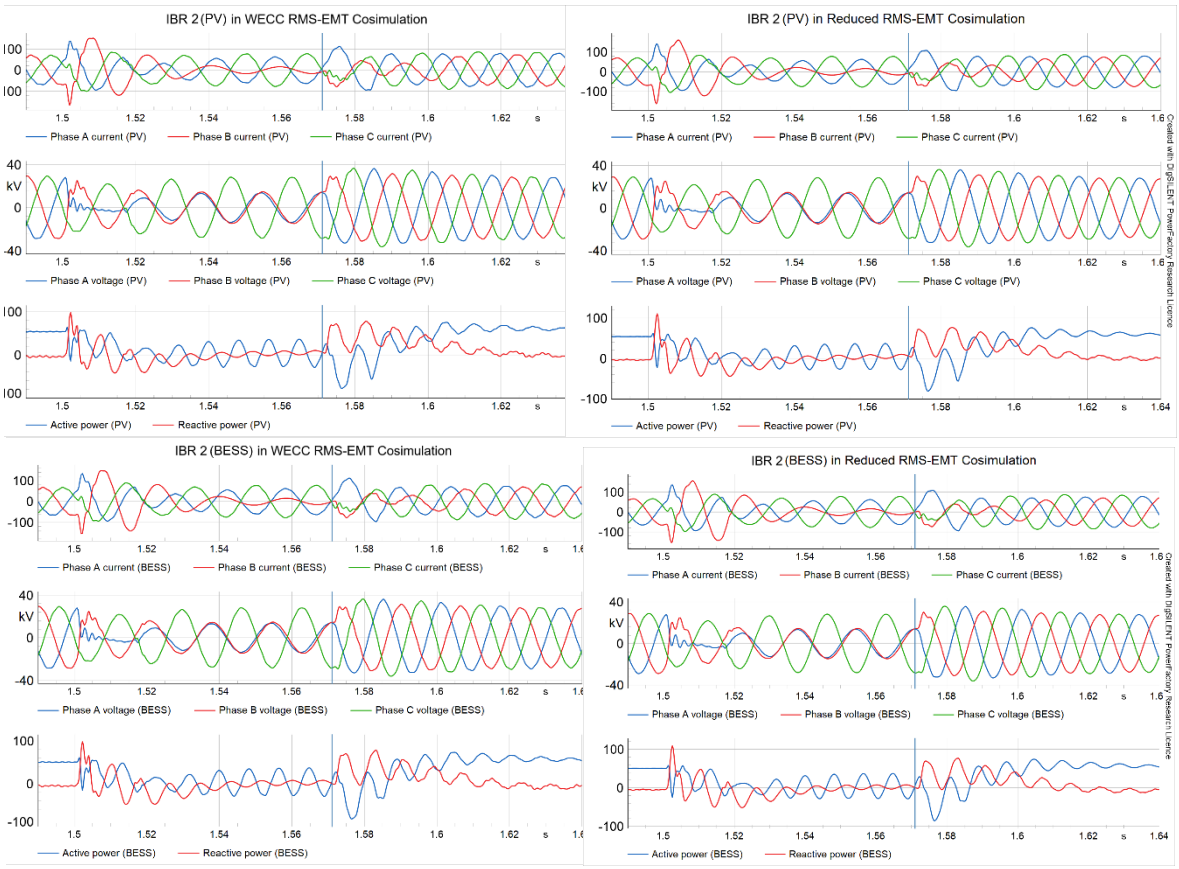


Figure 2.23: comparison of three-phase voltage and currents, active and reactive power output of IBR plant 2 in the reduced co-simulation and full WECC co-simulation.

As previously mentioned, the only observable difference lies in the rotor angle values due to the change in reference machine. Figure 2.24 compares the rotor angle profiles of generators in the SRP network for the reduced co-simulation and the full WECC co-simulation during this contingency, demonstrating that the overall dynamic behavior remains aligned.

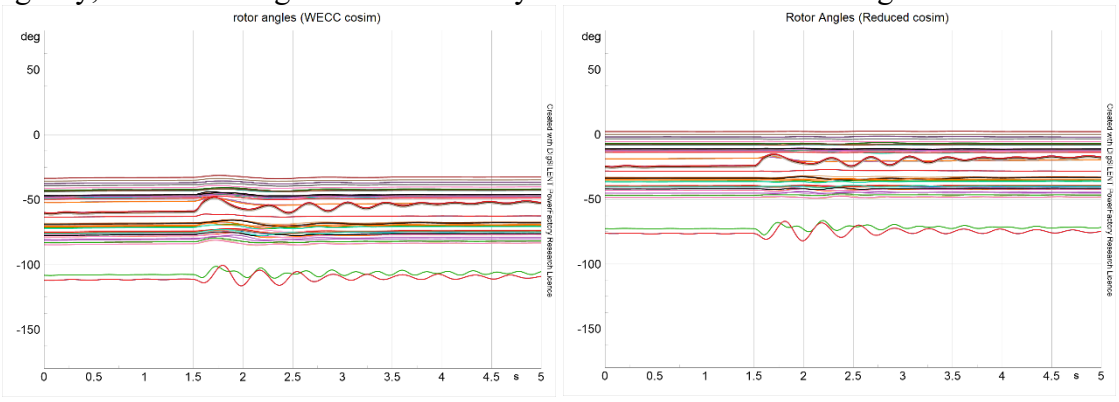


Figure 2.24: Relative rotor angle profiles comparison.

Figure 2.25 presents the impedance trajectories of the relays on each side of the faulted line. As mentioned before, the behavior of the protection system in both cases is identical, so here figure

2.25 is from the WECC co-simulation case. As shown, the impedance trajectories for both relays entered the first protection zone. This indicates that they correctly detected the fault and sent trip signals to their local circuit breakers.

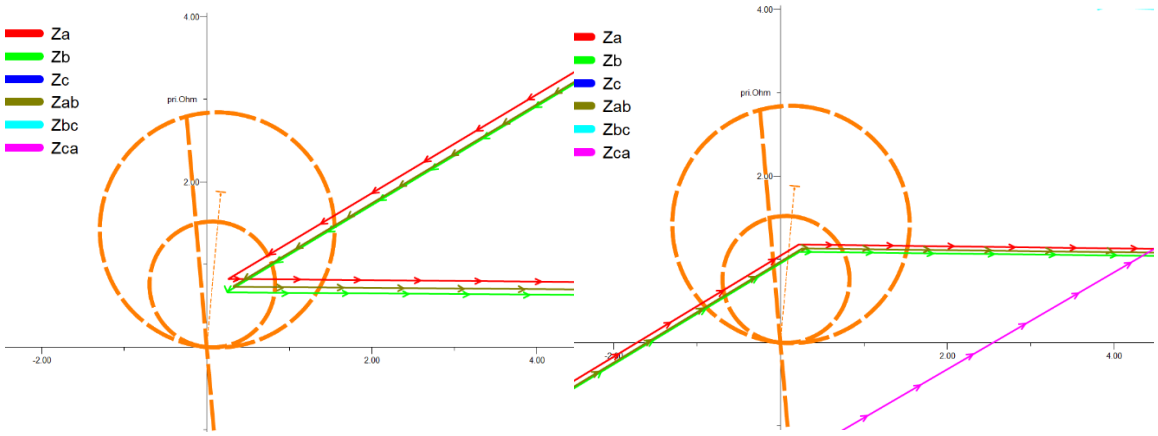


Figure 2.25: Impedance trajectories of distance relays on each side of faulted transmission line.

Figures 2.26, and 2.27 show the responses of IBR Plant 3 (PV and BESS) and IBR Plant 4 (BESS) respectively, which are located farther from the fault. Their behavior under this disturbance was also minor and consistent with expectations, showing minimal deviation. Since the reduced simulation yielded the same dynamic behavior for these distant IBRs, their plots from the reduced co-simulation are omitted for brevity.

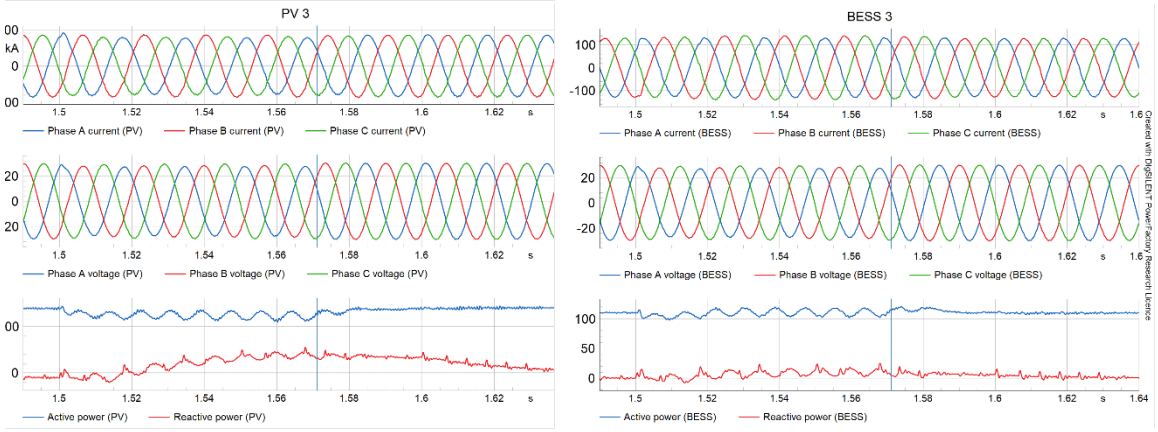


Figure 2.26: IBR 3 response in RMS-EMT co-simulation.

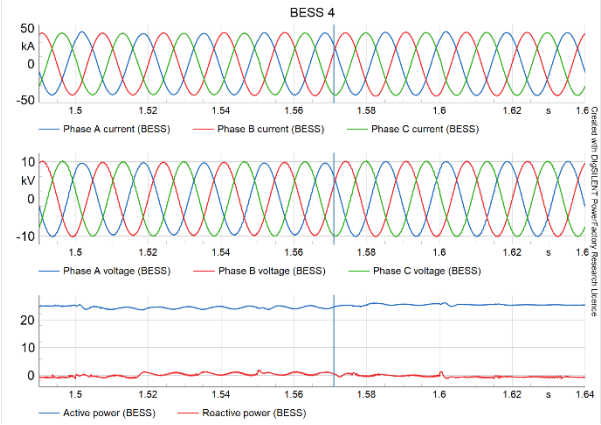


Figure 2.27: IBR 4 response in RMS-EMT co-simulation.

2.9 Conclusion

This chapter presented the development and evaluation of multiple co-simulation scenarios to study the dynamic performance of the WECC system with EMT-modeled inverter-based resources. Different fault types and locations were examined, with particular attention to the interaction between EMT and RMS regions. The studies confirmed that the co-simulation setup can accurately capture both local and system-wide dynamic responses, including the performance of protection systems, rotor angle stability, and the behavior of IBR models under various contingencies. The results also highlighted the effects of data transformation across EMT-RMS boundaries and demonstrated how co-simulation configuration can influence the speed of the analysis. These findings provide a solid basis for refining co-simulation strategies and improving computational efficiency in future large-scale dynamic studies. A reduced-network, two-stage workflow (full-system RMS for operating point and screening, followed by focused RMS–EMT around IBR regions) yields substantial speedups with minimal loss of fidelity in variables of interest (IBR terminals, relay operation, and rotor angles).

Next chapter leverages a co-simulation environment to generate disturbance datasets and trains machine-learning models for fast, protection-aware DSA, enabling real-time decision support while preserving the key behaviors identified here.

3. Online ML-Based Dynamic Security Assessment

3.1 Introduction

This chapter presents an online machine learning-based DSA framework designed to predict the operation of protective distance relays using high-fidelity co-simulation data. The approach leverages RMS-EMT hybrid simulations of the IEEE 39-bus system, augmented with IBRs, to generate a comprehensive dataset under diverse fault scenarios. Using impedance trajectories derived from PMU locations, individual relay models are trained using both CNN and RF classifiers. The chapter details the data preprocessing techniques, model architecture, training pipeline, and evaluation metrics. Furthermore, it demonstrates the real-time prediction capabilities of the proposed models through case studies, confirming their potential for enhancing operational awareness and supporting remedial action schemes in modern power systems.

3.2 Proposed Machine Learning-Based Dynamic Security Assessment Framework

The proposed machine learning-based DSA framework aims to predict the operation of distance relays following disturbances by leveraging the correlation between impedance trajectories and subsequent relay actions. Fig. 3.1 illustrates the conceptual workflow of the approach.

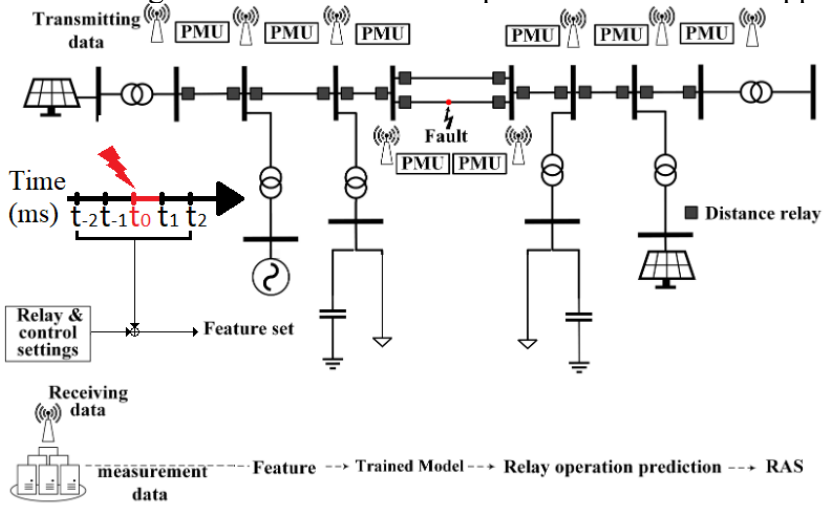


Figure 3.1 Overview of the proposed ML-based DSA framework using PMU data around fault time for real-time relay operation prediction and remedial action schemes.

The process begins with the creation of a comprehensive and diverse dataset through offline time-domain simulations conducted in DIgSILENT PowerFactory. This platform supports EMT-RMS hybrid co-simulation and includes manufacturer-validated relay models, making it particularly well-suited for generating realistic training data. A large number of contingency scenarios are simulated, including both N-1 and N-2 events, with random fault types occurring at various locations along the transmission lines to ensure coverage of a wide range of operating conditions. During each simulation, it is assumed that PMUs are installed at every distance relay location. These PMUs transmit relevant signal data to the control center in real time. The signal data can be used to calculate the impedance values. Around each disturbance event, a time window of 5 milliseconds, comprising two steps before and two steps after the fault occurrence, is extracted

from the PMU signal stream. This window represents the data used for model training. It is important to note that the 5 ms window is not fixed and can be adjusted based on the PMU sampling rate and application requirements.

Using this data, each distance relay is labeled based on whether it issues a trip signal within 10 seconds following the fault. A label of 1 indicates operation; otherwise, the label is 0. These labeled samples are used to train two different machine learning models for each relay, one using a CNN and the other using an RF classifier. While both models process the same impedance-based time-series input, they offer complementary strengths in learning and generalization.

Once trained, these models can be deployed in real-time settings at the control center. As new PMU data continuously arrives, it is combined with previously received data to form input sequences, which are then passed into the CNN and RF models corresponding to each relay. This streaming-based prediction process allows the timely detection of potential relay operations before they occur.

The predictions from the DSA tools serve as valuable decision-support signals, enabling operators to initiate preventive control actions or remedial action scheme (RAS) selection to reduce the risk of cascading outages and maintain system stability. Using both CNN and RF models improves robustness and redundancy in prediction, thereby increasing operator confidence in actionable outcomes.

This framework assumes that PMU data is available and sampled synchronously at each distance relay location. However, because the architecture includes one CNN and one RF model per relay, predictions can still be performed independently for relays where PMU data is available, even if some data streams are lost or delayed. This makes the framework more flexible and practical for real-world deployment in complex and evolving power systems.

3.2.1 Data Cleaning, Augmentation, and Normalization

To train the CNN and RF models effectively, impedance data from each relay was extracted within a short window surrounding the fault event. Specifically, a total of 5 milliseconds of data were retained, spanning from 2 steps before to 2 steps after the fault inception, captured at 1 millisecond intervals. This window captures the immediate transient response, which is critical for characterizing the dynamic behavior of relays in response to contingencies.

Synthetic noise was added to the impedance features to better reflect the variability and imperfections found in real-world measurements. This augmentation was performed by injecting zero-mean Gaussian noise into each impedance value based on a randomly chosen signal-to-noise ratio (SNR) ranging from 10 dB to 20 dB. These values were selected to emulate realistic measurement conditions typically observed in PMU recordings. Noise was injected into each individual sample to introduce variability across the augmented dataset and ensure statistical diversity.

In real power system operations, the vast majority of relays do not operate during a given contingency. As a result, the raw dataset is heavily imbalanced, with label 0 (non-operation)

dominating label 1 (operation). This imbalance is particularly problematic for training CNN models, which are sensitive to imbalanced class distributions. To address this, noisy versions of the data samples labeled with one were selectively generated to balance the dataset for each relay. Only the minimum number of additional noisy label-1 samples required to match the number of label-0 samples were created, ensuring statistical parity without overfitting.

Finally, to standardize the input features and ensure stable convergence during model training, all impedance values were normalized using z-score normalization on a per-relay basis. The mean and standard deviation of the 12 impedance features for each relay were computed from the clean dataset. These statistics were then used to normalize both clean and noisy samples by subtracting the mean and dividing by the standard deviation.

3.2.2 Random Forest-Based Relay Operation Prediction

The RF algorithm is an ensemble learning method that constructs multiple decision trees using bootstrap aggregation. Each tree is trained on a randomly sampled subset of the dataset, and during inference, the final prediction is determined by majority voting among all trees [24]. This ensemble structure enhances model robustness and generalization.

In this study, a separate RF classifier is developed for each distance relay based on features derived from local impedance measurements. Each input sample consists of a 5 ms time window that includes five time steps of impedance trajectories. Since there are 12 impedance features per time step, each sample contains a total of 60 input features. The ground truth label is binary and indicates whether the corresponding relay operated within 10 seconds following a disturbance.

Although the RF algorithm has been shown to perform well even in the presence of imbalanced class distributions [25], a balanced dataset was used in this study to maintain consistency with the CNN training setup. This was achieved by augmenting the minority class (relay operation cases) with noise-injected samples, as described in the previous subsection.

The combined dataset for each relay was partitioned into three subsets. 70% of the samples were used for training, 15% for validation, and the remaining 15% for testing. This stratified split ensures adequate model tuning while reserving unseen data for performance evaluation.

The RF approach offers several advantages for dynamic security assessment in power systems. Its structure enables rapid training and fast inference. Furthermore, RF models are inherently parallelizable and can be trained independently for each relay, allowing for localized prediction and flexible deployment even in systems with partial observability.

3.2.3 Convolutional Neural Network-Based Relay Operation Prediction

CNNs are a class of feedforward deep learning architectures that have achieved notable success across various domains, including image classification [26], speech processing, and time-series signal analysis. Their ability to automatically extract localized patterns through convolutional operations makes them effective for learning transient behaviors in power systems.

In this study, a dedicated CNN model is trained for each distance relay using local impedance trajectories measured around the fault occurrence. Each training sample consists of impedance data from a 5 ms time window centered on the fault, where each time step includes 12 impedance features representing phase-to-ground and phase-to-phase measurements. These data are reshaped into a three-dimensional input of shape [1, 5, 12], where the dimensions correspond to the channel, temporal window, and impedance features, respectively.

The CNN architecture comprises two sequential 2D convolutional layers. The first convolutional layer uses 16 filters with a kernel size of 3*12, effectively spanning three consecutive time steps and all impedance features at once. This layer outputs a tensor of shape [16, 3, 1], capturing short-term temporal dynamics and cross-phase interactions. The second convolutional layer employs 32 filters with a kernel size of 3*1, reducing the temporal dimension and producing an output of shape [32, 1, 1]. Batch normalization and the Rectified Linear Unit (ReLU) activation function are applied after each convolution to stabilize and accelerate training.

Following the convolutional layers, the output tensor is flattened into a one-dimensional vector of size 32 and passed through two fully connected (FC) layers. The first FC layer receives an input of size 32 and outputs 64 neurons, enabling higher-level feature abstraction. The second FC layer takes this 64-dimensional vector and maps it to a single output neuron, which uses a sigmoid activation function to produce the final binary classification indicating whether the corresponding relay will operate.

Although pooling layers are commonly used in CNNs to reduce model complexity and achieve translation invariance, they are intentionally omitted in this architecture. Since a separate CNN is trained for each relay, the total number of parameters remains manageable, and preserving fine-grained temporal resolution is more critical than dimensionality reduction. Avoiding pooling operations allows the network to retain subtle variations in fault dynamics that are essential for accurate relay operation prediction.

Each model is trained using binary cross-entropy loss and the Adam optimizer. Training data is split into 80% for training, 10% for validation, and 10% for testing. The use of a dedicated CNN per relay ensures localized decision-making and scalability in large-scale deployments. This structure allows for capturing the detailed dynamics of each relay's impedance trajectory and enables the deployment of CNN-based DSA tools for real-time remedial action selection.

3.2.4 Evaluation Metrics

The performance of the proposed RF and CNN models is evaluated using standard classification metrics, including accuracy, precision, recall, and F1-score, computed on the test datasets of each relay. These metrics provide a balanced assessment of the models' ability to correctly identify relay operations and non-operations under diverse contingency scenarios. In addition to these metrics, prediction time is also considered, as it is critical for real-time DSA applications. The average inference time per relay is measured for both RF and CNN models, demonstrating that both models offer sufficiently low latency for practical online deployment. This ensures their effectiveness as decision-support tools in time-sensitive control environments.

- **Accuracy**

Accuracy quantifies the proportion of correct predictions out of all predictions made by the model.

- **Precision**

Also known as the positive predictive value (PPV), precision is defined as the ratio of correctly predicted positive cases to all cases predicted as positive. A high precision value indicates that the model's predictions of relay operation are consistently accurate, minimizing unnecessary or incorrect control actions.

- **Recall**

Also referred to as the true positive rate (TPR), recall measures the proportion of actual positive cases that are correctly identified. A high recall value ensures that most relay operations are detected, reducing the risk of overlooking critical fault responses.

- **F1-Score**

The F1-score is the harmonic mean of precision and recall. The F1-score is especially relevant in binary classification tasks where both false positives and false negatives have important implications. It balances the trade-off between detecting true relay operations and avoiding incorrect predictions.

These metrics offer complementary perspectives to evaluate both correct and incorrect predictions for relay operation detection, ensuring reliable model performance across all classification scenarios.

3.3 Test System and Performance Evaluation

To generate the dataset for training and evaluating the proposed DSA models, the IEEE 39-bus system was used and modified in DIgSILENT PowerFactory. This system was selected due to its realistic scale and its availability within PowerFactory, which supports RMS-EMT hybrid co-simulation and provides built-in manufacturer-based relay models.

Distance relays based on the SEL 411L model were installed at both ends of every transmission line. Each relay was configured with two mho zones. Zone 1 covered 80% of the protected line length and operated without intentional delay. Zone2 extended the protection reach to 120% of the line length and included a 300 ms intentional delay before issuing a trip command. These generic relay settings are used in this paper without loss of generality. If relay data are available, actual manufacturer-based models with accurate settings could be used in the proposed framework. While PMUs do not directly transmit impedance values, they provide sufficient signals (such as voltage and current phasors) from which all impedance values can be calculated in a suitable format for use as DSA model features. However, for simplicity, this paper directly uses the relay-measured impedance values as features.

Each distance relay provides 12 impedance-related features that serve as input to the DSA models. These features consist of the real and imaginary parts of six impedance measurement units. Three of these units measure the phase-to-ground impedance for phases A, B, and C, while the other three measure the phase-to-phase impedance between phases AB, BC, and CA. These impedance measurements reflect the local electrical response observed at each relay around the time of fault occurrence and are used as the primary input features for training the machine learning models.

The system was further modified to incorporate IBRs. Two synchronous generators, G6 and G9, connected to Bus 35 and Bus 38, respectively, were replaced with DIgSILENT's built-in PV models. These two PV units were placed in separate EMT regions, while the rest of the network remained in a single unbalanced RMS region, as shown in Fig. 3.2. Additionally, the nominal frequency of all elements in the system was set to 60 Hz. The zero-sequence impedance of transmission lines was set to be three times the positive-sequence impedance, while for transformers, the zero- and positive-sequence impedances were set to be equal.

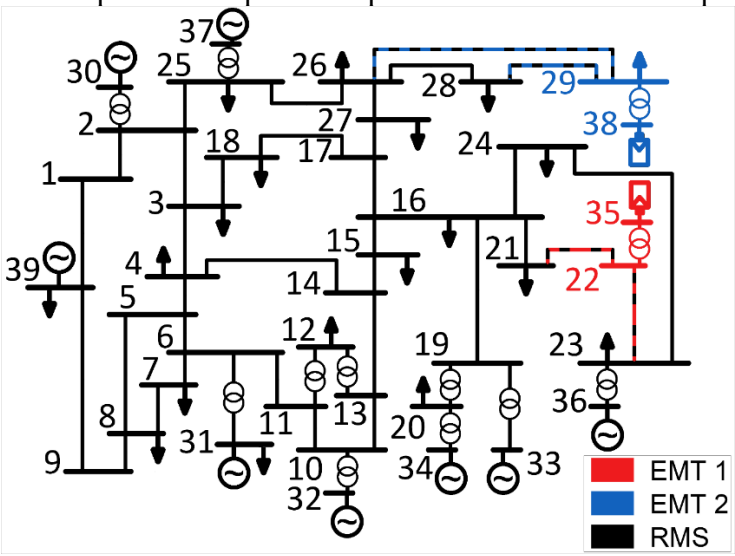


Figure 3.2 Modified IEEE 39-bus system with two PV models in EMT regions (red and blue) and the remaining network in a single RMS region (black).

A total of 1,057 N-1 and N-2 contingency scenarios were simulated, where the majority of the cases involved N-2 events. Faults were modeled to occur randomly on various transmission lines, with randomized parameters including fault type (single-line-to-ground, line-to-line, double-line-to-ground, or three-phase), fault resistance (uniformly distributed from 0 ohm to 20 ohms), faulted phases, and fault inception time. Each RMS-EMT co-simulation was executed for a duration of 10 seconds following the fault occurrence, and for every case, PMU-based phasor data, impedance trajectories, and relay operation statuses were recorded.

The trained models included one CNN and one RF classifier per distance relay. Table 3.1 summarizes the average performance metrics across all relays. Both models demonstrated strong predictive performance, with the RF model achieving higher accuracy, precision, recall, and F1-score on average. While CNN models did not outperform RF models in these metrics, they still exhibited highly competitive results.

Table 3.1 Performance Metrics of CNN and RF Models Averaged Across All Relays.

Model	CNN	RF
Accuracy	0.928	0.986
Recall	0.946	0.987

Precision	0.915	0.985
F1 Score	0.929	0.986
Prediction time (ms)	5.72	6.18

CNNs are generally well-suited for time-series learning tasks, as they can capture local temporal patterns in input sequences. However, RF models are not inherently designed for sequential data. In this study, the RF models were provided with a well-aligned time window of impedance features around the fault onset. This assumes the availability of a perfect fault detection mechanism, which may not be guaranteed in real-world scenarios. Therefore, while RF models offer high performance under idealized conditions, CNN models provide greater robustness in practical applications where the timing of data windows may be uncertain.

It is also worth noting that both CNN and RF models demonstrated fast inference times, supporting their deployment in real-time DSA systems. Their ability to produce timely predictions makes them well-suited for integration with the RAS selection. Furthermore, both models showed robustness to noisy phasor measurements, which is critical for practical deployment in PMU-based monitoring environments.

To illustrate the operation of the proposed ML-based DSA framework, a representative N-2 contingency scenario is considered. As shown in Fig. 3.3, the first fault occurs between buses 26 and 29 at 1.032 seconds. The distance relays protecting this line correctly detect the fault, and the line is disconnected at 1.403 seconds. The second fault then occurs between buses 26 and 28 at 1.886 seconds, and the line is disconnected at 1.969 seconds due to relay operation. In addition, the relays protecting the adjacent line between buses 28 and 29 also initiate the trip signals. The local circuit breaker of R1 opens at 2.36 seconds, followed by the local circuit breaker of R2 at 2.441 seconds.

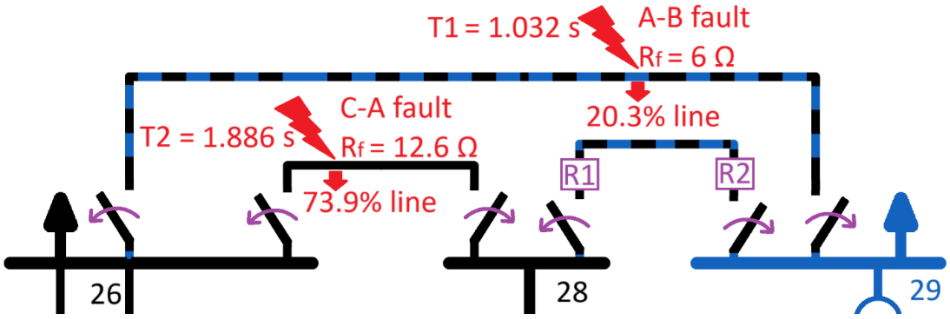


Figure 3.3 Locations of the two fault events and the three disconnected transmission lines during the analyzed N-2 contingency scenario.

For all relays, local impedance measurements around the time (5 milliseconds window) of each fault were extracted and used as input to the DSA models. Both CNN and RF classifiers accurately predicted the operation of tripped relays and those that did not within a few milliseconds. Specifically, the RF models of R1 and R2 predicted 100% probability of operation within the next 10 seconds, while the CNN model of R1 predicted its operation within the next 10 seconds with a probability of 98.5% and the CNN model of R2 predicted its operation within the next 10 seconds

with a probability of 99.4%. This confirms the effectiveness and reliability of the proposed machine learning-based DSA approach in handling complex contingency scenarios.

3.4 Conclusion

This chapter presented a machine learning-based DSA framework that integrates realistic modeling of protective distance relays within a hybrid RMS-EMT co-simulation environment. The IEEE 39-bus system was used as the testbed, and two synchronous generators were replaced with IBR models in the EMT domain, allowing the study to capture the complex interactions between protection systems and evolving grid conditions.

Distance relays were modeled at both ends of every transmission line, each equipped with two mho zones. A total of 1,057 contingency scenarios, including both N-1 and N-2 events with various types and parameters of fault, were simulated to generate a comprehensive dataset. PMUs were assumed to be installed at all relay locations, and local impedance trajectories were used as input features for model training. The dataset was carefully augmented, balanced, and normalized to ensure robustness and generalizability of the proposed approach.

Two types of classifiers, RF and CNNs, were trained independently for each relay. RF models exhibited superior performance in terms of classification metrics, including accuracy, precision, recall, and F1-score. However, CNNs demonstrated competitive results and offer better adaptability in real-time deployments due to their inherent ability to learn temporal features and tolerate variability in data alignment. Both models achieved low inference latency and were robust to measurement noise, confirming their suitability for real-time DSA.

To further validate the framework, a representative N-2 contingency involving sequential line-to-line faults was examined. The CNN and RF models accurately predicted the operation status of all affected relays within milliseconds, confirming the effectiveness and responsiveness of the proposed approach under complex fault scenarios. Future work includes testing this framework for WECC system model.

4. Conclusions

This report presented a comprehensive framework for DSA of power systems integrating IBRs, based on a hybrid RMS-EMT co-simulation environment. The first part of the study focused on building a high-fidelity co-simulation testbed for the WECC system using DIgSILENT PowerFactory. The developed testbed incorporated realistic protection system modeling, including manufacturer-based distance relays, and enabled detailed EMT-RMS hybrid simulation with multiple IBRs represented in the EMT domain. Strategies to accelerate co-simulation runtime while preserving dynamic equivalence were also introduced, including the two-stage simulation approach that netted boundary injections from a prior full-domain Unbalanced RMS simulation.
In the second part, a machine learning-based DSA framework was developed to predict relay operations following fault disturbances using impedance trajectories derived from PMU locations. The proposed approach employed both RF and CNN classifiers trained on co-simulation data generated from a modified IEEE 39-bus system. The models demonstrated high accuracy and fast inference times, confirming their suitability for real-time deployment. A representative N-2 contingency case was analyzed to validate the effectiveness of the trained models in predicting relay responses under complex fault sequences.

Together, the co-simulation platform and AI-based DSA tools establish a practical path toward integrating protection system behavior into dynamic security assessments, enabling more accurate and timely response to system disturbances.

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1. Introduction and Objectives

1.1 Introduction

We investigated, designed and developed effective approaches to include protection and control (P&C) systems in dynamic security assessment (DSA) methods of modern power systems with high penetration of IBRs. This work provides the tools to realistically assess the response of the system to faults, capturing the performance of P&C systems as well as the interactions between the power system legacy components and IBRs. NERC annual reports and post analysis of disturbances consistently rank P&C systems as the number one contributor to major system disturbances [1]. Recent major system disturbances (blackouts) have been traced to the interaction between legacy power systems and P&C systems with IBRs; specifically, routine transients in legacy power systems that normally will not cause any issues or concerns resulted in dropout of substantial PV generation in several events around the world [5]. These observations emphasize the importance of modeling P&C systems in DSA.

The impact of P&C performance on power system reliability has been demonstrated in the 1980's [6] using simple P&C models to define independent and common mode contingencies. These simple P&C models demonstrated that the effects on reliability were substantial using static security assessment.

The deployment of IBRs escalated the criticality of the inclusion of P&C systems in DSA. IBRs are transforming the power system towards lower levels of inertia, reduced short circuit current levels, and different characteristics of fault currents, specifically reduced negative and zero sequence fault current components. Synchronous machines can provide high inductive short-circuit currents during a fault. P&C systems have been traditionally designed to identify faults and their location based on the behavior of legacy power systems, namely, high fault currents to detect incipient faults, negative sequence components to detect direction of faults, and others. These issues emphasize the necessity of accurate evaluation of the impact of P&C systems on DSA for IBR dominated power systems. Moreover, the classical root-mean square (RMS) stability analysis may not be sufficient to capture all relevant stability issues in power systems with high penetration of IBRs. More detailed electromagnetic transient (EMT) simulation may be necessary. This project proposes a co-model of power system, IBRs, and protection and control system and co-simulation of both RMS and EMT fault analyses to enable evaluation of IBR-dominated power and P&C system response to disturbances.

Dynamic response of power systems during extreme events highly depends on P&C system performance. Adversely, modern power systems are more prone to N-k events due to the threat of cyber-attacks [7], P&C system failures and weather-related events, e.g., intermittency of renewable output and severe weather conditions. Multiple types of cyber-attacks, e.g., alteration of relay settings (sleeper attacks), insertion of malicious relay controls, GPS spoofing, and others can endanger reliability of P&C systems and threaten system security. Analysis of protection system operations/mis-operations are critical to identify extent of outages during an event and to guide development of preventive and corrective measures. This project focused on comprehensive dynamic security assessment of the integrated system (power and P&C) with high penetration levels of IBRs. A critical contribution of this work is the design and development of a *three-phase,*

physically based breaker-oriented, P&C inclusive co-model with ability to automatically generate the positive sequence co-model (which is usually employed in DSA studies) to assess system security and resiliency accurately and effectively. The first co-model (three-phase, high fidelity) has been used for analysis of system response during fault conditions, while the extracted co-model (positive sequence equivalent) has been used for analysis of post-fault conditions.

1.2 Objectives

The objective of this work is to analyze the performance of P&C systems in response to faults or equipment failures during faults and post fault transient period via the co-model of the three-phase physically-based breaker-oriented power system and the P&C system. This co-model is able to capture protection response to asymmetrical faults and the interactions with the controls of IBRs and identifies the extent of the disturbance, i.e., does it lead to an independent outage event? Or does it lead to a common mode multi-outage event? Or it will lead to follow up outages? Cascading outages? An important requirement for this analysis is modeling of both grid-forming and grid-following IBRs. We relied on our prior work that resulted in high fidelity inverter models [8]. Conventional approaches of relying on positive sequence analysis using bus-oriented models are deemed inadequate for dynamic security assessment while modeling protection schemes especially for single phase faults and for systems with high penetration level of IBRs. The proposed analysis of extent of disturbances has been partitioned into two parts. The first part considers the response of the system during the fault conditions, immediate relay responses and a short period of time after all faults have been cleared. This analysis is performed using the three-phase physically based breaker-oriented, P&C inclusive co-model. This type of analysis captures the immediate response of the P&C system for any type of disturbance, including asymmetrical faults, and it is relatively short. The longer dynamics of the system are examined with the second part of the analysis. During this period, the system is unfaulted and analysis is performed using the second co-model (positive sequence equivalent, P&C inclusive). For this simulation period, methods for fast DSA of the post fault period have been explored. We concluded that the use of energy function methods for this analysis, assisted with the results obtained from the detailed simulation during the fault and a short period after faults have been cleared is the best and most efficient approach.

After faults have been cleared, the system is in a disturbed state and the dynamics of the system may take a longer period to settle or to cause follow up events, such as tripping an unstable generator. This part of the analysis identifies the effects of the long-term dynamics on the stability of the system. First, the team explored using RMS-EMT co-simulation with protection and IBR representations. Available commercial software do not address the issue of converting between EMTP type modeling and simulation and RMS-based modeling and simulation. Software are segregated from the modeling point of view. The accuracy of the co-simulation and whether commercially available software can model a modern power system dominated with IBRs is still an open question.

The issue of computational efficiency has been addressed. As mentioned earlier, an energy-based method has been used for the long term dynamics. Specifically, for the long term dynamics, after all relay actions have been completed, we extract automatically the bus-oriented, P&C inclusive co-model for continuation of the long term simulation. To summarize, initially a co-simulation using a high fidelity three phase model is used during the faulty conditions up to the point when

all immediate relay actions are taken. Then we switch to the dynamic phasor model to continue the long term simulation. It should be noted that during the initial simulation, the manifold of the center of oscillations (CoO) has been identified via state estimation. The points on the CoO manifold are identified as points where the frequency is stationary or varies linearly with time [9]. The identification of the center of oscillation manifold allows the computation of the potential energy of each generator in the system as well as the potential energy barrier for each generator. Addition of the kinetic energy of each generator provides the total energy for each generator which is then compared to the barrier. This comparison determines whether a generator is stable or unstable. The unstable generator will be tripped and the system will be simulated in time domain to determine any follow–up events. The method is described in Chapter 4.

Modeling of P&C system failures: One critical component of the method is the failures of the protection and control system. In general, it is difficult to establish a probabilistic model for the reliability of the protection and control system. Yet, failures of the protection and control system have a dramatic effect on the final outcome of a disturbance. In this project, we model the failures of the P&C system probabilistically using historical data. Probabilistic models of breaker failure, hidden failures [10] and cyber-attacks [7] have been postulated. These models have been integrated into the simulation process. The overall methodology is easily implementable in a Monte Carlo type of approach. While the co-simulation has been developed as described above, the Monte Carlo simulation using these models has not been completed.

Power system resiliency assessment: The issue of power system resiliency has been addressed within the co-simulation of the high fidelity co-model by utilizing improved protection and control systems that minimize relay mis-operations and identify hidden failures and other causes of disturbances. The technology exists today to identify the causes of disturbances and correct in real time. This is an area which needs more attention. As a follow up we will continue our work to develop such methods.

2. Design and Development of an Integrated co-model

The integrated co-model will consist of (a) a breaker-oriented, physically based three-phase electric power system model, including IBRs, (b) the P&C system with links to the physical power system, and (c) automated procedures to extract the positive sequence and EMT co-model from (a) and (b). The co-model is symbolically shown in Fig. 1 comprising the power components, the relays, merging units and the interconnection between the power components and the protection devices. The co-model will enable the co-simulation of the power and P&C systems during a fault event to determine the response of the system, i.e., whether the fault will be properly cleared and there will be no follow-up events or whether there will be follow-up events, such as a common mode outage and cascading outages. It is important to note that it is possible that the response of the P&C system caused all of the above-mentioned follow-up events, even if the P&C system would have performed as designed, i.e., no failures within the P&C system. There is a certain probability that failures within the P&C can occur, such as breaker failure, hidden failures in instrumentation and devices as well as P&C changes due to cyber-attacks. We propose to use a probabilistic model of breaker failure, hidden failures and/or cyber-attacks of the P&C system. The probabilistic models will enable the co-simulation to capture the consequences of failures in the P&C system. We also propose the development of an automated procedure to convert part of the power system co-model into a positive sequence (per-phase equivalent) bus-oriented model. This co-model will enable faster simulation of the system when all faults have been cleared and will facilitate efficient application of other analysis methods such as the energy function method and time domain simulation of the un-faulted system (task 3). For demonstration purposes we will convert the IEEE 24 bus reliability system into a **24-substation**, three-phase, physically based, breaker-oriented, P&C system inclusive model. Each substation will have variable breaker arrangements, for example ring-bus, breaker and a half, double breaker, etc.

2.1 The IEEE 24 Substation (Bus) Reliability Test System:

A breaker-oriented co-model has been developed that integrates the power network with its protection and control (P&C) systems. Starting from the IEEE RTS-79 24-bus system [11], the network is remodelled as a 24-substation model in which each substation includes the power system equipment (lines, transformers, shunts, etc.) and the associated P&C elements (relays, CTs/PTs, isolation switches, and breakers). Substations implement a mix of ring-bus, breaker-and-a-half, and double-bus arrangements as indicated in Figure. 2.1. For system studies, the model is partitioned into seven operating zones (Zones 1–7), with the slack area located in Zone 4. The number of protection zones within a substation depends on its topology and equipment.

The model also incorporates inverter-based resources (IBRs) at configurable penetration levels; scenarios span light and high penetration. The co-model is used to evaluate P&C performance—and the resulting dynamic security—under load changes, faults, and switching events. During a fault, all relays observe abnormal currents and voltages; the design objective is selectivity, i.e., isolating only the faulted element while all other relays restrain. Inadequate coordination can produce mis-operations that trip healthy equipment or create unintended islands. These behaviours are studied across the defined scenarios. Figure 2.1 summarizes the 24-substation layout and zone partitioning.

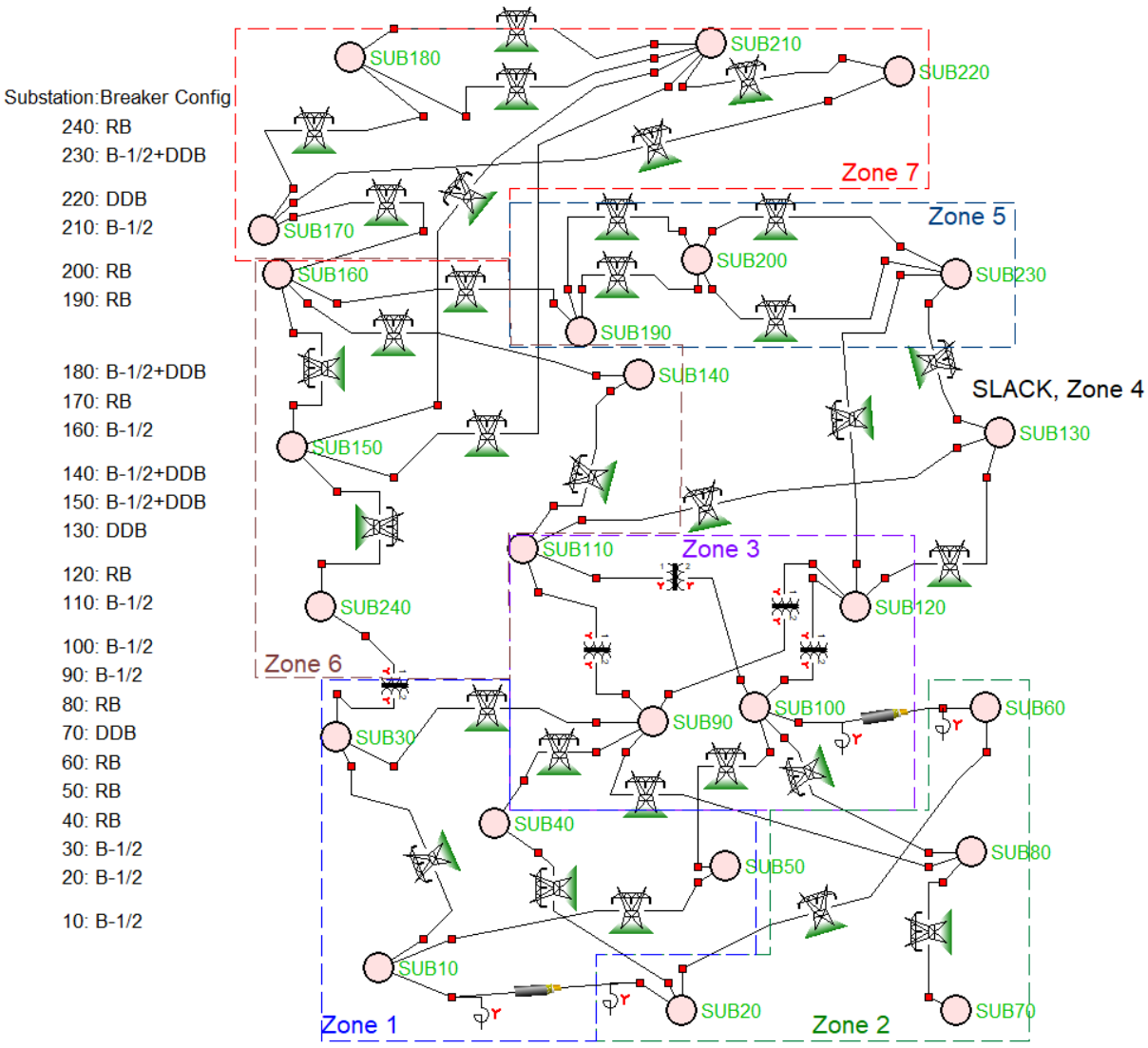


Figure 2.1 Breaker Oriented IEEE RTS 24-Substation Model.

2.1.1 IEEE RTS 24-Substation Design:

The IEEE 24 bus RTS is modeled as 24 substations, the co-model of each substation contains the primary equipment (power system) and the relays and controls (protection and control) that run it. The system contains 138-kV and 230-kV networks. Each substation is also modeled into specific breaker configuration such ring bus, double-bus, breaker-and-a-half, etc. The reason for modeling the substations into breaker configurations instead of a bus configuration (each device only contains two breakers on either side for isolation) is that breaker configurations expose the actual breakers and switching paths, letting you check per-breaker duty, interrupting ratings, and relay coordination accurately. They also capture real topology changes and three-phase/unbalanced behavior, enabling realistic fault, reliability, and protection studies that a lumped bus model can't support [12].

The co-model of each substation includes devices such as generators/inverters, step-up and step-down transformers, industrial loads, transmission lines, distribution loads, shunt reactors, etc. Additionally, it can be noted that Substations 240,110 and 120 link the two voltage levels (138kV and 230kV) within the system so that the areas (138kV and 230kV) can operate together. The main purpose of this co-model is to study relay coordination and identify any mis operation.

A brief description of individual substations is given below:

1. Sub-10: 138 kV; transmission lines connected to 30/20/50. It has a breaker and a half configuration. Substation 10 has eleven protection zones: (a) four generator/inverter-XFMR unit protection zones, (b) two Bus protection zones, (c) three transmission line protection zones, (d) one transformer protection zone and (e) load protection zone.

2. Sub-30: 138 kV; transmission lines connected to 10/90/240. It has a ring bus configuration. Substation 30 has four protection zones: (a) three transmission line protection zones, (b) one transformer protection zone.

3. Sub-40: 138 kV; transmission lines connected to 20/90. It has a ring bus configuration. Substation 40 has three protection zones: (a) two transmission line protection zones, (b) one transformer protection zone.

4. Sub-50: 138 kV; transmission lines connected to 10/100. It has a ring bus configuration. Substation 50 has three protection zones: (a) two transmission line protection zones, (b) one transformer protection zone.

5. Sub-20: 138 kV; transmission lines connected to 10/40/60. It has a breaker and a half configuration. Substation 20 has ten protection zones: (a) four generator/inverter-XFMR unit protection zones, (b) two Bus protection zones, (c) three transmission line protection zones and (d) one transformer protection zone.

6. Sub-70: 138 kV; one transmission line connected to 80. It has a ring bus configuration. Substation 70 has five protection zones: (a) one transmission line protection zone, (b) one transformer protection zone and (c) three generator/inverter-transformer unit protection zones.

7. Sub-80: 138 kV; transmission lines connected to 100/90/70. It has a breaker and a half configuration. Substation 80 has four protection zones: (a) three transmission line protection zones, (b) one transformer protection zone.

8. Sub-60: 138 kV; transmission lines connected to 20/100. It has a ring bus configuration. Substation 60 has three protection zones: (a) two line protection zones, (b) one transformer protection zone.

9. Sub-100: 138 kV; transmission lines connected to 60/80/50/120/110. It has a breaker and a half plus double bus configuration. Substation 100 has seven protection zones: (a) five,

line protection zones, (b) one transformer protection zone and (c) one Busbar protection zone.

10. Sub-90: 138 kV; transmission lines connected to 30/40/80/110/120. It has a breaker and a half plus double bus configuration. Substation 90 has seven protection zones: (a) five, line protection zones, (b) one transformer protection zone and (c) one Busbar protection zone.

11. Sub-110: 138 kV/230 kV; 138-kV transmission lines connected to 90/120, a 230-kV transmission line connected to 130. It has a breaker and a half configuration. Substation 110 has six protection zones: (a) four transmission line protection zones, (b) two transformer protection zones.

12. Sub-120: 138kV/230 kV; two 230-kV transmission lines connected to 130/230, and two 138-kV lines connected to 100/90. It has a breaker and a half configuration. Substation 120 has six protection zones: (a) four transmission line protection zones, (b) two transformer protection zones.

13. Sub-130: 230 kV; transmission lines connected to lines to 110/120/230. It has a ring bus configuration. Substation 130 has seven protection zones: (a) three transmission line protection zones, (b) one transformer protection zone and (c) three generator/inverter-transformer unit protection zones.

14. Sub-230: 230 kV; four transmission lines connected—two to 200, one to 120, one to 130. It has a ring bus configuration. Substation 230 has seven protection zones: (a) four transmission line protection zones and (b) three generator/inverter-transformer unit protection zones.

15. Sub-200: 230 kV; four 230-kV transmission lines (connected to 190×2/230×2). It has a ring bus configuration. Substation 200 has five protection zones: (a) four transmission line protection zones and (b) one transformer protection zone.

16. Sub-190: 230 kV; transmission lines connected to 200×2 and 160. It has a breaker and a half configuration. Substation 190 has four protection zones: (a) three transmission line protection zones and (b) one transformer protection zone.

17. Sub-140: 230 kV; transmission lines connected to 150/160/240. It has a breaker and a half configuration. Substation 140 has four protection zones: (a) two transmission line protection zones, (b) one inverter-transformer unit protection zone and (c) one transformer protection zone.

18. Sub-240: 230/138-kV; 230-kV transmission line connected to Sub-150, 138-kV line connected to 30, and a 230→138-kV grid transformer. It has a ring bus configuration. Substation-240 has three defined protection zones: (a) two transmission line protection zones and (b) one transformer protection zone.

19. Sub-150: 230 kV; four 230-kV transmission lines (connected to 210×2/240/160). It has a breaker and a half plus double bus configuration. Substation 150 has fourteen protection zones: (a) six generator/inverter-XFMR unit protection zones, (b) three Bus protection zones, (c) four transmission line protection zones and (d) one transformer protection zone.

20. Sub-160: 230 kV; transmission lines connected to 150/180/230. It has a breaker and a half configuration. Substation 160 has seven protection zones: (a) one inverter-XFMR unit protection zone, (b) one Bus protection zone, (c) four transmission line protection zones and (d) one transformer protection zone.

21. Sub-170: 230 kV; transmission lines connected to 180/220/160. It has a ring bus configuration. Substation-170 has four defined protection zones: (a) three transmission line protection zones and (b) one transformer protection zone.

22. Sub-180: 230 kV; transmission lines connected to 170/210. It has a breaker and a half configuration. Substation 180 has seven protection zones: (a) one generator-XFMR unit protection zone, (b) one Bus protection zone, (c) three transmission line protection zones and (d) two transformer protection zones.

23. Sub-210: 230 kV; transmission lines connected to 150/180/220. It has a breaker and a half configuration. Substation 210 has eight protection zones: (a) one generator-XFMR unit protection zone, (b) two Bus protection zones, and (c) five transmission line protection zones.

24. Sub-220: 230 kV; transmission lines connected to 170/210. It has a ring bus configuration. Substation 220 has five protection zones: (a) two transmission line protection zones and (c) three generator/inverter-transformer unit protection zones.

Detailed information on individual substation co-model design is given in Appendix A.

2.2 The Need for Proper IBR Modeling

The ever-increasing grid integration of inverter-based resources (IBRs) such as solar and wind power generation, battery energy storage systems (BESS) and HVDC systems challenge power systems control and operations. In recent years, several major power outages have occurred in power grids with large integration of IBRs, mainly due to the distinct dynamics of IBR-dominated power grids compared to the dynamics of conventional power systems dominated by synchronous generators. For instance, Southern California region with large integration of PV systems has faced a series of major power outages. One of the main contributing factors to such power outages was identified as sub-cycle overvoltage experienced by PV inverters due to faults [1]. The event analysis report by NERC [2] mentions that the interconnection system models that were used for determining planning and operating criteria could not represent the actual behavior of the solar plants which had resulted in overly optimistic planning assessments and substandard operational responses. In 2011, many wind turbines were tripped in northwest wind farms of China due to the temporary overvoltage during the fault recovery period[1]. In 2012, a high voltage excursion in the transmission system of Germany after a two-phase fault on a transmission line caused tripping

of wind turbines [4]. Figure 2.2 shows the recorded temporary overvoltage after the short-circuit in this incident. Detailed dynamic stability studies for southern Idaho power grid have also shown wind plants at 161 kV transmission systems may trip because of the high voltage excursion following the fault clearing period [5].

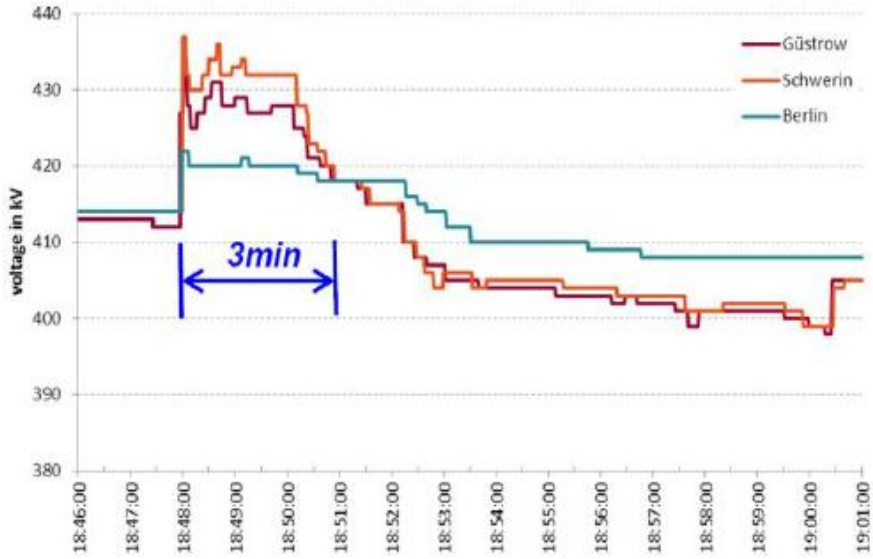


Figure 2.2 Temporary overvoltage subsequent to a short-circuit in the German transmission system in 2012 that caused tripping of wind turbines [4]

2.3 Literature review of Inverter-Based Resource Models for Transient Analysis

There are multiple studies conducted to observe the impact of modeling IBRs on the dynamic response of protection relays as well as the overall transient response. A slight deviation from the correct model can result in mis-operation of protection relays as well as not having proper EMT dynamic response.

The number of model parameters for IBR is essential to run EMT simulations with accurate transients' representation. The issue is that not many models are available to conduct EMT analysis along with sudden events or disturbances. The parameters the user is allowed to change do not have the capability to view the dynamic behavior of systems that experience sudden events [15].

Reference [47] indicates that there is almost no generally accepted models for EMT analysis in IBR dominated bulk power systems. In this work, the authors have developed a three-phase PV model via laboratory tests for commercial PV inverters. The developed model include active and reactive power models, DC source controller models, PI controller and current limiter for active and reactive power control, grid interconnection protection models, and converter models. Figure 3.3 shows the block diagram of the IBR model developed in [13].

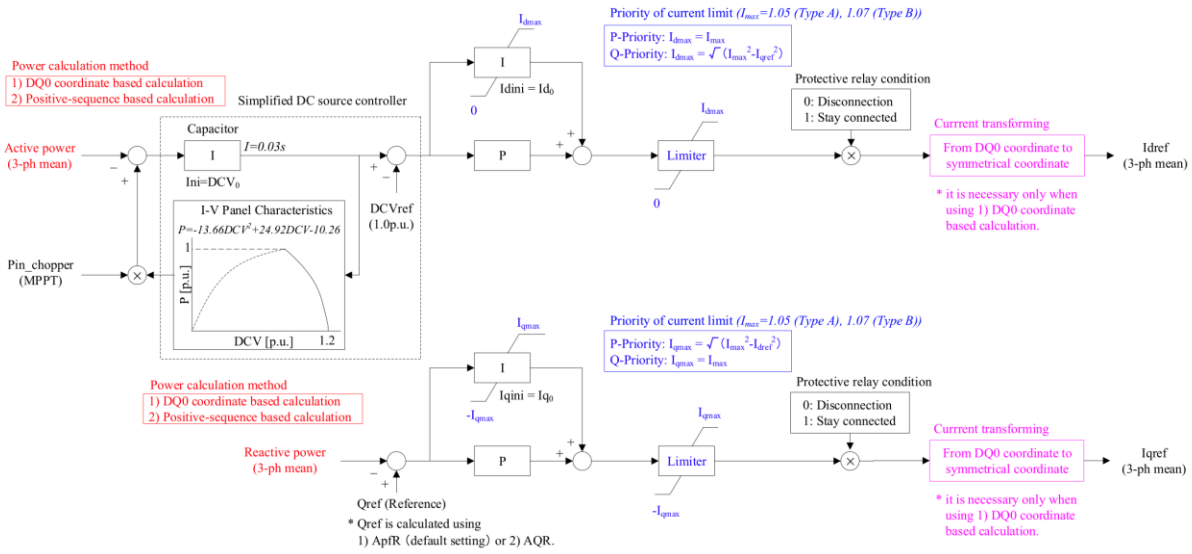


Figure 2.3 Block diagram of the IBR model developed in [13].

EPRI, University of Washington, University of Illinois Urbana Champaign, and University of Minnesota have developed IBR generic grid forming positive sequence models to be implemented in PSCAD simulations [10][14]. The models can represent four types of control methods such as droop-characteristic based models and virtual synchronous machine-based models. The model is a structure as a modular fashion where parameters can be adjusted in a graphical user interface. This model is widely used in the industry for EMT modeling but requires having the PSCAD software. Figure 2.4 shows the mathematical block diagram for the PSCAD model.

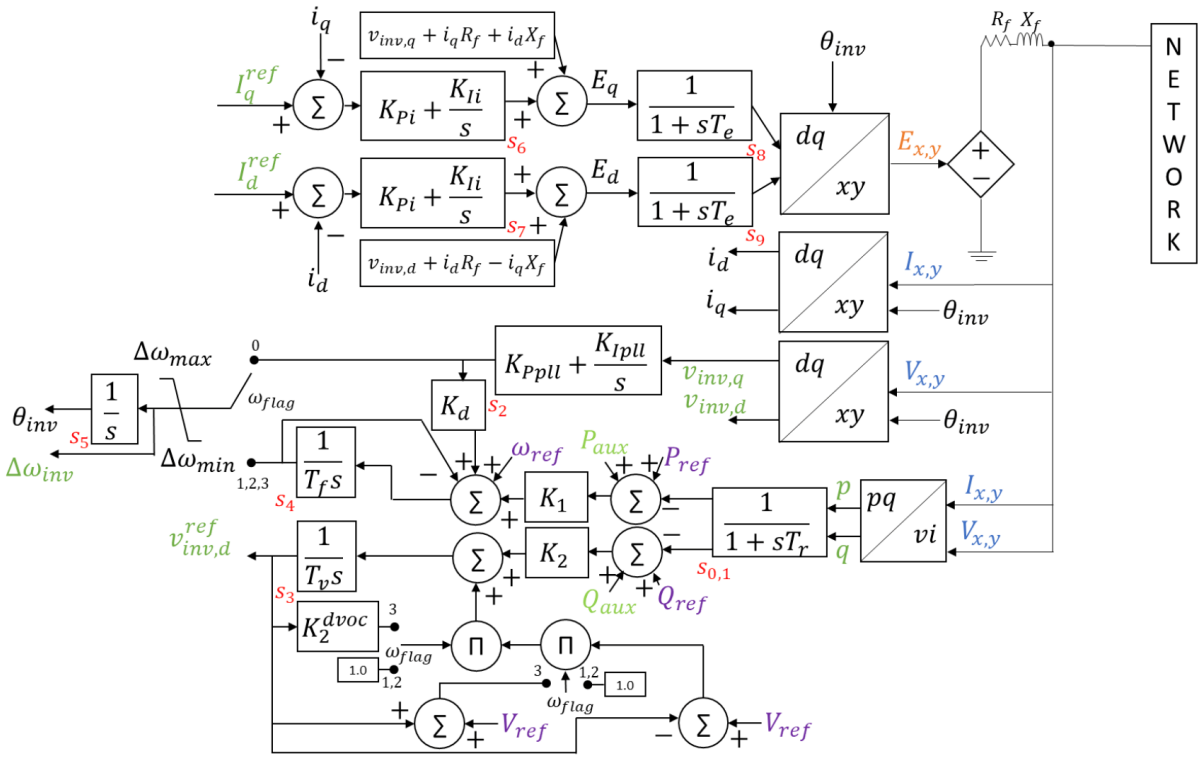


Figure 2.4 Block diagram of the IBR model developed in [10][14].

Reference [19][16][19] describes modules for central station PV plants connected to 60 kV or above transmission networks. Figure 3.5 presents distributed PV modules that integrate multiple subsystems into a single dynamic model. The models follow IEEE Standard 1547 where deployed models operate in constant power factor of constant reactive power control modes.

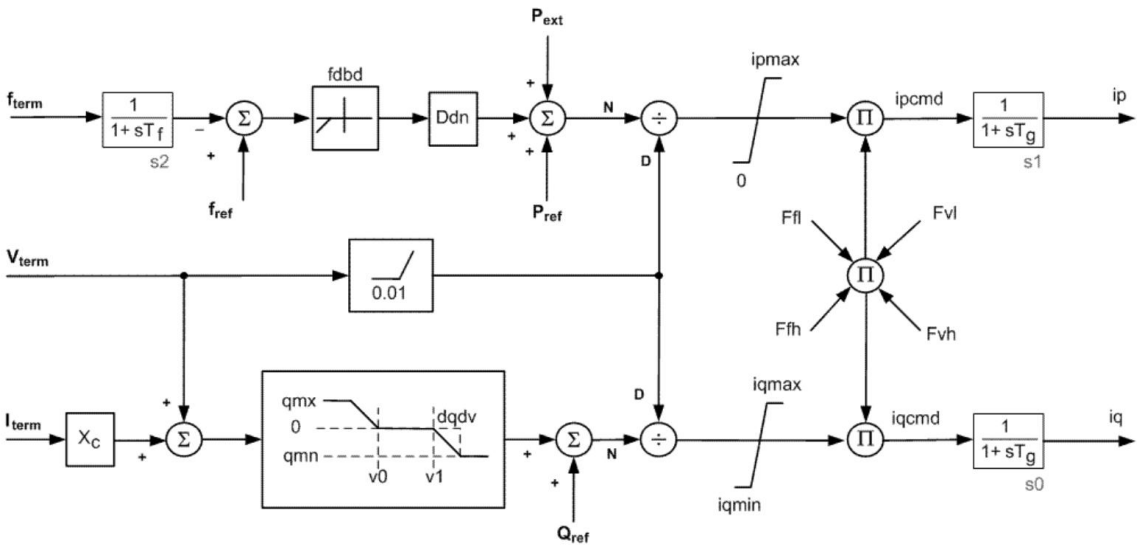


Figure 2.5 Block diagram of the IBR model developed in [19].

2.4 Developed Models of IBR for this Project

The developed model of the IBR is used for (a) estimation-based protection of IBRs, and (b) simulation of temporary overvoltages in IBR dominated power systems. The initial step in implementing a Dynamic State Estimation (DSE) based protection system involves developing a high-fidelity model for the protection zone. This modeling process is divided into two main tasks. First, detailed mathematical models are constructed for each key component within the protection zone, including transmission lines, generators, transformers, and IBRs. An example IBR model is shown in Figure 2.5. These models are based on the physical characteristics of each component to ensure an accurate representation of their functionality and operational dynamics.

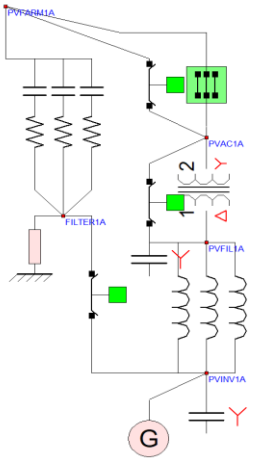


Figure 2.6 Inverter model developed in this project

Following this, the individual models are integrated to form a comprehensive network model that encapsulates the entire power system which includes all the protection zones. This aggregate model enables a holistic view of the system interactions and behaviors. To develop these individual device models, each physical circuit is meticulously described through mathematical equations. These are then cast in the State and Control Quadratized Device Model (SCQDM) format. The SCQDM model syntax is given below:

$$i(t) = Y_{eqx1}\mathbf{x}(t) + Y_{equ1}\mathbf{u}(t) + D_{eqxd1}\frac{d\mathbf{x}(t)}{dt} + C_{eqc1} \quad (1)$$

$$0 = Y_{eqx2}\mathbf{x}(t) + Y_{equ2}\mathbf{u}(t) + D_{eqxd2}\frac{d\mathbf{x}(t)}{dt} + C_{eqc2} \quad (2)$$

$$0 = Y_{eqx3}\mathbf{x}(t) + Y_{equ3}\mathbf{u}(t) + \left\{ \begin{array}{c} \vdots \\ \mathbf{x}(t)^T \left\langle F^i_{eqxx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{array} \right\} + \left\{ \begin{array}{c} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equu3} \right\rangle \mathbf{u}(t) \\ \vdots \end{array} \right\} + C_{eqc3} \quad (3)$$

Where **x**(t) and *i*(t) represent the state variables and interface currents of the model, respectively, and *Y*, *D*, and *F* are coefficient matrices, with *C* being a constant vector. Equations that position interface currents on the left-hand side are termed interface current equations. Equations that are governed by physical laws and result in zero values on the left-hand side are identified as internal equations.

The protection zone may encompass multiple power devices, which necessitates the integration of these device models into a unified network-level model. Typically, a device model comprises three types of equations: (a) interface current equations at the boundary of the protection zone, (b) interface current equations at nodes shared by multiple devices, and (c) internal equations specific to each device. For equations of type (a) and (c), the states of individual devices are integrated into the overall network states. For type (b), all interface current equations related to a common node are aggregated, and Kirchhoff's Current Law (KCL) is applied to formulate a single equation for each node.

2.5 Measurement Model

Any physical quantity can be expressed in terms of an equation in terms of the state variables of the SCQDM model. We refer to this equation as the measurement model. The development of the measurement model follows first principles. This requires a detailed understanding of the types and locations of measurements, which are typically categorized as follows:

1. Actual Measurements: These are direct readings obtained from instrumentation within the system.
2. Derived Measurements: Calculated from one or more actual measurements.
3. Virtual Measurements: Represent constraints within the system, typically set as zeros in the equations of virtual linear and quadratic models.
4. Pseudo Measurements: these are estimated values for physical quantities that are not directly measured (e.g., neutral voltages, neutral currents, etc.). A high degree of uncertainty is also assigned for these measurements.

The inclusion of virtual and pseudo measurements enhances the system's observability and augments redundancy. Utilizing data from these measurements alongside the dynamic model of the protection zone, we construct a comprehensive network-level measurement model. For measurements taken across components, the model equation is formulated based on the corresponding states from the network-level model. For through measurements, it is derived from the current equations of the respective devices. The general formulation of the measurement model is expressed as follows:

$$z(t) = Y_{zx}\mathbf{x}(t) + \left\{ \begin{array}{c} \vdots \\ \mathbf{x}(t)^T \left\langle F_{zx}^{i} \right\rangle \mathbf{x}(t) \\ \vdots \end{array} \right\} + D_{zx}\frac{d\mathbf{x}(t)}{dt} + C_{zx} + \eta \qquad (4)$$
$$= h(x) + \eta$$

where **z**(t) is the measurement vector, **x**(t) is the network state vector, η is the noise introduced by the meter, Y_{zx}, D_{zx}, F_{zx} matrices are coefficient matrices and C_{zx} is the constant vector

There are two types of high-fidelity simulation methods to study electrical transients of the system, time-domain and frequency-domain analysis. Note that both time domain and frequency domain modeling and simulation are based on the SCQDM modeling of each component of the system.

For this study, we use time domain simulation to study temporary overvoltages. This is the most detailed representation of the system.

For this study, we also use the frequency domain method to study the response of legacy protection systems in IBR dominated power systems. In frequency domain, we represent the inverters as well as the PV panels as a single equivalent voltage source with the appropriate parameters to mimic the behavior of the inverters. The value of the rms voltage for this voltage source is equivalent to the average voltage being produced by the PV panels during the day. In addition, it models the current limiting controllers of the inverter.

2.6 Summary

This chapter presents the IEEE 24 Substation RTS system and reviews prior work on modeling inverter-based resources (IBRs) for transient simulation analysis. The discussion emphasizes the balance between highly detailed models, which require significant simulation time and computational resources, and simplified models that may not fully capture transient dynamics. A high-fidelity representation of IBRs is adopted in this project to ensure accurate transient analysis while maintaining computational efficiency. This approach enables the capture of fast overvoltage phenomena, ensuring that protection functions operate effectively within the required time frame.

3. Investigation of protection response and P&C failures

The overall objective of this task is to identify events which may result in major system disturbance by triggering common mode outages, follow-up outages and/or cascading outages. For this purpose, the co-model will be utilized to perform co-simulation to answer the following questions: (a) how long of a co-simulation is needed to capture all the effects of a fault event, and (b) can part of co-simulation switch to single phase (positive sequence) co-simulation once faults have been cleared so that the co-simulation can proceed with the much more efficient analysis of positive sequence based models, and (c) can and at what point in the time domain co-simulation one can switch to other direct DSA methods to determine whether the system is stable. P&C failures will be integrated into the co-simulation using a Monte Carlo type approach. We will also investigate the feasibility of developing selection of critical P&C failures via sensitivity methods, which are expected to be more efficient. The time simulation period is expected to be the duration of the fault(s) plus a short time after the fault(s) have been cleared to establish the post fault level of disturbance of the system. The post fault(s) conditions of the system will be used to assess dynamic security as described in Task 3.

3.1 Protection and Control in Power Systems:

Power system protection is fundamentally concerned with detecting abnormal occurrences such as faults and clearing them promptly to restore the system to a stable operating state. Protective devices are broadly classified as reactionary devices, which detect hazards like short circuits and isolate faulted components, and safeguard devices, which act to mitigate hazardous environmental conditions (e.g., supplementary cooling, fire suppression). Protection systems operate through functional elements: measurement, comparison, decision-making, and action, with overall clearing time being a critical factor for coordination and system stability [20].

Design of protective systems requires careful consideration of reliability, security, sensitivity, and selectivity. Selectivity ensures only the faulted portion of the network is isolated, while backup relays provide redundancy in case of primary system failure. Protection zones, coordinated thresholds, and time delays are essential for minimizing unnecessary outages and ensuring continuity of service. Furthermore, protection strategies must account for system disturbances ranging from small fluctuations and overloads to large-scale events such as line faults, cascading outages, and generator trips where prompt and accurate protective action is vital to prevent instability and blackouts [20].

Over the past century, power system protection has advanced from electromechanical relays to microprocessor-based numerical relays. Conventional schemes such as overcurrent, directional, distance, and differential protection remain the backbone of protection, but modern developments have introduced adaptive relaying, artificial intelligence (AI)-based approaches, and transient-based methods to improve fault detection speed and reliability [21].

The rise of high-speed communication has enabled wide-area protection, leveraging synchronized phasor measurements (PMUs) and GPS timing to coordinate system-wide fault detection and stability control. Integrated protection consolidates multiple functions within intelligent relays and across substations, paving the way for Integrated Wide-Area Protection and Control (IWAPC)

systems. IWAPC employs a hierarchical architecture local, substation, and regional levels supported by real-time synchronized communication platforms to merge protection and control into a unified scheme. Finally, emerging technologies such as cloud computing and big data analytics are being integrated into protection platforms, supporting wide-area fault location, adaptive relay settings, and predictive asset management. These innovations enhance situational awareness, resilience, and reliability, ultimately ensuring that modern protection and control systems can meet the challenges of increasingly complex, interconnected, and renewable-rich grids [21].

3.2 Protective devices in Power Systems:

Protective devices form the backbone of reliable and secure power system operation by ensuring timely detection, isolation, and mitigation of abnormal conditions such as faults, overloads, and voltage instabilities. These devices include relays, fuses, circuit breakers, surge arresters, reclosers, and protection schemes present within substations and networks. Their coordinated action prevents equipment damage, maintains system stability, and enhances safety for both operators and consumers. Protective devices are characterized by their operating principles, time-current characteristics, and selectivity, which together determine their ability to discriminate between normal and abnormal events. Modern developments further integrate these devices with communication and control systems, enabling adaptive protection, improved fault location, and faster restoration of service [22] .

Protective devices in power systems can be broadly categorized into two groups: primary interruption devices such as circuit breakers, reclosers, fuses, etc. and detection and control devices, primarily protective relays. The protective relays play a central role, as they issue the trip signals that activate the primary interruption devices. Consequently, when discussing protection and control systems, the primary emphasis is placed on the operation and coordination of protective relays.

3.2.1 Primary Interruption Devices:

Primary interruption devices protect electrical circuits from damage by interrupting the flow of electricity when a fault or overload occurs. They are crucial for maintaining the safety and reliability of power systems by preventing equipment damage and potential hazards like fires.

Some of the most common types of interruption devices include fuses, circuit breakers and reclosers.

Fuses and Switches:

Fuses and switches are essential components in power systems, serving both protection and operational functions. A fuse provides automatic protection by melting its element when excessive current flows, thereby interrupting the circuit and preventing equipment damage. Its simple design, fast response, and reliability make it widely used in distribution networks [23].

Switches, on the other hand, are manually or automatically operated devices that establish or interrupt current flow under normal operating conditions. While they do not provide fault-clearing capability like fuses or circuit breakers, they are crucial for isolating equipment, enabling maintenance, and reconfiguring networks. Together, fuses and switches enhance system safety, ensure continuity of service, and simplify fault management by providing cost-effective, localized protection and operational flexibility [23].

Circuit Breakers:

Circuit breakers are critical protective devices that automatically interrupt abnormal current flow to prevent damage to electrical systems. Unlike fuses, which operate once and must be replaced, circuit breakers can be reset and reused, offering more flexibility and reliability. They are designed to detect faults such as short circuits or overloads and quickly disconnect the faulty section to safeguard equipment and ensure system stability. Circuit breakers are classified based on their construction and operating mechanisms, including air, oil, vacuum, and SF_6 types, each suited for specific voltage levels and applications. Their operation involves arc extinction methods that vary depending on the breaker type, ensuring safe interruption of high fault currents. In modern power systems, circuit breakers play an essential role in coordination with relays, enabling selective isolation of faults while maintaining continuity of supply in unaffected parts of the system [23].

Reclosers:

A recloser is an advanced type of circuit breaker engineered to rapidly open and then reclose, distinguishing it from standard breakers that remain open after tripping. Designed to minimize extended outages, reclosers detect transient faults such as those caused by lightning strikes or foreign objects and swiftly restore power, since roughly 80% of such faults clear on their own. This feature is codified under the IEC/IEEE Recloser standard (C37.60/IEC 62271-111), which specifies performance requirements not covered by basic circuit breaker standards. The automatic reclosing capability, known as auto-reclosing, can be applied in both medium- and high-voltage networks: in distribution systems, standalone autoreclosers integrate control systems, high-voltage switchgear, and remote SCADA, while in transmission systems, single-phase reclosing is used to maintain synchronism and continuity.

3.2.2 Detection and Control Devices:

Detection and control devices are crucial for monitoring system status, identifying abnormal conditions, and initiating corrective actions to maintain stable and reliable power delivery. These devices work together with primary interruption devices in a coordinated manner to ensure the power system operates within safe and optimal parameters.

Some of the most common types of detection and control devices include Current Transformers (CTs), Potential Transformers (PTs), Protective relays, etc. The focus of this section is on Protective relays specifically on Legacy and Estimation Based protection.

Legacy Protection and Control:

Legacy Protection refers to traditional relays that operate based on predefined "settings". These settings define protective functions using physical parameters such as line currents and voltages, obtained from CTs and PTs respectively. Common types of legacy protection include distance relays (21), differential relays (87), time-overcurrent relays (51), and others.

In the early 20th century, protective relays were bulky, electromechanical devices relying on physical principles. With the introduction of microprocessors in the late 1970s, numerical relays emerged, integrating multiple protective functions into a single compact device. Today, numerical relays are the standard when referring to legacy protection, as they incorporate elements such as distance, differential, and overcurrent protection in one unit. Moreover, manufacturers offer specialized numerical relays tailored to applications—for example, the SEL-787L, which primarily provides differential protection with backup functions, or the SEL-421, which is designed for distance protection with backup elements [25].

Some of the most common types of legacy protection functions are described below:

Distance Protection Function (21):

A distance relay is a protection device that determines whether a fault lies within a protected line section by comparing the measured impedance (ratio of voltage to current) with a predefined threshold. Its operation is based on the principle that the apparent impedance seen from the relay location decreases as the fault moves closer. The relay is typically set in zones: the first zone provides instantaneous protection covering 80–90% of the line, while the second and third zones extend protection to the remainder of the line and into adjacent lines (typically 125% and 250% of the line), often with intentional time delays to ensure selectivity. The key characteristics of distance relays are represented in the R–X (impedance) plane, commonly as circular or polygonal characteristics, which define the region where the relay will trip. Settings involve specifying the reach (impedance threshold), directional discrimination, and time delays to achieve reliable fault detection and coordination with other protection devices [26].

Equations (1) to (6) form the foundation of the distance protection function for identifying conventional fault types in a power system. When a fault occurs at a distance L from the relay, the relay measures the apparent impedance, denoted as z_1L. For a three-phase distance relay, this impedance measurement is crucial for fault classification. For instance, in the case of a line-to-ground (A–G) fault, Equation (4) determines the apparent impedance, which corresponds to z_1L *[*25].

$$\frac{k_1(V_a^{'} - V_b^{'})}{k_2(I_a^{'} - I_b^{'})} \quad (1)$$

$$\frac{k_1(V_b^{'} - V_c^{'})}{k_2(I_c^{'} - I_c^{'})} \quad (2)$$

$$\frac{k_1(V_c^{'} - V_a^{'})}{k_2(I_c^{'} - I_a^{'})} \quad (3)$$

$$\frac{k_1 V_a^{'}}{k_2(I_a^{'} + mI_0^{'})} \quad (4)$$

$$\frac{k_1 V_b^{'}}{k_2(I_b^{'} + mI_0^{'})} \quad (5)$$

$$\frac{k_1 V_c^{'}}{k_2(I_c^{'} + mI_0^{'})} \quad (6)$$

Where k_1 and k_2 are the instrumentation transformer turns ratio and $I_0^{'}$ is the zero-sequence current measured by the distance relay. m is also called the compensation factor.

The most common application of the distance protection function is on transmission lines.

Differential Protection Function (87):

The differential protection function operates on the principle of comparing the current entering and leaving the protected zone. If the difference between these currents exceeds a set threshold, a fault exists within the zone. This method ensures high sensitivity to internal faults while remaining secure against external faults, since for external faults the current entering equals the current exiting (by Kirchhoff's law). The equations formalize this by expressing the differential current as the vector sum of currents at the terminals, and the protection logic issues a trip when this differential current surpasses a predefined setting, effectively isolating the faulted section [27].

Differential Current:

$$I_{diff} = \sum I_{in} - \sum I_{out} (based\ on\ KCL)$$

Restraining Current:

$$I_{res} = \frac{\left|\sum I_{in}\right| + \left|\sum I_{out}\right|}{2}$$

Operating Condition: (7)

Relay trips if: $I_{diff} > k.I_{res} + I_{pickup}$

where,

k – CT ratio

I_{pickup} – pickup current (minimum sensitivity threshold)

Time Overcurrent Protection Function (51):

Time overcurrent protection operates by delaying the relay tripping action in proportion to the severity of the fault current. Essentially, the higher the current above the pickup value, the faster the relay trips, while for lower overcurrents, it allows a longer time before operating. Two main approaches are used: inverse-time and definite-time. Inverse-time relays trip faster as the fault current increases, following a standardized curve, making them effective for grading and selectivity. Definite-time relays, on the other hand, trip after a preset fixed time once the current exceeds the pickup value, independent of magnitude. In modern systems, coordination between these two schemes is challenging due to the presence of distributed energy resources, variable fault levels, and dynamic system configurations. Proper relay setting is crucial to balance sensitivity, selectivity, and reliability, ensuring protection without unnecessary disconnections [28] .

Inverse-Time Overcurrent Relay (IEEE standard):

$$t = \frac{K \cdot TMS}{\left(\frac{I}{I_{pickup}}\right)^{\alpha} - 1}$$

Where,
t = operating time of relay (s)
I = fault current (A)
I_{pickup} = pickup current (A)
TMS = Time Multiplier Setting
K, α = inverse constants

Typical inverse constants:
Standard Inverse K = 0.14; $\alpha = 0.02$
Very Inverse K = 13.5; $\alpha = 1$
Extremely Inverse K = 80; $\alpha = 2$

Definite-Time Overcurrent Relay:

$$t = T_d \; ; \; for \; I \geq I_{pickup}$$

Where,
t = relay operating time (s)
T_d = fixed time delay setting (s)
I_{pickup} = pickup current (A)

Instantaneous Overcurrent Relay:

$$t \approx 0 \; ; \; for \; I \geq I_{inst}$$

Where,
I_{inst} = instantaneous pickup current

Estimation Based Protection and Control:

Dynamic State Estimation–Based Protection (also referred to as "setting-less" protection) is based on the principle of differential protection and extends it into a generalized framework. In classical differential protection, currents at all terminals of a zone are measured, and their weighted sum must equal zero according to Kirchhoff's Current Law; as long as this condition is met, no trip is issued. EBP generalizes this idea by utilizing all available measurements within a protection zone such as line currents, voltages, machine speed, torque, even thermal states and checking them against the physical laws that govern the system, including Kirchhoff's laws, motion laws, and thermodynamics. These laws are captured in a high-fidelity dynamic model of the protection zone, and through a dynamic state estimation procedure, the relay verifies whether the measurements satisfy the model. If the measurements (h matrix) do not match the model (z matrix), which occurs under an internal fault (including high-impedance or complex internal faults), the abnormality is detected and a trip signal is issued, while external faults are ignored. To achieve this, each device (usually the protection zone) is represented by a Quadratized Dynamic Model (QDM), a set of differential and algebraic equations that describe both terminal behavior and internal dynamics, reduced to at most quadratic nonlinearities for computational efficiency [29].

Details on the QDM equations and the measurement model can be referenced in sections 2.4 and 2.5 respectively.

3.3 Importance of Critical Clearing Time:

The Critical Clearing Time (CCT) is defined as the maximum duration a fault can persist in a power system before it must be cleared to maintain system stability. If the fault is cleared within this time, the system can return to a stable operating state; however, if it remains beyond the CCT, the system may lose synchronism and become unstable. The value of CCT is influenced by several factors, including the fault location (with faults nearer to generation sources typically having shorter CCTs), the type of fault, the pre-fault operating conditions such as system loading and power transfer, and the inherent inertia and damping characteristics of the power system. Systems with higher inertia and damping generally exhibit longer CCTs, offering greater stability margins[30].

It can be noted that the Critical Clearing Time (CCT) plays a fundamental role in the coordination of protection systems, as it defines the maximum allowable fault duration before the system loses synchronism and transient instability occurs. The study in [31] demonstrates that CCT is strongly dependent on both machine parameters (inertia, damping, and transient reactance) and network characteristics (line, transformer, and fault impedances), with solid three-phase faults and line outages yielding the lowest CCT values. In terms of protection standpoint, this means that relays and circuit breakers must operate within the CCT margin to ensure stability. If the actual clearing time exceeds the CCT, the accelerating rotor angles or equivalent system states will diverge, resulting in a loss of synchronism. Consequently, CCT provides a quantitative benchmark for setting relay operating times and breaker response requirements, ensuring that protection schemes are fast enough to maintain system stability while avoiding unnecessary equipment stress or misoperation [31].

3.4 Effect of IBRs on Protection and Control:

The increasing penetration of inverter-based resources (IBRs) significantly impacts protection and control specifically traditional protection and control schemes. Conventional protection systems are designed around synchronous machine behavior, which provides strong fault currents and predictable dynamics that enable reliable relay operation and coordination. In contrast, IBRs contribute limited and controlled fault currents, often with fast current-limiting controls, which reduce the effectiveness of overcurrent, distance, and differential protections. Moreover, the fast and nonlinear dynamics of IBR controls introduce challenges in accurately modeling system response and coordinating relays across different protection zones. As a result, false trips, blinding of protection, and reduced sensitivity of fault detection are more likely in IBR-dominated networks. These issues necessitate the adoption of advanced methods, such as protection schemes that incorporate dynamic state estimation, adaptive relays, and communication-assisted strategies, to ensure dependable fault detection, isolation, and system stability in modern power grids [32].

In addition to their impact on fault detection and relay performance, inverter-based resources (IBRs) also influence the Critical Clearing Time (CCT) of a power system. The integration of large-scale wind generation, for instance, alters system inertia distribution and power flow patterns, which directly affects transient stability margins. As demonstrated in [33] , the connection of 1833 MW of wind power in Taiwan increased the CCT in the northern and southern regions, thereby improving stability, but slightly reduced the CCT in the central region due to heavier transmission loading. A reduction in CCT implies that protective relays and breakers must operate more quickly to maintain synchronism; otherwise, the system risks losing stability once the actual clearing time exceeds the allowable limit. Hence, the effect of IBRs on CCT underscores the critical link between renewable integration, transient stability, and the performance requirements of modern protection systems.

3.5 Example Protection Zone in IEEE 24 Substation RTS:

A protection zone in a power system is the portion of the system safeguarded by protective devices, typically primary interruption devices such as circuit breakers. These zones are usually defined by the circuit breakers themselves beginning at one circuit breaker and ending at another so that any equipment within the boundary is fully protected. This ensures that, in the event of a fault, only the affected zone is isolated without disturbing the rest of the system. Protection zones are generally named after the main equipment they encompass. For example, a zone that includes both a generator and its transformer is commonly referred to as a generator-transformer unit protection zone.

An example of a protection zone in Substation 170 in the IEEE 24 Substation RTS is given below (detailed information is given in the appendix section):

Substation-170 has a ring bus configuration. This substation has eight defined protection zones: (a) three transmission line protection zones, (b) four Bus protection zones, (c) one Distribution protection zone.

Figure 3.1 shows one of the protection zones 170PZ1 from the co-model of Substation-170 (Detailed co-model present in appendix). There are five MUs present in 170PZ1 that gather information of the line currents and line voltages from the CTs and PTs present on either side of the circuit breaker. The locations of the current and voltage measurements for each MU are labelled with red and blue dashed lines, respectively. The MUs present within the protection zones send the measurements to the protective relays.

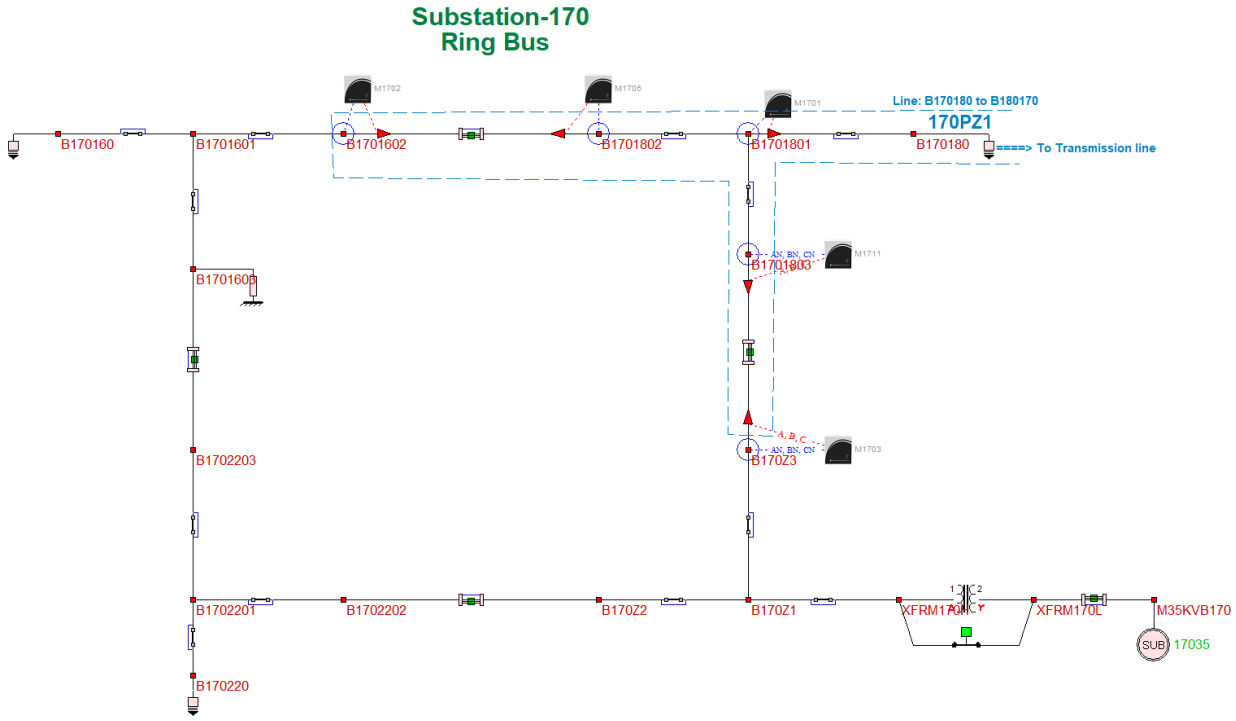


Figure 3.1 Protection Zone 170PZ1 (Substation 170). Merging Unit and Relays

170PZ1 protects the transmission line B170180 to B180170, the protection zone consists of one transmission line, two circuit breakers with two current and voltage transformers (CT/PT) each and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone (Detailed information is given in the appendix section).

3.6 Setup of the Protection and Control System in the IEEE 24 Substation RTS:

An example of how the protection and control is set up in the IEEE 24 Susbtation RTS is given below. The example is for the Susbtation 170 which has a ring bus configuration. Substation-170 has 4 protection zones and each zone has Merging Units (MUs) and relays protecting it. Detailed information on Substation 170 can be found in the appendix section.

3.6.1 Setup of Legacy Protection and Control (Distance Relay)

The distance relay can be set up with the following details:

(a) Measurements from MUs of protection zones
(b) Positive and zero sequence impedance of the transmission line

We know that the distance relay utilizes the following equations to calculate the minimum value which indicates where the fault is located:

$$\frac{k_1(V_a^{'} - V_b^{'})}{k_2(I_a^{'} - I_b^{'})} \quad (1)$$

$$\frac{k_1(V_b^{'} - V_c^{'})}{k_2(I_c^{'} - I_c^{'})} \quad (2)$$

$$\frac{k_1(V_c^{'} - V_a^{'})}{k_2(I_c^{'} - I_a^{'})} \quad (3)$$

$$\frac{k_1 V_a^{'}}{k_2(I_a^{'} + mI_0^{'})} \quad (4)$$

$$\frac{k_1 V_b^{'}}{k_2(I_b^{'} + mI_0^{'})} \quad (5)$$

$$\frac{k_1 V_c^{'}}{k_2(I_c^{'} + mI_0^{'})} \quad (6)$$

Where k_1 and k_2 are the instrumentation transformer turns ratio and $I_0^{'}$ is the zero-sequence current measured by the distance relay. m is also called the compensation factor.

$$m = \frac{Z_0 - Z_1}{Z_1} \quad (8)$$

Equations (1) to (6) are instrumental for the distance protection function in diagnosing the type of conventional fault within a system. If a fault occurs at a distance L from the relay, the minimum impedance, denoted as z_1L, is measured by the distance relay. For a three-phase distance relay, this impedance calculation is critical in identifying the nature of the fault. For example, in the case of a line-to-ground (A-G) fault, the calculated value according to Equation (4) would be z_1L.

For the distance relay to utilize the above equations to calculate the minimum value, it requires measurements from the merging units of the respective protection zone it monitors.

After the measurements are collected by the relay, the user needs to input the **impedance zone** value of the distance relay (these **impedance zones** are usually set up to monitor a percentage of the transmission line, for example impedance zone 1 is set up to monitor 80% of the transmission line and **should not be confused with protection zones**).

To input the impedance zone, the user needs the following data:

1. Positive sequence impedance (Z_1)
2. Zero sequence impedance (Z_0)

In WinIGS-T the user can collect this data by selecting the transmission line that is being monitored and then selecting: Tools→Circuit Parameters→Sequence parameters.

After the sequence parameters are selected, the user can find the Z_1 and Z_0 values present and note it down. Note: The user needs to calculate the value of the compensation factor (m) using Z_1 and Z_0 respectively. Figure 3.2 shows the sequence parameters of transmission line B170220 to B220170.

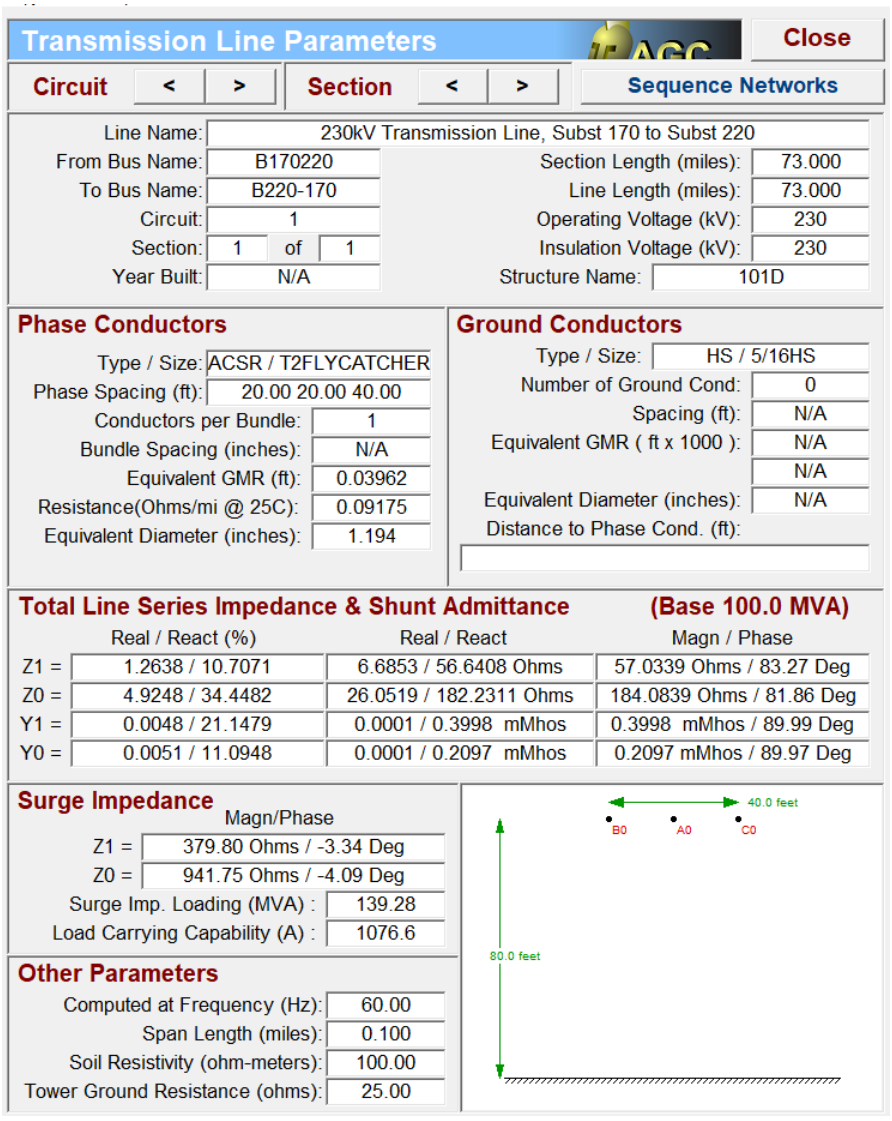


Figure 3.2 Sequence parameters of transmission line B170220 to B220170.

Using the above sequence parameters, the user now sets up the three impedance zones monitoring 80%, 125% and 250% of the transmission line respectively.

The settings of the distance relay for protection zones 1,2 and 3 in substation-170 can be seen below:

Setup of Protection Zone 1 (170PZ1) Distance Relay

The settings of the distance relay monitoring the protection zone-1 (transmission line B170180 to B180170) of Substation-170 can be seen below:

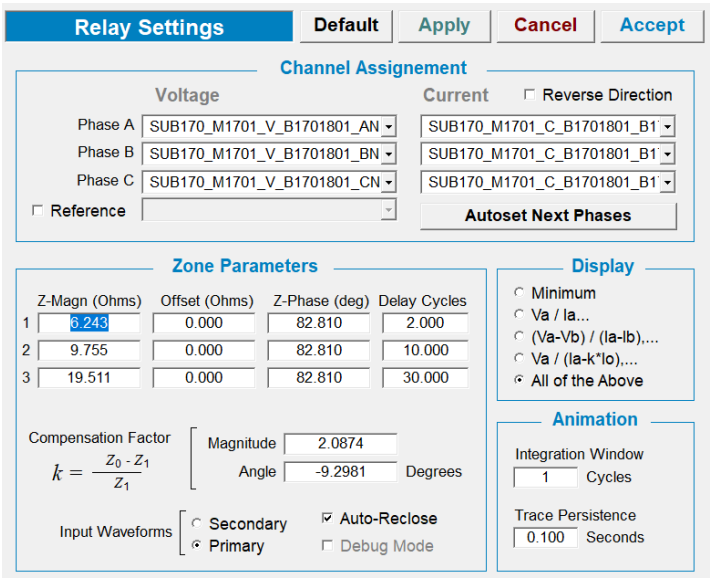


Figure 3.3 Distance relay settings of 170PZ1.

Setup of Protection Zone 2 (170PZ2) Distance Relay

The settings of the distance relay monitoring the protection zone-2 (transmission line B170160 to B160170) of Substation-170 can be seen below:

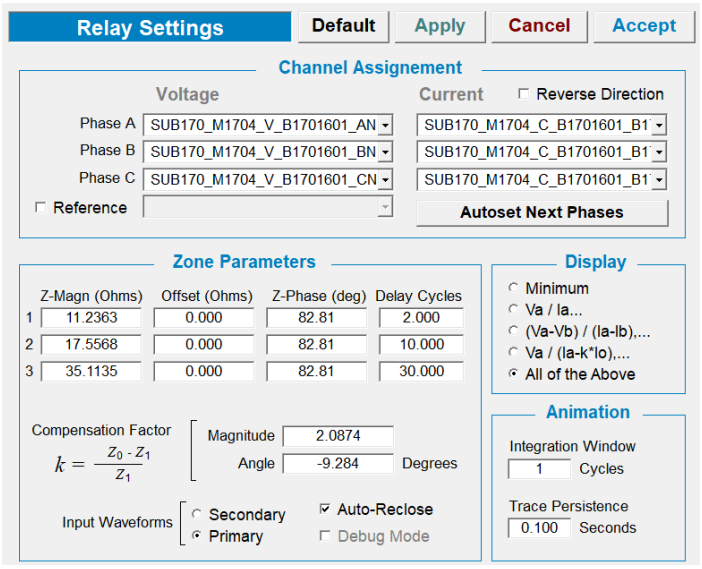


Figure 3.4 Distance relay settings of 170PZ2.

Setup of Protection Zone 3 (170PZ3) Distance Relay

The settings of the distance relay monitoring the protection zone-3 (transmission line B170220 to B220170) of Substation-170 can be seen below:

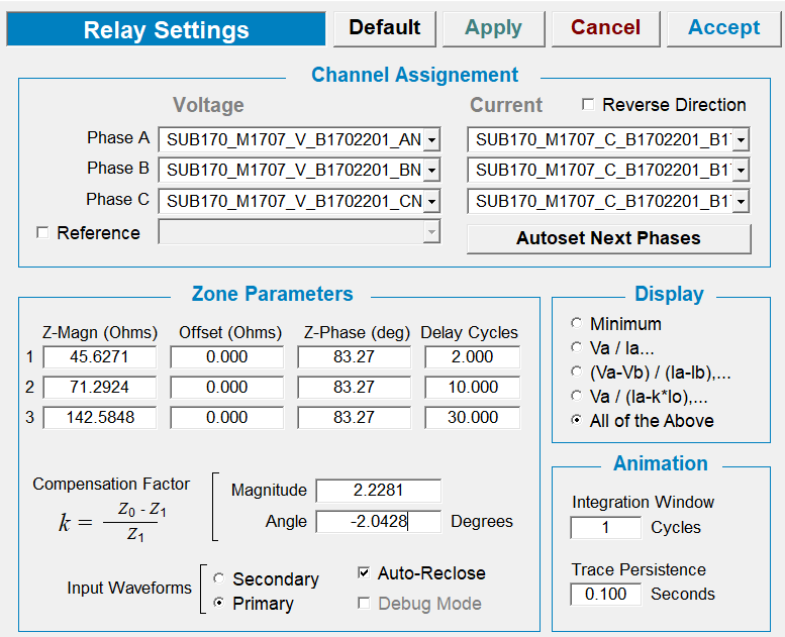


Figure 3.5 Distance relay settings of 170PZ3.

The above example is for the setup of the distance relay for the three transmission line protection zones in Substation-170 of the IEEE 24 Substation RTS. All the other protection zones are also protected by a protective relay. It can be noted that this setup is an example for the setup of legacy protection and control in the IEEE 24 Substation RTS.

A similar example for Substation 170 is given for Estimation Based Protection in the next section.

3.6.2 Setup of Estimation Based-Protection and Control

As mentioned in section 3.2.2 the estimation based protection utilizes the quadratized dynamic model (QDM) which contains a set of differential and algebraic equations (DAEs) that describe the complete dynamics of the device.

The procedure to generate the EBP model file begins with building a system model in WinIGS-T. The WinIGS-T model may 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 MUs.

- The breakers/switches that enable the protection of the zone.

The WinIGS-T model for Substation-170, is provided in Appendix.

After building the model, the protection zones are also defined based on the architecture of Substation-170 and the available measurements, these are also detailed in the appendix section of this document.

The setup of the EBP relay requires two main files: (1) the protection zone model and (2) the COMTRADE file (measurements) containing the data from the Merging units within the protection zone.

Exporting the protection zone model and the measurements in Win-IGS-T has been reduced to a very simple procedure. Specifically, once the co-model has been developed and entered into the program, the definition of the protection zone and measurements is achieved as follows:

Setup of Protection Zone 1 (170PZ1) EBP Relay

Measurements and Protection Zone Model: For the protection zone, all the devices within the protection zone are selected by right mouse clicks. That includes the interrupting devices for the protection zone (breakers) as well as all IEDs (MUs) that collect data from the protection zone. A demonstration of how to export the measurement and protection zone model for protection zone 1 is presented in Figure 3.6. First, all the devices inside the protection zone are selected (devices highlighted with green), and all the IEDs inside the protection zone are selected (IEDs surrounded with a red square). Then, execute the SCAQCF Export command of the Tools menu by clicking on the toolbar icon:  (See also Figure 3.7) to export the measurement definition file and protection zone model file.

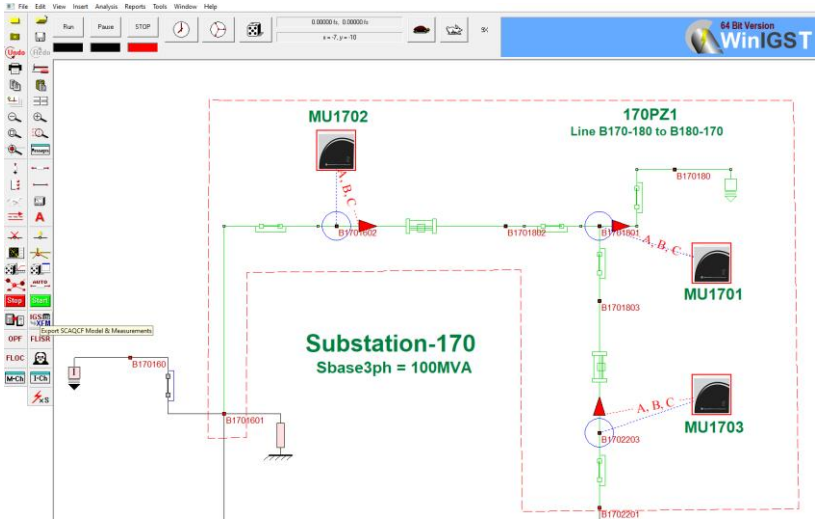


Figure 3.6 Selecting all the devices within the protection zone 1.

Subsequently, the dialog of Figure 3.9 pops up. The dialog allows the user to specify where the protection zone model should be stored and at what rate the data will be coming into the relay. Once the path is specified, the user needs to simply press Export. This action automatically generates the protection zone model file as well as the measurement definition file. Note that the EBP relay will read these files and set the protection functions automatically.

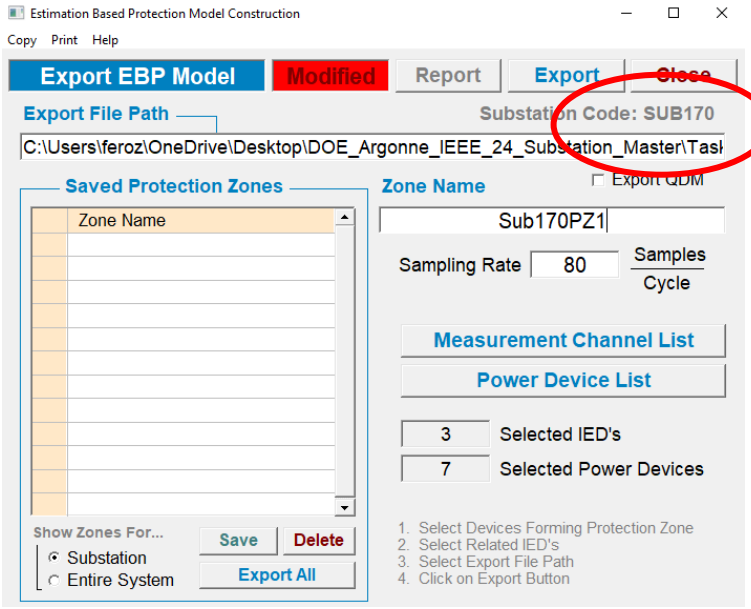


Figure 3.7 User Dialog for Exporting the Protection Zone Model for Protection Zone 1.

Setup of Protection Zone 2 (170PZ2) EBP Relay

The setup process for the protection zone 2 EBP relay is like the steps mentioned previously in protection zone 1.

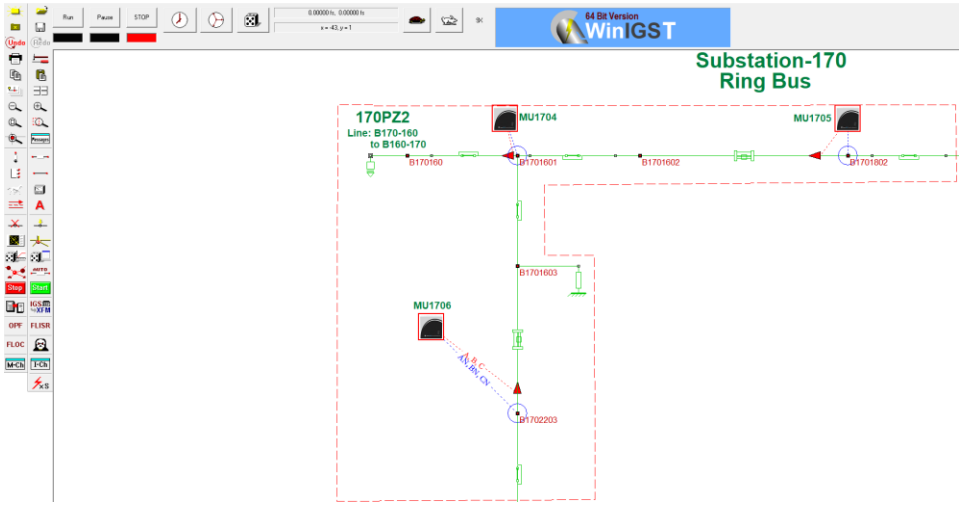


Figure 3.8 Selecting all the devices within the protection zone 2.

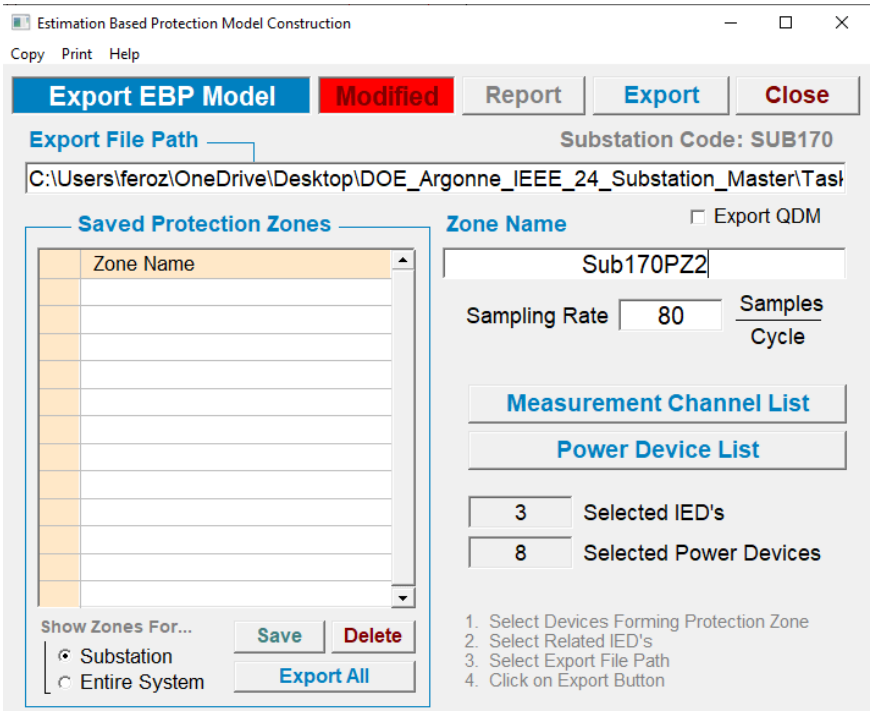


Figure 3.9 User Dialog for Exporting the Protection Zone Model for Protection Zone 2.

Setup of Protection Zone 3 (170PZ3) EBP Relay

The setup process for the protection zone 2 EBP relay is like the steps mentioned previously in protection zone 1.

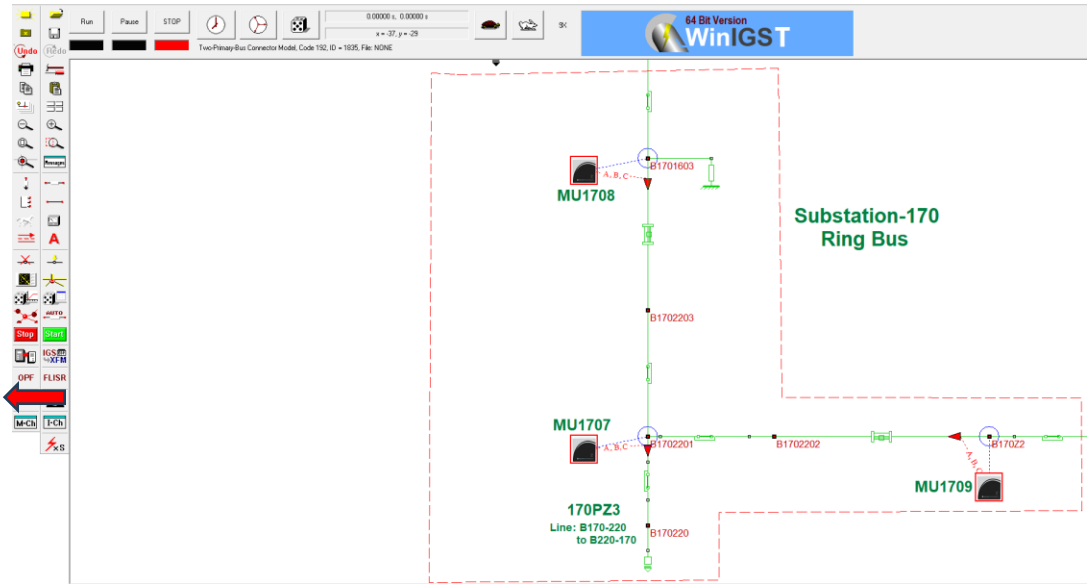


Figure 3.10 Selecting all the devices within the protection zone 3.

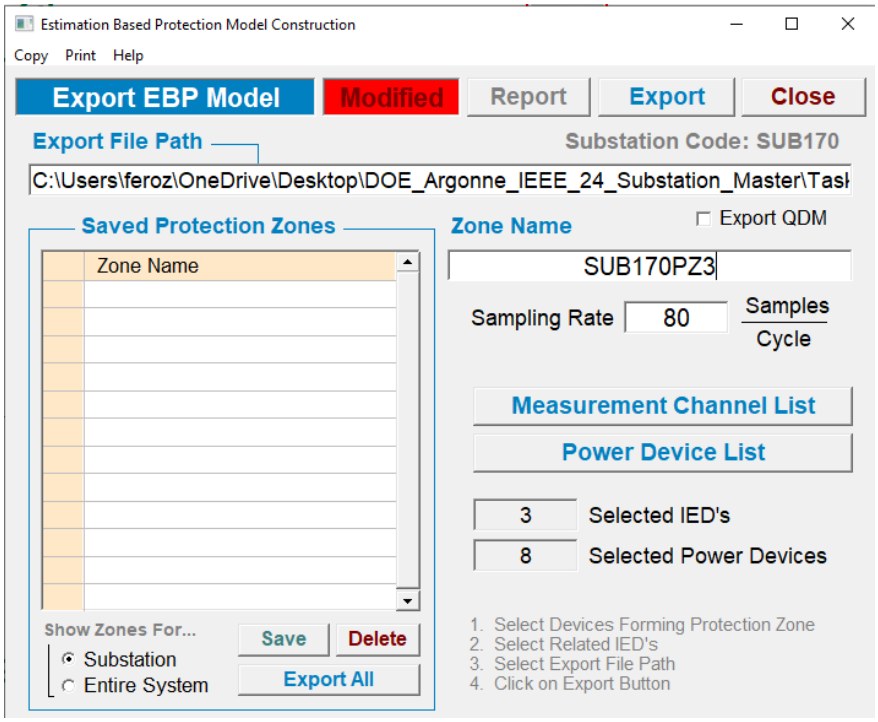


Figure 3.11 User Dialog for Exporting the Protection Zone Model for Protection Zone 3.

3.7 Co-simulation Example Results

Using the co-model, the response of the combined power system, IBRs and protection and control system was co-simulated for various events. The response of the system was studied, and conclusions were reached.

The detailed results of the co-simulation are provided in Appendix B.

A summary of the co-simulation results is presented in Tables 3.1, 3.2, 3.3, 3.4 and 3.5.

Table 3.1: Summary of Co-Simulation Results for Event-1.

Sub Events	Legacy Protection Response			EBP Response		
	170PZ1 (DistanceRelay)	170PZ2 (DistanceRelay)	170PZ3 (DistanceRelay)	170PZ1	170PZ2	170PZ3
1	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal
2	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal
3	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal
4	**Trips**	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal
5	**Trips**	No trip signal	No trip signal	No trip signal	No trip signal	No trip signal

Table 3.2: Summary of Co-Simulation Results for Event-2.

Sub Events	Legacy Protection Response		EBP Response	
	240PZ1 (Distance Relay)	240PZ3 (Distance Relay)	240PZ1	240PZ3
1	**Trips in Zone-3**	No trip signal	**Trips immediately**	No trip signal
2	No trip signal	**Trips in Zone-2**	No trip signal	**Trips immediately**

Table 3.3: Summary of Co-Simulation Results for Event-3.

Sub Events	Legacy Protection Response		EBP Response	
	50PZ1 (Distance Relay)	50PZ2 (Distance Relay)	50PZ1	50PZ2
1	**Trips in Zone-3**	No trip signal	**Trips immediately**	No trip signal
2	No trip signal	**Trips in Zone-3**	No trip signal	**Trips immediately**

Table 3.4: Summary of Co-Simulation Results for Event-4.

Sub Events	Legacy Protection Response		EBP Response	
	40PZ1 (Distance Relay)	40PZ2 (Distance Relay)	40PZ1	40PZ2
1	No trip signal	**Trips in Zone-3**	No trip signal	**Trips immediately**
2	**Trips in Zone-3**	No trip signal	**Trips immediately**	No trip signal

Table 3.5: Summary of Co-Simulation Results for Event-5.

Sub Events	Legacy Protection Response		EBP Response	
	70PZ1 (Distance Relay)	70PZ2 (Differential Relay)	70PZ1	70PZ3
1	**Does not trip**	No trip signal	**Trips immediately**	No trip signal
2	No trip signal	**Trips immediately**	No trip signal	**Trips immediately**

It can be noted that the red text indicates a misoperated trip signal, while the green text highlights correct trip operations.

From the tables, it is observed that legacy protection and control misoperated with increasing penetration of IBRs in the IEEE 24 Substation system, whereas estimation-based protection (EBP) operated correctly under the same conditions. The misoperation of legacy protection and control

is because IBRs suppress the negative and zero-sequence components of fault currents, effectively reducing the fault current contribution. Traditional “settings” based relays depend on these fault current characteristics and therefore fail to operate correctly. On the other hand, EBP is immune to this limitation, as it continuously estimates the system states at each time step, making it robust against the reduced fault current contribution of IBRs.

3.8 Summary

This chapter investigated the performance of protection and control (P&C) in the IEEE 24 Substation RTS through a series of simulated events designed to identify conditions that may trigger major disturbances such as common-mode or cascading outages. Fundamental protection concepts and devices are introduced, along with the role of Critical Clearing Time (CCT) in linking fault clearing speed to system security. A key focus was the impact of inverter-based resources (IBRs), which suppress fault current sequence components and caused legacy relays, particularly distance relays, to misoperate. By contrast, estimation-based protection (EBP) operated reliably and was immune to the IBR characteristics.

4. Dynamic security assessment: A Framework for IBR Dominated Power Systems

The objective of this task is to determine the long-term dynamics after the fault(s) have been cleared and whether the post fault dynamics will result in more relay actions such as tripping of an unstable generator. First, dynamic security assessment was conducted in RMS-EMT co-simulation. Second, we use energy function methods for faster DSA as follows: continue the time domain co-simulation of the co-model for a short period after the last fault has been cleared. By experimentation, four cycles are enough to characterize the system conditions after the last relay action was completed. At that time, we switch to an energy function method using the approach described in [9]. Specifically, the manifold of the center of oscillations has been computed from the time domain co-simulation data using estimation methods. The center of oscillations manifold is identified as points in the system for which the frequency varies linearly with time (does not oscillate). Knowledge of the center of oscillations enables the computation of the total energy of each generator, i.e. kinetic and potential energy, as well as the potential barrier of each generator. The kinetic energy of each generator is readily computed. The potential energy requires the manifold of the center of oscillation and the present state of the generator. Once the total energy is computed, a direct comparison to the potential energy barrier determines the stability or instability of the specific generator. The investigation determined that four cycles of co-simulation time is required to accurately extract the Center of Oscillations manifold which is a critical information needed for determining the stability of each generator.

4.1 Security Assessment

Security Assessment in power systems refers to the evaluation of whether the grid can operate securely under both normal and disturbed conditions. It encompasses two primary components: static security assessment, which checks steady-state constraints such as voltage limits, line flows, and power balance, and dynamic security assessment, which ensures that the system remains stable after contingencies such as faults, line outages, or generator trips. Modern security assessment frameworks integrate contingency analysis, state estimation, and real-time simulations to predict system response. The objective is not only to identify insecure operating points but also to determine corrective or preventive actions such as generation rescheduling, topology control, or fast protection schemes that maintain system reliability [34].

As mentioned, Security Assessment is classified into two types: Static Security Assessment and Dynamic Security Assessment. These are discussed below.

4.1.1 Static Security Assessment

Static Security Assessment (SSA) is the process of evaluating the steady-state operating condition of a power system to determine whether it can withstand a set of credible contingencies without violating operational limits. SSA primarily relies on power flow analysis, contingency enumeration, and performance indices such as voltage stability margin, line overload indices, and security margins. Traditional approaches focus on deterministic AC load flow analysis for contingency screening and ranking, but these become computationally intensive for large-scale

systems with high uncertainty. To address this, recent developments have introduced faster and more scalable methods, including sensitivity-based screening, probabilistic SSA, and machine learning approaches that predict post-contingency states with reduced computational burden. Overall, SSA serves as a critical tool for system operators, providing early warning of insecure operating points and guiding preventive control actions to maintain secure operation [35].

4.1.2 Dynamic Security Assessment

Dynamic Security Assessment (DSA) is a real-time or near real-time process that evaluates the ability of a power system to maintain stability after a disturbance by analysing its dynamic behaviour. DSA focuses on transient angular stability, frequency stability, and voltage recovery through time-domain simulation, direct methods such as Single Machine Equivalent (SMIB), and hybrid approaches that combine detailed modelling with reduced-order representations. By continuously monitoring and predicting the system's response to credible contingencies, DSA allows operators to predict instability, take preventive actions, and avoid cascading outages. With the increasing penetration of renewable energy sources and the consequent reduction in system inertia, DSA has become a critical tool for maintaining system reliability and security under uncertain and fast-changing operating conditions [36].

Compared with Static Security Assessment (SSA), DSA provides a more complete and accurate representation of system security. While SSA evaluates steady-state constraints such as voltages, line flows, and power margins, it does not capture the transient electromechanical and electromagnetic dynamics that arise after a fault or switching event. DSA addresses this gap by modelling the time-domain response of the system, thereby enabling the assessment of rotor angle stability, frequency excursions, and voltage recovery. Real-time implementations integrate contingency screening, dynamic simulations, and energy function methods to evaluate stability margins more reliably than SSA. For this reason, DSA is considered indispensable for secure operation of modern grids, particularly under high renewable penetration and reduced inertia conditions [37].

4.2 Stability in Power Systems:

Electric power systems are subject to both planned and unplanned disturbances, including lightning strikes, faults, and accidental outages, which may result in the loss of generating units, tripping of circuits, or load shedding. Such disturbances often cause rotor oscillations in synchronous generators, causing issues in the overall stability of the system. Power systems include both mechanical inertia, associated with rotating masses, and electrical inertia, associated with inductive and capacitive elements, resulting in a range of transient phenomena: electromagnetic (1 μs–10 ms), electrical (0.1 ms–0.5 s), and electromechanical (1 ms–5 s). Due to inherently low system resistance, these oscillations have very low damping, making them more persistent and challenging to mitigate. Stability is fundamentally the system's ability to return to an equilibrium state characterized by synchronous speed and steady power flow following a disturbance, and its accurate assessment is important to both protection and control strategies [38]. Literature has extensively classified stability into transient (rotor angle), small-signal, and voltage stability [39], [40]. Classic works by Kundur [39] and Sauer and Pai [40] highlight the electromechanical interactions and methods of analysis, while Pai [41] discusses a Lyapunov

energy function. J. Shair et al.[42], Muhammad Murad et al.[43] address the impact of inverter-based resources, reduced inertia, and system uncertainty on stability margins, emphasizing the need for probabilistic and data-driven tools. Collectively, these studies demonstrate that while the traditional frameworks remain essential for understanding synchronous machine dynamics, the evolving grid necessitates advanced methods to capture emerging stability challenges.

4.2.1 Types of Stability

As discussed in 4.2 Stability is classified depending on the analysis but can be generally classified into three main categories: 1. Rotor angle stability, 2. Frequency Stability and 3. Voltage Stability. Different literature classify stability as a combination of these three. Some of the most common types of classification include: 1. Transient Stability (Large Signal Stability) and 2. Small Signal Stability.

Transient Stability:

It refers to the ability of the system to maintain synchronism after being subjected to a significant disturbance, such as a fault or a sudden change in load. It is a measure of how well the system can withstand sudden changes without losing the ability of its generators to stay synchronized and avoid widespread outages [38]. It can be noted that transient stability differs from dynamic stability. Dynamic stability is more long term whereas transient stability is more short term focused.

Small Signal Stability:

It refers to the ability of the system to maintain synchronism and return to a stable operating state after it has been exposed to a small disturbance or perturbation.

4.2.2 The Classical Swing Equation

The swing equation forms the fundamental basis for analyzing generator stability and is expressed as the dynamic balance between mechanical input power, electrical output power, and damping effects.

$$\frac{2H}{\omega_s}\frac{d^2\delta(t)}{dt^2} = P_{m,p.u} - P_{e,p.u} - D\frac{d\delta(t)}{dt} \qquad (1)$$

Disturbances in a power system affect two main parameters: 1. Generator terminal voltage and 2. Electrical power transferred by the generator, which in turn influences the rotor dynamics. To study stability, the system is typically examined over three time periods: pre-fault, during the fault, and post-fault conditions. Across these conditions, the critical states of the system include voltage magnitudes, voltage angles (including the rotor angle δ), angular frequencies (ω), and the power delivered by generators. These main parameters can be used to determine whether the system can maintain synchronism following a disturbance [38].

4.2.3 Transient Stability Analysis

As discussed in section 4.2.1, Transient stability refers to the ability of a power system to remain in synchronism after a fault or a sudden change in load. The swing equation plays an important role in assessing this stability, as it describes the dynamic response of the generator rotor. Transient stability analysis therefore involves studying the system's swing equation to determine whether synchronism is preserved after a major disturbance. Since transients are short-lived but rapidly changing phenomena, the analysis must capture these fast dynamics accurately. Methods for conducting transient stability studies are generally divided into two main categories: indirect methods and direct methods [38].

Indirect Methods

There are several indirect methods given in literature. The most common types of indirect methods in power systems are:

Exact Solution:

The exact method analytically solves the differential equations governing rotor motion to assess transient stability. For a simple generator-infinite bus system, the swing equation can be expressed separately during the fault and after the fault is cleared. During the fault, the solution of the swing equation can be obtained in closed form as a quadratic function of time. However, after the fault is cleared, the differential equation involves a nonlinear sine term, leading to solutions in the form of elliptic integrals, which are not easily solvable. Because of this complexity, the exact method is impractical for real-world systems, and numerical approaches are typically used instead to simulate the full transient response [38].

Numerical methods:

Numerical integration methods are widely used in indirect stability analysis of power systems, as the nonlinear nature of the swing equation makes analytical solutions impractical for most real-world problems. These methods approximate the system's dynamic response by solving the swing equation step by step over time, allowing assessment of whether the system returns to equilibrium after a disturbance. Common approaches include the Euler method, modified Euler, trapezoidal integration, Runge-Kutta methods, quadratic integration, and Lobatto collocation methods. Among these, techniques such as trapezoidal and Runge-Kutta are most used due to their accuracy and reliability in transient stability studies [38].

Direct Methods

Direct methods in stability analysis evaluate system stability without simulating the full time-domain trajectory. They are faster and computationally more efficient than indirect methods because they directly estimate stability margins and critical clearing times. This makes them especially useful for large-scale systems where full numerical simulations are time-intensive. The most common types of direct methods are the Equal area Criterion and the Lyapunov's direct method.

Equal Area Criterion

The Equal Area Criterion (EAC) is a classical direct method used for transient stability analysis in power systems. It provides a graphical technique to evaluate whether a synchronous machine will maintain synchronism following a disturbance. According to the criterion, stability is ensured if the accelerating area representing the excess mechanical power during the fault is balanced by the decelerating area representing the excess electrical power after fault clearing on the power-angle curve. If the decelerating area is smaller, the rotor angle will continue to diverge, resulting in loss of synchronism. The EAC is particularly applicable to single-machine infinite-bus (SMIB) systems and offers an effective way to estimate critical clearing time and stability margins with relatively simple analysis [39].

An application of the EAC called the Extended EAC has been used in literature in multi-machine systems but the most common type of direct method in literature for a multi-machine system is the Lyapunov method also called the energy function method.

Lyapunov's direct method (Energy Function)

The Lyapunov energy method is a direct approach to power system stability assessment that relies on constructing a suitable Lyapunov (energy) function to characterize system dynamics. By Lyapunov's theorems, if a continuously differentiable positive-definite function can be found such that its time derivative along system trajectories is negative-definite, the equilibrium point is asymptotically stable. In power systems, the chosen function typically represents the total system energy, including kinetic and potential terms, and its derivative corresponds to the system's energy dissipation. This formulation avoids explicit time-domain simulations by estimating the region of attraction, which defines the set of initial conditions from which the system converges back to synchronism. Although constructing appropriate energy functions for large multi-machine systems is challenging, advances such as extended equal-area criteria, vector Lyapunov functions, and convex optimization approaches have broadened its applicability. The Lyapunov energy method thus provides an efficient alternative to numerical integration, enabling direct estimation of stability margins and critical clearing times [44]-[46].

A generalized Lyapunov energy function can be written as:

$$V(\omega,\delta)=\frac{1}{2}M\omega^2-\int_{\delta_s}^{\delta}P_{m,post-fault}-P_{e,post-fault}\sin\delta_x d\delta_x \qquad (2)$$

where,

$$M=\frac{2H}{\omega_s};\ H=\frac{\frac{1}{2}J\omega_s^{\,2}}{S_{base}}$$

4.2.4 Stability analysis of a multi-machine network

Stability analysis of a multi-machine power system is considerably more complex than that of a single-machine infinite bus (SMIB) system, due to the nonlinear and highly coupled interactions among multiple synchronous machines. Each generator is described by its own swing equation,

and the resulting system of differential-algebraic equations becomes high-dimensional and computationally intensive. Applying indirect methods requires solving these equations numerically for all machines, which is often impractical for large-scale systems, while direct methods based on Lyapunov energy functions face challenges in constructing valid energy functions that accurately capture the dynamics of all machines. As a result, it is common practice to reduce the system to an equivalent model in order to simplify the stability analysis while preserving essential dynamic characteristics [39].

4.3 The Two Generator Problem:

A two Bus-Generator system is utilized for the analysis of post-fault dynamic behaviour. It can be noted that any multi-machine network can be inherently reduced into an equivalent two Generator problem and as such this model forms the framework for analysing post-fault dynamic behaviour in multi-machine systems.

This model is high-fidelity and built as a physics-based representation that includes all physical

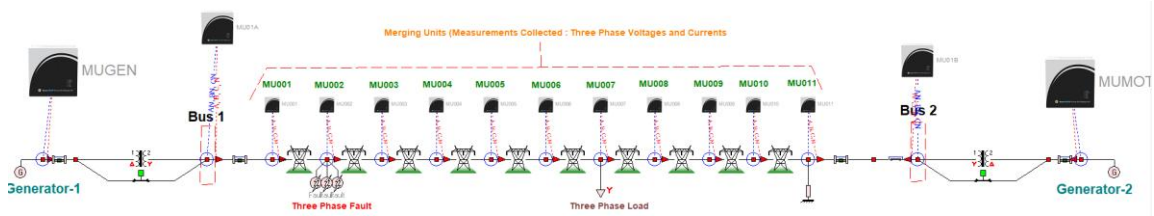


Figure 4.1 Two Bus-Generator System Network.

and electrical details such as phases, neutrals, ground wires, and grounding arrangements. As shown in Figure 4.1, the system consists of two generators, each connected to a step-up/down transformer. The low-voltage side of each transformer is connected to the generator, while the high-voltage side is connected to the 230 kV transmission line that connects the two buses. Additionally, a three-phase load is connected at 70% of the transmission line length. All relevant device parameters are normalized using a 450 MVA base and are summarized in Table 4.1.

Table 4.1 Two-Generator System Parameters

Name of the Device	S (MVA)	V (kV)	Z (p.u)	H (sec)
Generator-1	450	15	j0.2	2.5
Generator-2	150	18	j0.2	3.0
Transformer-1	450	15:230	j0.075	-
Transformer-2	150	18:230	j0.08	-
Three Phase Load	-	230	0.2389+j0.23	-
Transmission Line (Line Length = 50 miles)	-	230	j35 ohms	-
Initial conditions				

All the parameters will be expressed in pu on 450 MVA and the local rated voltage.

Table 4.2 Two-Generator System Initial Conditions

Name of the device	Total Power	Terminal Voltage (Vt)
Generator-1	0.53+0.j p.u.	$1\angle 0^{\circ}$ p.u

The system is further modelled in detail using a set of differential-algebraic equations (DAEs), which are solved using the trapezoidal numerical integration method. This approach enables us to explicitly track all state variables of the system such as voltage magnitudes, phase angles, angular frequencies, and reactive powers throughout the different periods of simulation i.e. pre-fault, during fault and post-fault.

A three-phase fault is introduced 5 miles from Generator-1, starting at 0.5 seconds and clearing at 0.75 seconds. The model solves for 45 states in total during pre-fault, 83 states during and post-fault: 13/15 voltage magnitudes, 15 voltage angles, 15 angular frequencies across the network, and 2 reactive power variables (one for each generator). The governing equations include swing equations for the generators, nodal voltage balance equations split into real and imaginary components, and angular velocity equations. Each equation is integrated over time using the trapezoidal method with a time step of 208.3333 μs which corresponds to a sampling frequency of 4800 Hz.

This modelling technique is different from the simplified textbook models such as the Single Machine Infinite Bus (SMIB) system. In the SMIB configuration, a single generator is connected to an infinite bus whose voltage and angle are assumed constant (typically taken as $V_{\infty}\angle 0°$), and the generator's rotor angle δ and angular frequency ω are observed across pre-fault, fault, and post-fault intervals. While it is useful to perform basic stability analysis, the SMIB system fails to capture the mutual dynamic interactions between multiple generators present in real-world networks. Therefore, the two-generator system is a more practical model. This allows the study of self-dynamics of each generator in addition to the cross-coupled effects of their interactions via the shared transmission line.

The solution has steady-state values as initial conditions and a dynamic phasor-based simulation is performed under fault conditions. The equations are discretized using trapezoidal integration, and each nonlinear term (e.g., involving sine and cosine of angles) is treated either directly or through the addition of auxiliary variables. At every time step, the DAEs are solved as a linearized system $A(t-h)\cdot x(t) = b(t-h)$, where $x(t)$ is the vector of unknown states, and the matrix A and vector b are assembled based on previous step values.

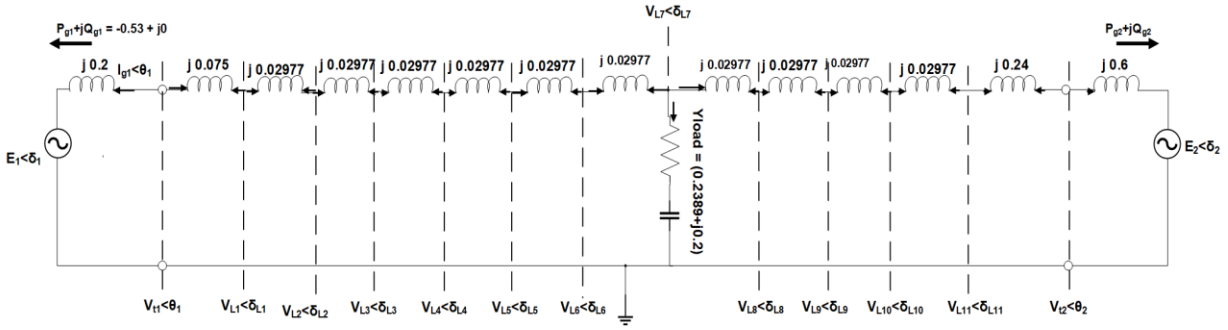


Figure 4.2 Pre-Fault Network Model.

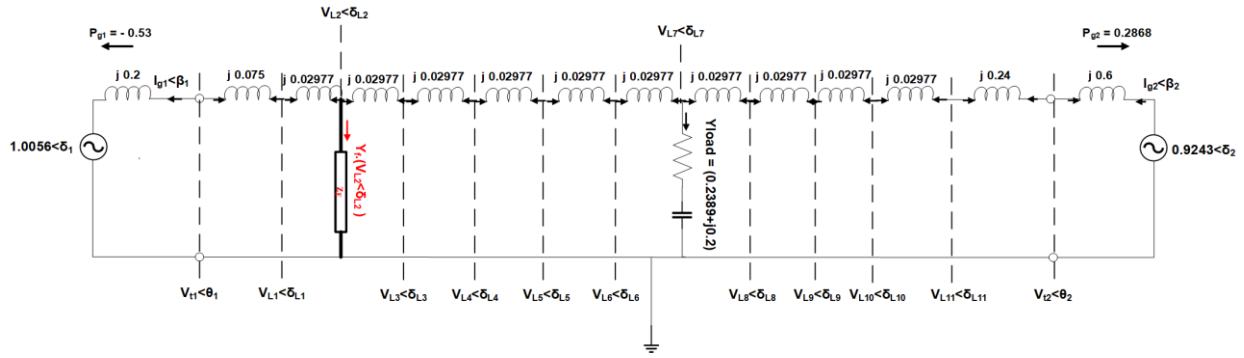


Figure 4.3 Fault Network Model.

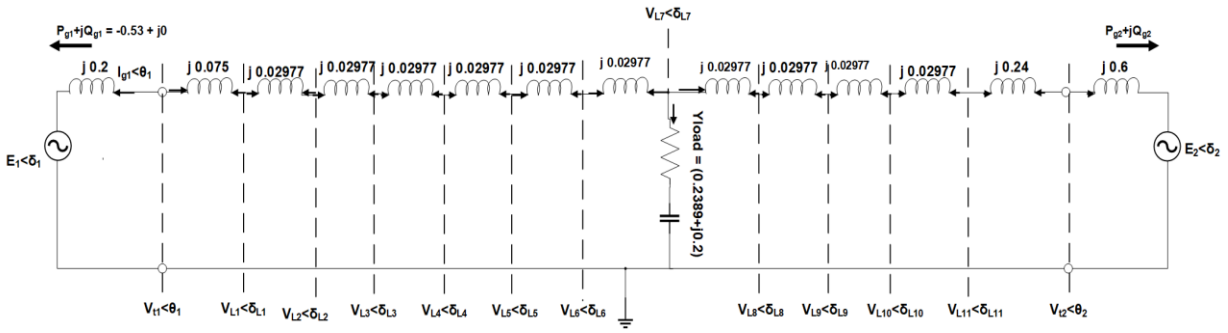


Figure 4.4 Post-Fault Network Model.

This type of analysis determines the location of the Center of Oscillations. The model also shows that the frequency along a circuit has a linear distribution. This means that if the frequency at the two ends of a circuit have been computed, the frequency at any point along the circuit can be computed via a simply linear interpolation. This simplifies the analysis tremendously. Specifically, one needs to compute the frequency at each bus of the system. The frequency along a circuit will be derived from a linear interpolation using only the frequencies at the terminal busses of the circuit.

There are several methods to determine the stability of the system post-fault. We utilize a direct method more specifically the Lyapunov's direct method (energy function method) to determine

the stability of the system. To summarize the method, a Lyapunov function is chosen which will help determine the region of stability for the system. In power systems an energy-based function is used, more specifically the Lyapunov function is the total energy of the system which is the sum of the kinetic energy and the potential energy. DSE is used to monitor the states of the system and as such the kinetic energy of the system (generator specifically) can be computed easily. However, computing the total potential energy of the system is complex.

E. Farantatos et al.[9] describe a technique to compute the potential energy of the system by computing the center of oscillations (CoO) . The center of oscillation is defined as the point on the transmission line where the rate of change of frequency is "constant".

Once the transient behavior of voltages, frequencies, and angles is captured, we apply the CoO-based energy assessment framework to evaluate the post-fault stability of the system. The concept of the Center of Oscillation (CoO) plays a crucial role in simplifying the energy computation. The CoO is defined as the point on the transmission line where the rate of change of frequency is constant ($\frac{df}{dt} - c = 0$). While this is an idealization, in practice, it allows us to model the frequency profile across the line as a linear function:

$$f_{coo} = m.t + c.$$

Furthermore, since we measure frequencies at both ends of the transmission line, we can express f_{coo} using a convex combination:

$$f_{coo} = a_1 f_{1t} + a_2 f_{2t},$$

where f_1 and f_2 are the terminal frequencies and a is a weight between 0 and 1. We formulate an optimization problem that minimizes the mismatch between the linear model and the convex combination, yielding the parameters a, m, and c. The CoO's physical location is then determined as $(1-a)\cdot L$, where L is the total line length.

Using the CoO, we create a mirrored equivalent system where Generator-1 is treated as the generator of interest, and the rest of the system is reflected across the CoO. This concept reduces the two-generator system to an effective SMIB-like configuration, enabling us to compute potential energy. When combined with the kinetic energy obtained from angular frequency deviations, we compute the total energy of the generator. This energy is then compared against the maximum potential energy barrier (separatrix) to assess stability. If the total energy remains below the barrier, the system is considered stable. If it exceeds the threshold, the system is deemed unstable.

This CoO-based energy assessment is particularly insightful in interpreting which generator dominates system dynamics. A CoO closer to Generator-1 implies that Generator-1 contributes more to oscillations, and vice versa. Moreover, in cases where inverters or other power-electronic interfaces are present, the CoO may shift outside the traditional line segment, indicating non-traditional behaviour that warrants further study. Our framework provides a consistent methodology to analyse this behaviour.

4.4 Summary

This chapter discusses the concept of security assessment and its role in evaluating system performance after faults. Stability fundamentals are reviewed and methods such as indirect time-domain simulation and direct approaches such as the Equal Area Criterion and Lyapunov's energy method are also studied. A detailed two-generator model is developed in this chapter to explain post-fault dynamics, where RMS-EMT co-simulation captured system responses. Lyapunov's energy function, combined with the Center of Oscillation framework, is applied to determine stability properties. This framework establishes a physics-based method for assessing stability with an efficient and highly accurate method.

5. Conclusions

An investigation of the dynamic security of power systems with high penetration of inverter-based resources (IBRs) and complex protection and control systems by focusing on modelling, protection, and stability assessment. The work was structured across four main chapters, each addressing a specific aspect of the study.

Chapter 1 introduced the problem statement and highlighted real-world disturbances in systems with significant IBR penetration, emphasizing the importance of integrating protection and control (P&C) systems into dynamic security assessment. A co-model framework was proposed that incorporates both the physical power system and the associated P&C devices, enabling co-simulation in RMS and EMT domains. The need to probabilistically account for P&C failures, including breaker failures, hidden failures, and cyber-attacks, was also established as a critical component of the framework.

Chapter 2 presented the IEEE 24-Substation RTS system and reviewed prior work on modelling IBRs for transient analysis. A balance between high-fidelity models and computational efficiency was discussed, and a co-modelling approach was adopted to allow sufficient accuracy while maintaining tractability for dynamic studies. This system formed the testbed for the subsequent analysis of P&C performance.

Chapter 3 investigated the response of legacy and estimation-based protection under a series of simulated fault events in the IEEE 24-Substation RTS. The role of Critical Clearing Time (CCT) was emphasized in linking protection operation to system stability. Results demonstrated that legacy distance relays misoperated in IBR-dominated scenarios due to suppression of negative and zero sequence currents, while estimation-based protection (EBP) operated correctly and provided a setting-less alternative robust to IBR characteristics.

Chapter 4 established the framework for dynamic security assessment (DSA). The chapter first introduced stability fundamentals, including rotor angle, frequency, and voltage stability, and reviewed classical indirect and direct stability methods such as numerical integration, the Equal Area Criterion, and Lyapunov's energy function. A detailed two-generator model was then developed to analyse post-fault dynamics, with RMS-EMT co-simulation providing time-domain trajectories and a CoO-based Lyapunov framework enabling efficient computation of stability margins and CCT. Finally, this framework could be extrapolated to a modified two generator problem where the synchronous generators are replaced by IBRs specifically Grid Forming Inverters, where the interaction of the GFMs and the post-fault dynamics of a GFM dominated network can be studied.

Overall, this report presented a comprehensive study of IBR-dominated power systems, from modelling and protection failures to advanced stability analysis methods. The results underscore the need to move beyond legacy protection schemes and classical stability tools, adopting high-fidelity co-models, estimation-based protection, and energy-function-based stability frameworks to ensure secure operation of future grids.

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Appendix A: IEEE 24 Substation RTS co-model

This Appendix presents detailed information of the IEEE 24 Substation RTS co-model, i.e. the combined power system model with the protection and control model.

The overall co-model of the 24-substation reliability test system is presented in Chapter 2. In this appendix, we present detailed co-models of all the substations of the system.

A-1. Substation-10 System Description

This section of the document describes the Substation-10 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 1.1 shows the single line diagram of the system network model of Substation-10. There are two 138 kV transmission lines and one 138 kV overhead line/cable. These devices connect Substation-10 with other substations including Substation 30 (transmission line B10-30 to B30-10), Substation 50 (transmission line B10-50 to B50-10), and Substation 20 (overhead cable/line B10-20 to B20-10) respectively as can be seen in the figure.

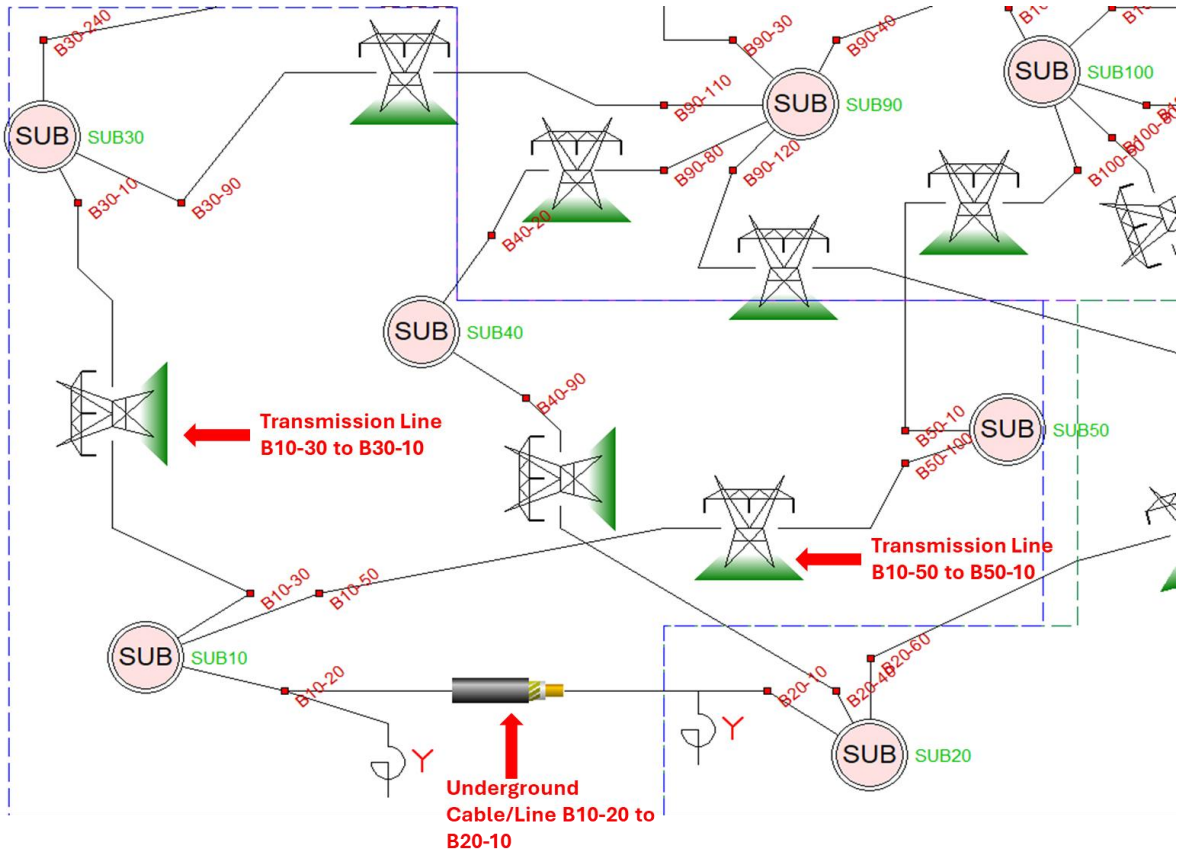


Figure A1.0.1 Single line diagram of system network connected to Substation-10.

The single line diagram of Substation-10 is shown in Figure 1.2. Substation-10 is a 138 kV substation. It has a breaker and a half arrangement. This substation consists of three 138 kV lines

connecting Substation 10 to Substations 30, 20 and 50, four generator/inverter – step-up transformer units, one step-down transformer unit and two substation buses. The substation model is represented with twenty-one (21) three-phase nodes, nineteen (19) circuit breakers, and twenty-eight (28) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-10 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

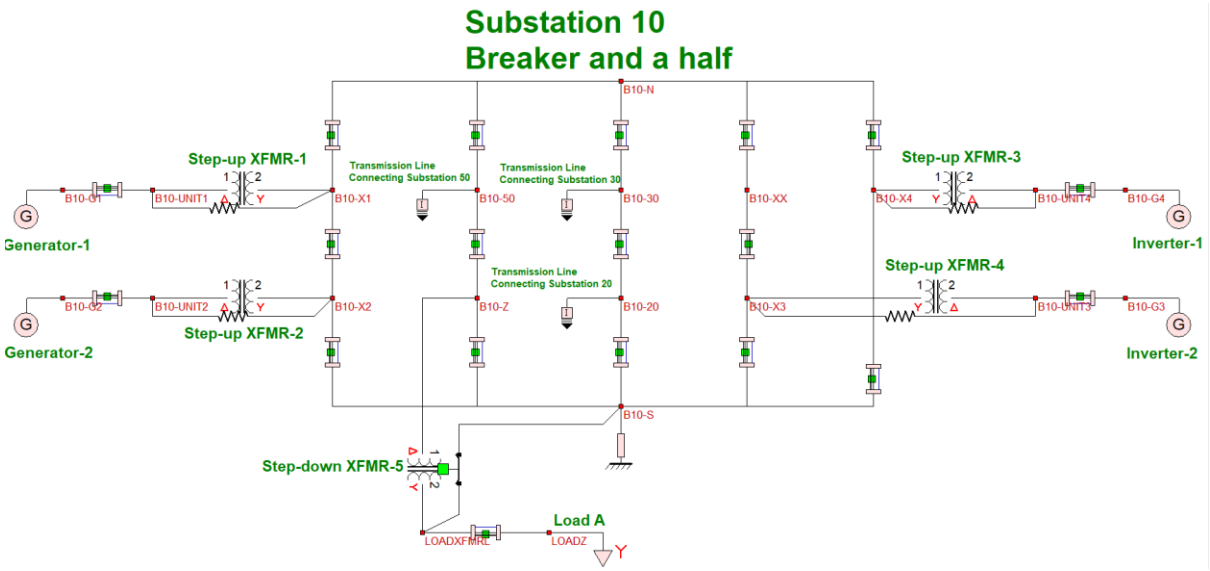


Figure A1.2 Substation-10: Breaker and a Half Configuration, Single Line Diagram

Protection and Control of Substation 10
Description of Substation 10

The substation-10 has a breaker and a half configuration. Figure 1.4 shows the co-model of Substation-10 (power system + protection and control). The protection zones defined in Substation-10 can be seen in the figure. Substation 10 has eleven protection zones: (a) four generator/inverter-XFMR unit protection zones, (b) two Bus protection zones, (c) three transmission line protection zones, (d) one transformer protection zone and (e) load protection zone. There are thirty-five MUs in Substation-10. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

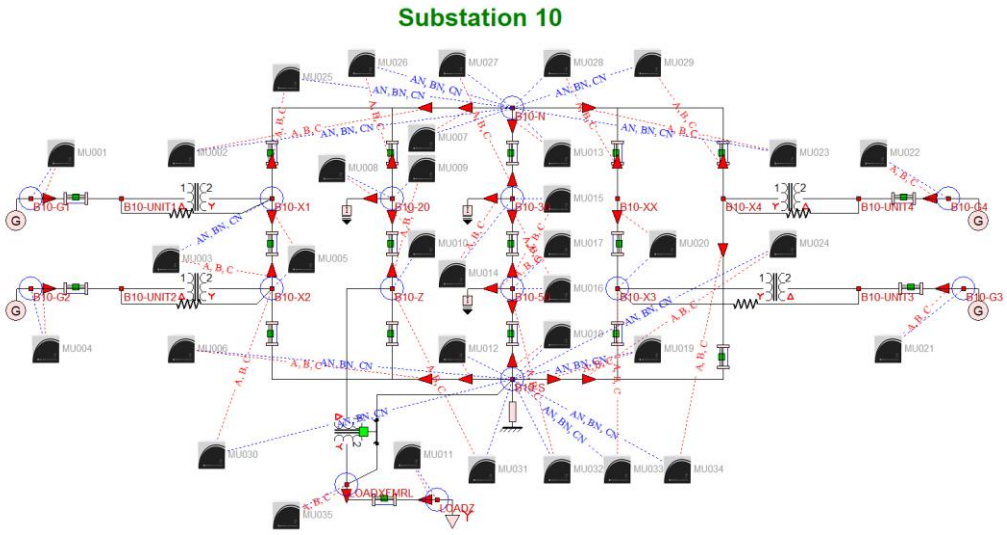


Figure A1.3 Substation 10: Merging Units Location

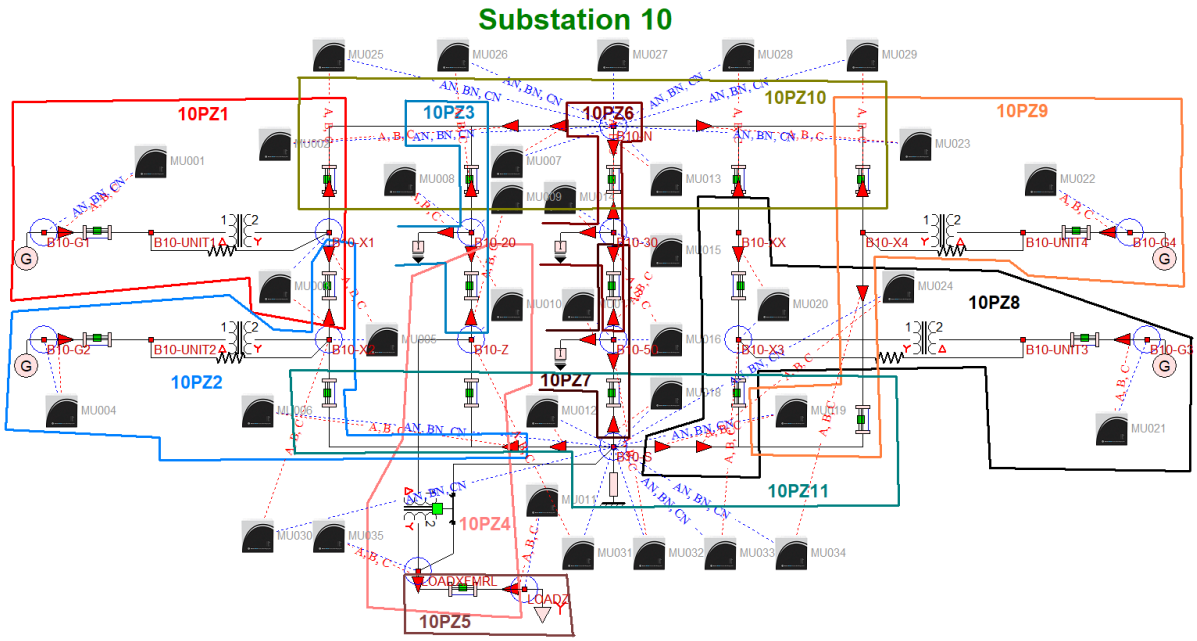


Figure A1.4 Co-model of Substation 10: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The eleven protection zones are briefly described below.

1. 10PZ1 protects the generator-XFMR at B10-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

2. 10PZ2 protects the generator-XFMR at B10-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 10PZ3 protects the overhead line B10-20 to B20-10, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 10PZ4 protects the transformer LOADXFMRL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 10PZ5 protects the Load connected at node LOADZ, it has one three phase wye connected load, one circuit breaker with two sets of three phase current and voltage transformers (CTs/PTs) and two merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 10PZ6 protects the transmission line B10-30 to B30-10, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 10PZ7 protects the transmission line B10-50 to B50-10, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
8. 10PZ8 protects the inverter-XFMR at B10-G3, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
9. 10PZ9 protects the inverter-XFMR at B10-G4, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
10. 10PZ10 protects the North side Bus B10-N, it has one bus, five circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and nine merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
11. 10PZ11 protects the South side Bus B10-S, it has one bus, five circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and ten merging units

measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 10PZ1

This protection zone consists of:

1. A three phase generator that has a 13.8kV, 100 MVA rating. A step-up XFMR with a setting of 13.8:138kV, 100 MVA. The 138kV is Wye connected and the 13.8kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B10-G1 to B10-UNIT1) and has a rating of 13.8kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B10-N to B10-X1; B10-X2 to B10-X1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B10-N to B10-X1 and B10-X2 to B10-X1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B10-G1 to B10-UNIT1).

Note: As an example, B10-G1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using five merging units namely MU001, MU002, MU003, MU005 and MU025 respectively. Measurements are collected from six sets of

instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 10PZ2

This protection zone consists of:

1. A three phase generator that has a 13.8kV, 100 MVA rating. A step-up XFMR with a setting of 13.8:138kV, 100 MVA. The 138kV is Wye connected and the 13.8kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B10-G2 to B10-UNIT2) and has a rating of 13.8kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B10-S to B10-X2; B10-X2 to B10-X1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B10-S to B10-X2; B10-X2 to B10-X1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B10-G2 to B10-UNIT2).

Note: As an example, B10-G2 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 2 are collected using five merging units namely MU003, MU004, MU005, MU006 and MU030 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 10PZ3
This protection zone consists of:

1. The overhead cable/line that is connected between nodes B10-20 to B20-10, the cable is a 138 kV line that is 5000 ft long. The line is modelled as follows:

1. The phase conductors of the line are of the type ABB and size ABB-138KV-1000CMPCU with an kcmil of 1974 kcm.
2. The ground impedance is given as: R =50 ohms and X_c or X_L = 0 ohms.
3. The soil resistivity is 150 ohms-meter.
4. The span length is 5000 ft.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 10 and 20 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B10-N to B10-20 and B10-Z to B10-20 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B10-N to B10-20 and B10-Z to B10-20). One unit collects the voltage and current measurements from the CTs and PTs, at the node B10-20.

For EBP:
An EBP relay monitors the line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.

5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU007, MU008, MU009, MU010, and MU026 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 10PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 45 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (LOADZ to LOADXFMRL) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B10-20 to B10-Z; B10-S to B10-Z) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B10-20 to B10-Z; B10-S to B10-Z). two units collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (LOADZ to LOADXFMRL).

Note: As an example, LOADZ is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.

5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU009, MU010, MU011, MU012, MU031 and MU035 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 10PZ5
This protection zone consists of:

1. A three phase load that has a 34.5kV, 40 MVA rating.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There is one circuit breaker in total. One circuit breaker is connected to the wye terminal of the transformer (LOADZ to LOADXFMRL) and has a rating of 34.5kV and a 10kA interrupt capability. The circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units.

3. There are two Merging Units collecting measurements within the protection zone, two units collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker LOADZ to LOADXFMRL.

Note: As an example, LOADZ is a node.

For EBP:
An EBP relay monitors the load protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using two merging units namely MU011, and MU035 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements

for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 6 – 10PZ6
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B10-30 to B30-10, the transmission line is a 138 kV line that is 55 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 10 and 30 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B10-N to B10-30 and B10-50 to B10-30 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B10-N to B10-30 and B10-50 to B10-30). One unit collects the voltage and current measurements from the CTs and PTs, at the node B10-30.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.

5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU013, MU014, MU015, MU016, and MU027 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 10PZ7
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B10-50 to B50-10, the transmission line is a 138 kV line that is 22 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 10 and 50 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B10-50 to B10-30 and B10-50 to B10-S respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B10-50 to B10-30 and B10-50 to B10-S). One unit collects the voltage and current measurements from the CTs and PTs, at the node B10-50.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:

A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 7 are collected using five merging units namely MU015, MU016, MU017, MU018, and MU032 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 8 – 10PZ8

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:138kV, 100 MVA. The 138kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B10-G3 to B10-UNIT3) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B10-S to B10-X3; B10-X3 to B10-XX) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Four Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B10-S to B10-X3), one unit collecting the voltage and current measurements from the CTs and PTs, at the node B10XX of the circuit breaker B10-X3 to B10-XX connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B10-G3 to B10-UNIT3).

Note: As an example, B10-G3 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 8 are collected using four merging units namely MU020, MU021, MU024 and MU033 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 9 – 10PZ9

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:138kV, 100 MVA. The 138kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B10-G4 to B10-UNIT4) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B10-N to B10-X4; B10-S to B10-X4) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B10-N to B10-X4; B10-S to B10-X4). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B10-G4 to B10-UNIT4).

Note: As an example, B10-G4 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 9 are collected using five merging units namely MU022, MU023, MU024, MU029 and MU034 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 10 – 10PZ10

This protection zone consists of:

1. Five Circuit Breakers forms the substation north bus B10-N, namely B10-X1 to B10-N, B10-20 to B10-N, B10-30 to B10-N, B10-XX to B10-N, B10-X4 to B10-N. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Nine Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B10-X1 to B10-N, B10-20 to B10-N, B10-30 to B10-N, B10-XX to B10-N and B10-X4 to B10-N.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 10 are collected using nine merging units namely MU002, MU007, MU013, MU023, MU025, MU026, MU027, MU028 and MU029 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 11 – 10PZ11

This protection zone consists of:

1. Five Circuit Breakers forms the substation north bus B10-S, namely B10-X2 to B10-S, B10-Z to B10-S, B10-50 to B10-S, B10-X3 to B10-S, B10-X4 to B10-S. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Ten Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B10-X2 to B10-S, B10-Z to B10-S, B10-50 to B10-S, B10-X3 to B10-S, B10-X4 to B10-S.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 11 are collected using ten merging units namely MU006, MU012, MU018, MU019, MU024, MU030, MU031, MU032, MU033 and MU034 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-2. Substation-30 System Description

This section of the document describes the Substation-30 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 2.1 shows the single line diagram of the system network model of Substation-30. There are three 138 kV transmission lines. These devices connect Substation-30 with other substations including Substation 10 (transmission line B30-10 to B10-30), Substation 240 (transmission line B30240 to B24030), and Substation 90 (transmission line B30-90 to B90-30) respectively as can be seen in the figure.

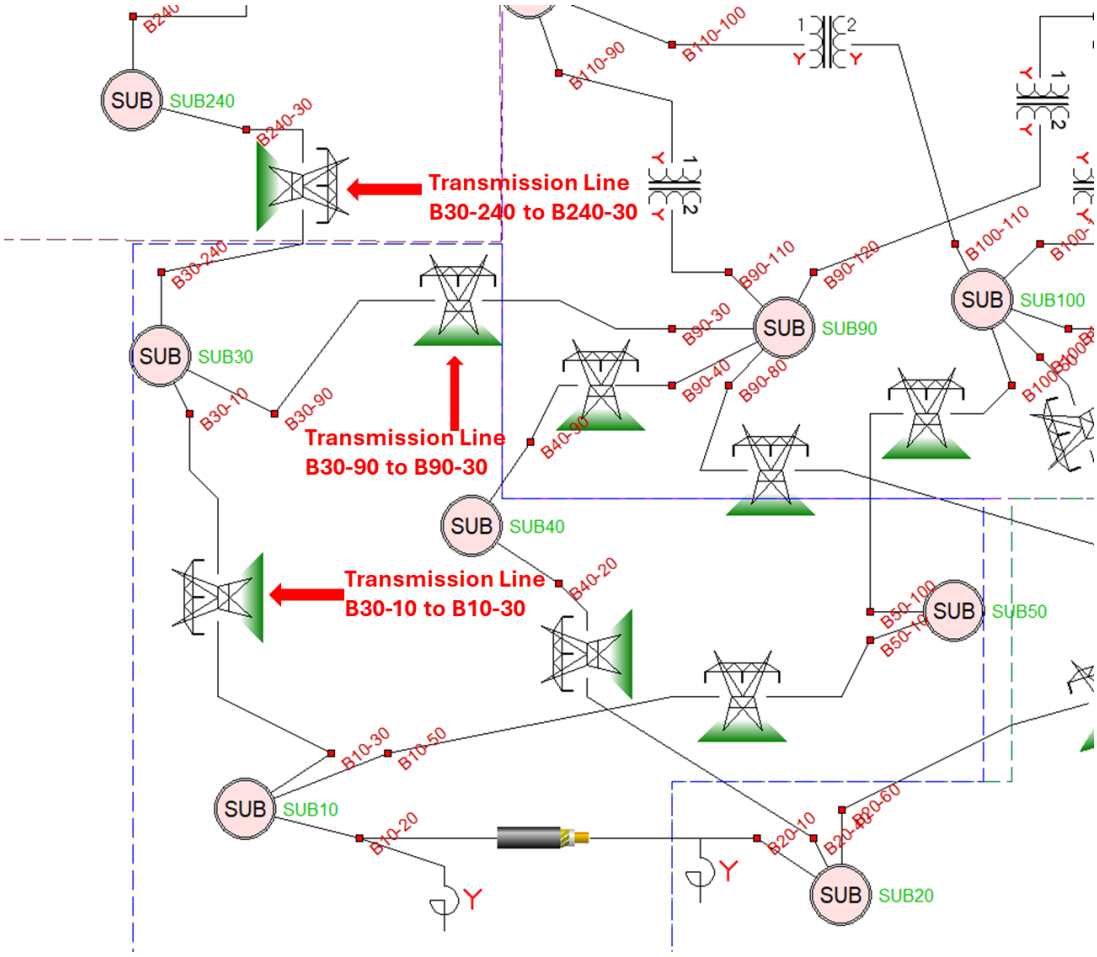


Figure A2.1 Single line diagram of system network connected to Substation-30.

The single line diagram of Substation-30 is shown in Figure 2.2. Substation-30 is a 138 kV substation. It has a ring bus arrangement. This substation consists of three 138 kV lines connecting Substation 30 to Substations 10, 90 and 240, one step-down transformer unit and multiple substation buses. The substation model is represented with eighteen (18) three-phase nodes, five (5) circuit breakers, and ten (10) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-30 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

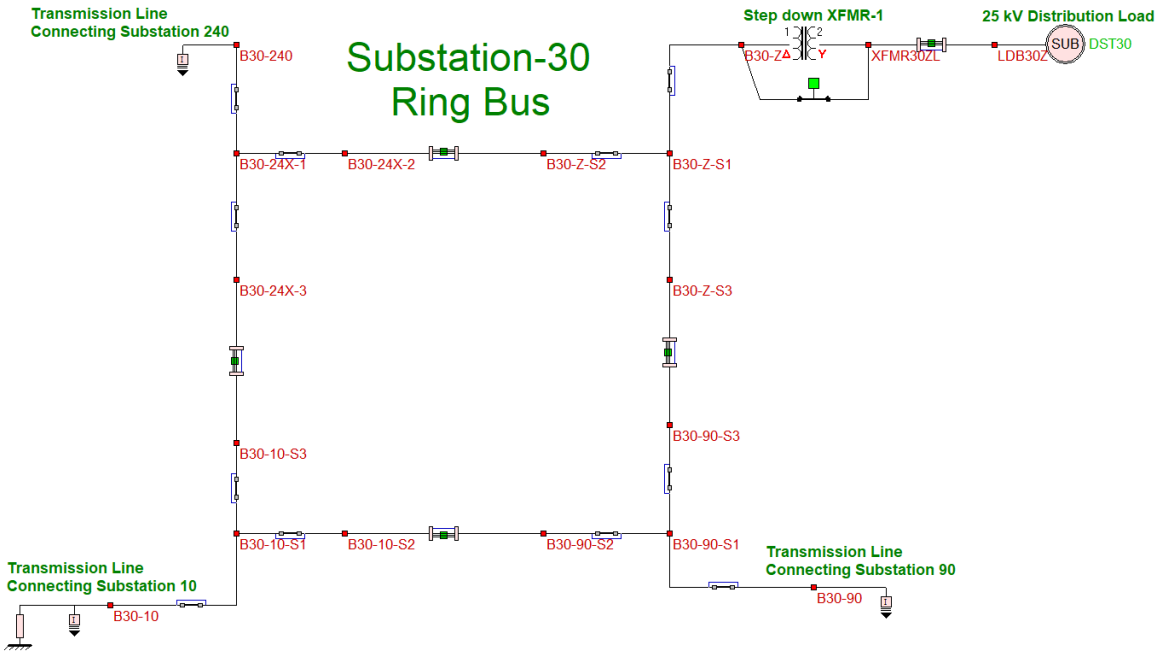


Figure A2.2 Substation-30: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 30
Description of Substation 30

The substation-30 has a ring bus configuration. Figure 2.3 shows the co-model of Substation-30 (power system + protection and control). The protection zones defined in Substation-30 can be seen in the figure. Substation 30 has four protection zones: (a) three transmission line protection zones, (b) one transformer protection zone. There are thirteen MUs in Substation-30. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

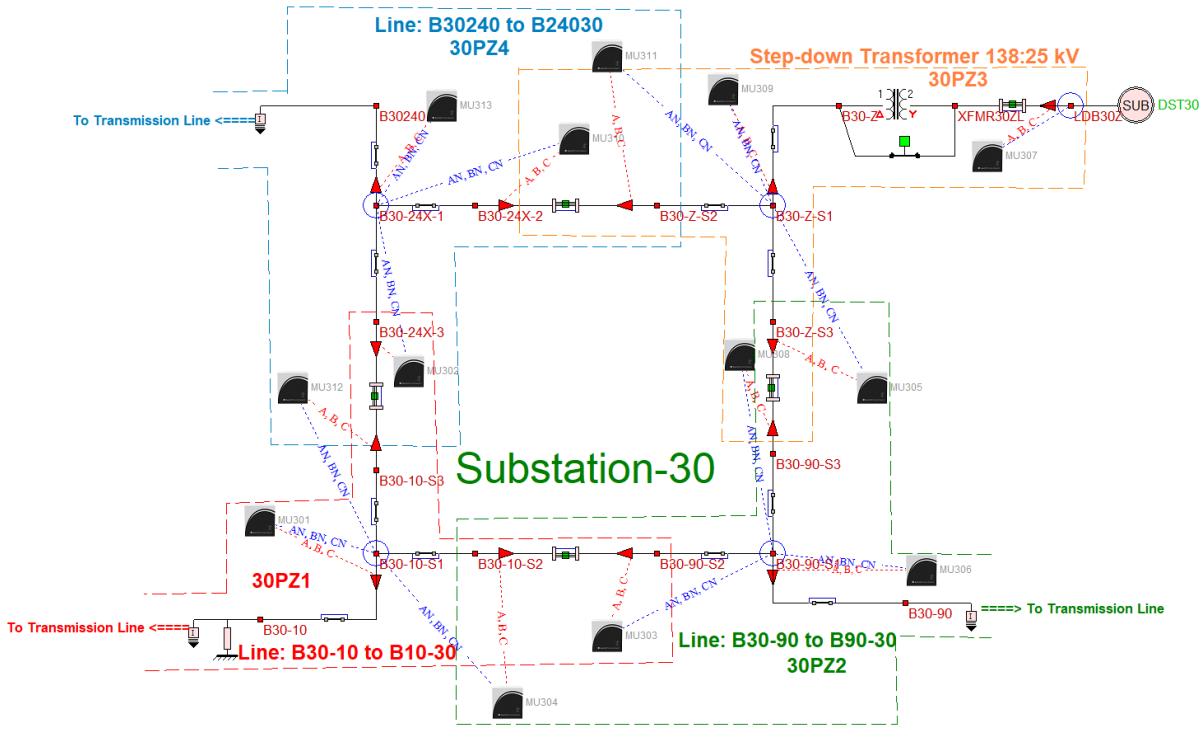


Figure A2.3 Co-model of Substation-30: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The four protection zones are briefly described below.

1. 30PZ1 protects the transmission line B30-10 to B10-30, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 30PZ2 protects the transmission line B30-90 to B90-30, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 30PZ3 protects the step-down transformer XFMR30ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 30PZ4 protects the transmission line B30240 to B24030, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 30PZ1
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B30-10 to B10-30, the transmission line is a 138 kV line that is 55 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 10 and 30 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B30-24-X3 to B30-10-S3 and B30-10-S2 to B30-90-S2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B30-24-X3 to B30-10-S3 and B30-10-S2 to B30-90-S2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B30-10-S1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU301, MU302, MU303, MU304, and MU312 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 30PZ2
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B30-90 to B90-30, the transmission line is a 138 kV line that is 30.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 30 and 90 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B30-Z-S3 to B30-90-S3 and B30-10-S2 to B30-90-S2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B30-Z-S3 to B30-90-S3 and B30-10-S2 to B30-90-S2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B30-90-S1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.

2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU303, MU304, MU305, MU306, and MU308 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 30PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 75 MVA rating. It is a step-down XFMR with a setting of 138:25 kV. The 25kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (LDB30Z to XFMR30ZL) and has a rating of 25kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B30-24X-2 to B30-Z-S2; B30-Z-S3 to B30-90-S3) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B30-24X-2 to B30-Z-S2; B30-Z-S3 to B30-90-S3). One unit collecting the voltage and current measurements at node B30-Z-S1 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (LDB30Z to XFMR30ZL).

Note: As an example, LDB30Z is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU305, MU307, MU308, MU309, MU310 and MU311 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 30PZ4
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B30240 to B24030, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 30 and 240 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B30-24X-2 to B30-Z-S2 and B30-24-X3 to B30-10-S3 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B30-24X-2 to B30-Z-S2 and B30-24-X3 to B30-10-S3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B30-24-X1.

For EBP: An EBP relay monitors the transmission line protection zone.

For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU302, MU310, MU311, MU312, and MU313 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-3. Substation-40 System Description

This section of the document describes the Substation-40 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 3.1 shows the single line diagram of the system network model of Substation-40. There are two 138 kV transmission lines. These devices connect Substation-40 with other substations including Substation 20 (transmission line B40-20 to B20-40) and Substation 90 (transmission line B40-90 to B90-40) respectively as can be seen in the figure.

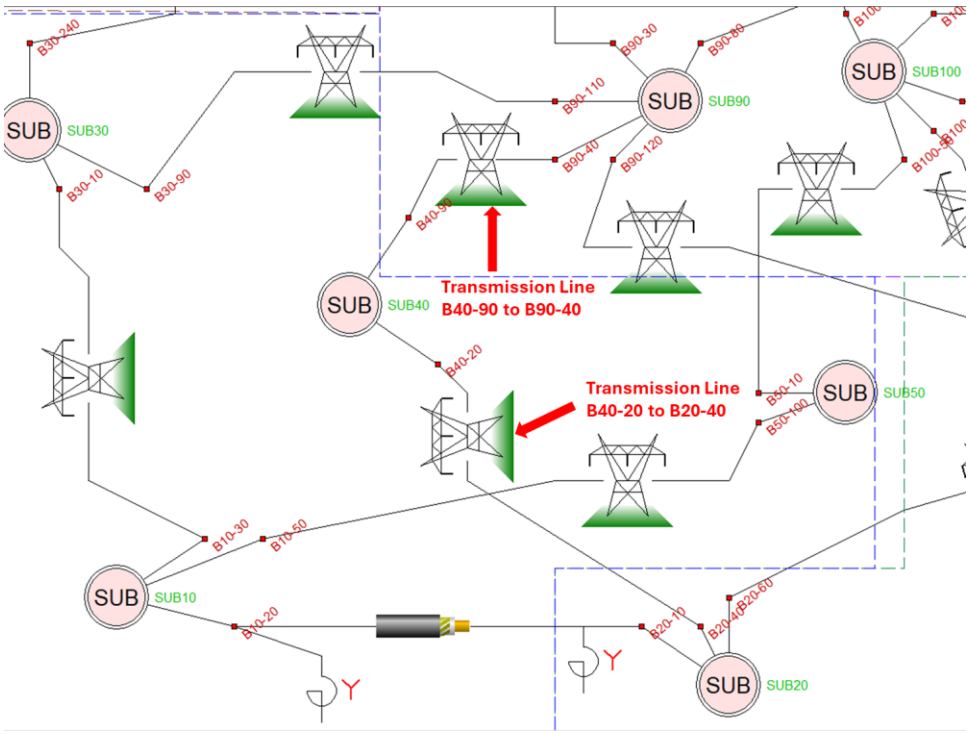


Figure A3.1 Single line diagram of system network connected to Substation-40.

The single line diagram of Substation-40 is shown in Figure 3.2. Substation-40 is a 138 kV substation. It has a ring bus arrangement. This substation consists of two 138 kV lines connecting Substation 40 to Substations 20 and 90, one step-down transformer unit and multiple substation buses. The substation model is represented with sixteen (16) three-phase nodes, four (4) circuit breakers, and eleven (11) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-40 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

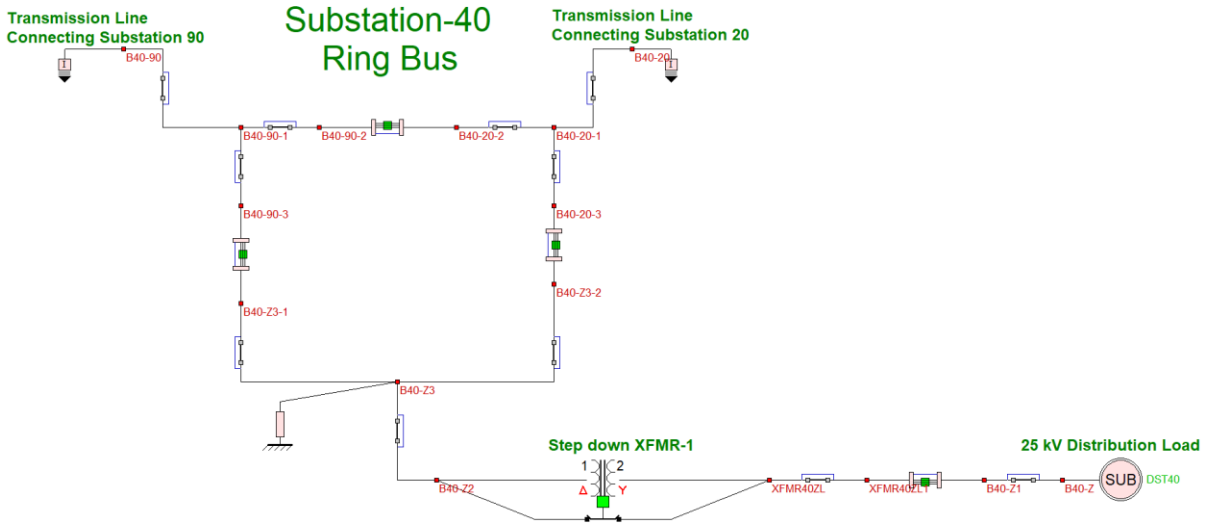


Figure A3.2 Substation-40: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 40
Description of Substation 40

The substation-40 has a ring bus configuration. Figure 3.3 shows the co-model of Substation-40 (power system + protection and control). The protection zones defined in Substation-40 can be seen in the figure. Substation 40 has three protection zones: (a) two transmission line protection zones, (b) one transformer protection zone. There are ten MUs in Substation-40. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

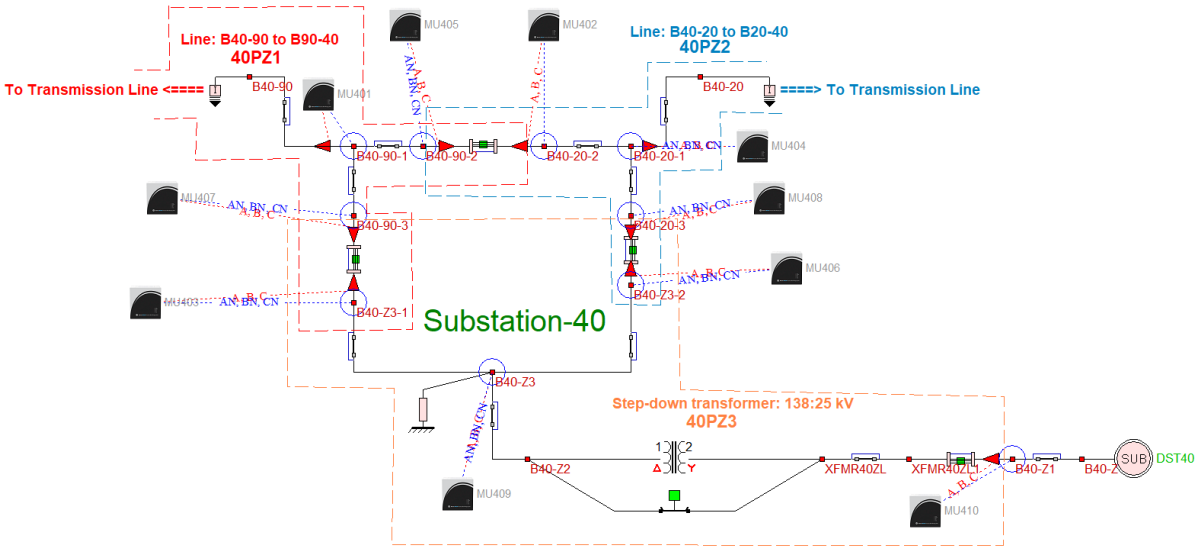


Figure A3.3 Co-model of Substation-40: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The three protection zones are briefly described below.

1. 40PZ1 protects the transmission line B40-90 to B90-40, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 40PZ2 protects the transmission line B40-20 to B20-40, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 40PZ3 protects the step-down transformer XFMR40ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 40PZ1
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B40-90 to B90-40, the transmission line is a 138 kV line that is 26.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 40 and 90 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B40-90-2 to B40-20-2 and B40-90-3 to B40-Z3-1 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B40-90-2 to B40-20-2 and B40-90-3 to B40-Z3-1). One unit collects the voltage and current measurements from the CTs and PTs, at the node B40-90-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU401, MU402, MU403, MU405, and MU407 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 40PZ2

This protection zone consists of:

1. The transmission line that is connected between buses B40-20 to B20-40, the transmission line is a 138 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 40 and 20 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from B40-90-2 to B40-20-2 and B40-20-3 to B40-Z3-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B40-90-2 to B40-20-2 and B40-20-3 to B40-Z3-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B40-20-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU402, MU404, MU405, MU406, and MU408 respectively. Measurements are collected from six sets of

instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 40PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 75 MVA rating. It is a step-down XFMR with a setting of 138:25 kV. The 25kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (B40-Z1 to XFMR40ZL1) and has a rating of 25kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B40-20-3 to B40-Z3-2; B40-90-3 to B40-Z3-1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B40-20-3 to B40-Z3-2; B40-90-3 to B40-Z3-1). One unit collecting the voltage and current measurements at node B40-Z3 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B40-Z1 to XFMR40ZL1).

Note: As an example, B40-Z1 is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU403, MU406, MU407, MU408, MU409 and MU410 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-4. Substation-50 System Description

This section of the document describes the Substation-50 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 4.1 shows the single line diagram of the system network model of Substation-50. There are two 138 kV transmission lines. These devices connect Substation-50 with other substations including Substation 10 (transmission line B50-10 to B10-50) and Substation 100 (transmission line B50-100 to B100-50) respectively as can be seen in the figure.

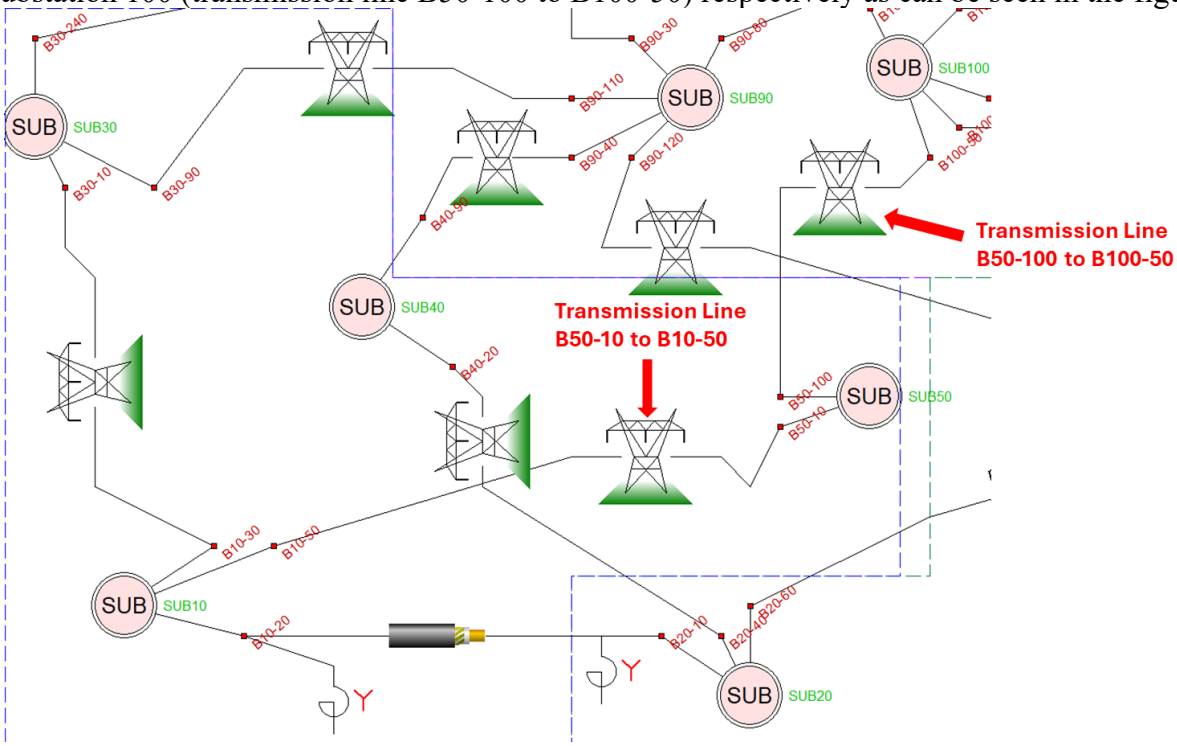


Figure A4.1 Single line diagram of system network connected to Substation-50.

The single line diagram of Substation-50 is shown in Figure 4.2. Substation-50 is a 138 kV substation. It has a ring bus arrangement. This substation consists of two 138 kV lines connecting Substation 50 to Substations 10 and 100, one step-down transformer unit and multiple substation buses. The substation model is represented with sixteen (16) three-phase nodes, four (4) circuit breakers, and eleven (11) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-50 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

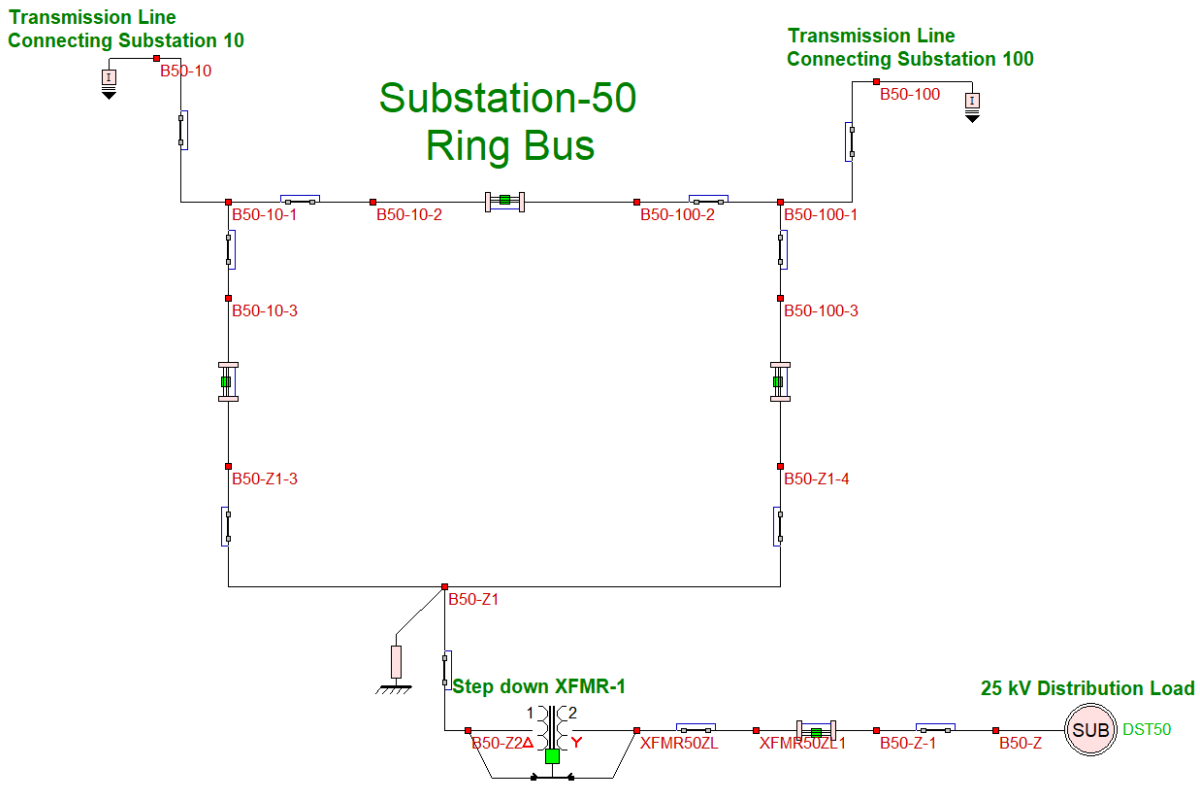


Figure A4.2 Substation-50: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 50
Description of Substation 50

The substation-50 has a ring bus configuration. Figure 4.3 shows the co-model of Substation-50 (power system + protection and control). The protection zones defined in Substation-50 can be seen in the figure. Substation 50 has three protection zones: (a) two transmission line protection zones, (b) one transformer protection zone. There are ten MUs in Substation-50. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

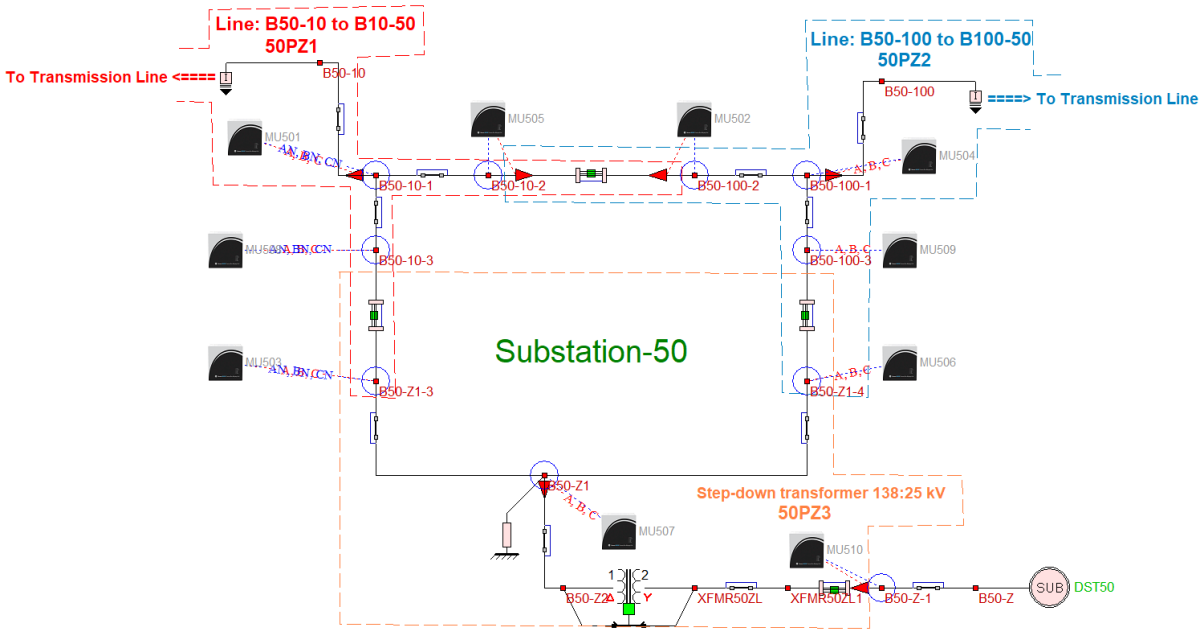


Figure A4.3 Co-model of Substation-50: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The three protection zones are briefly described below.

1. 50PZ1 protects the transmission line B50-10 to B10-50, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 50PZ2 protects the transmission line B50-100 to B100-50, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 50PZ3 protects the step-down transformer XFMR50ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 50PZ1
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B50-10 to B10-50, the transmission line is a 138 kV line that is 22 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 50 and 10 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B50-10-2 to B50-100-2 and nodes B50-10-3 to B50-Z1-3 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B50-10-2 to B50-100-2 and nodes B50-10-3 to B50-Z1-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B50-10-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU501, MU502, MU503, MU505, and MU508 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 50PZ2
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B50-100 to B100-50, the transmission line is a 138 kV line that is 22.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 50 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected B50-10-2 to B50-100-2 and nodes B50-100-3 to B50-Z1-4 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B50-10-2 to B50-100-2 and nodes B50-100-3 to B50-Z1-4). One unit collects the voltage and current measurements from the CTs and PTs, at the node B50-100-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU502, MU504, MU505, MU506, and MU509 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 50PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 75 MVA rating. It is a step-down XFMR with a setting of 138:25 kV. The 25kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (B50-Z-1 to XFMR50ZL1) and has a rating of 25kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B50-10-3 to B50-Z1-3; B50-100-3 to B50-Z1-4) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B50-10-3 to B50-Z1-3; B50-100-3 to B50-Z1-4). One unit collecting the voltage and current measurements at node B50-Z1 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B50-Z-1 to XFMR50ZL1).

Note: As an example, B50-Z-1 is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.

5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU503, MU506, MU507, MU508, MU509 and MU510 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-5. Substation-20 System Description

This section of the document describes the Substation-20 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 5.1 shows the single line diagram of the system network model of Substation-50. There are two 138 kV transmission lines and one 138 kV overhead line/cable. These devices connect Substation-20 with other substations including Substation 60 (transmission line B20-60 to B60-20), Substation 40 (transmission line B20-40 to B40-20), and Substation 10 (overhead cable/line B20-10 to B10-20) respectively as can be seen in the figure.

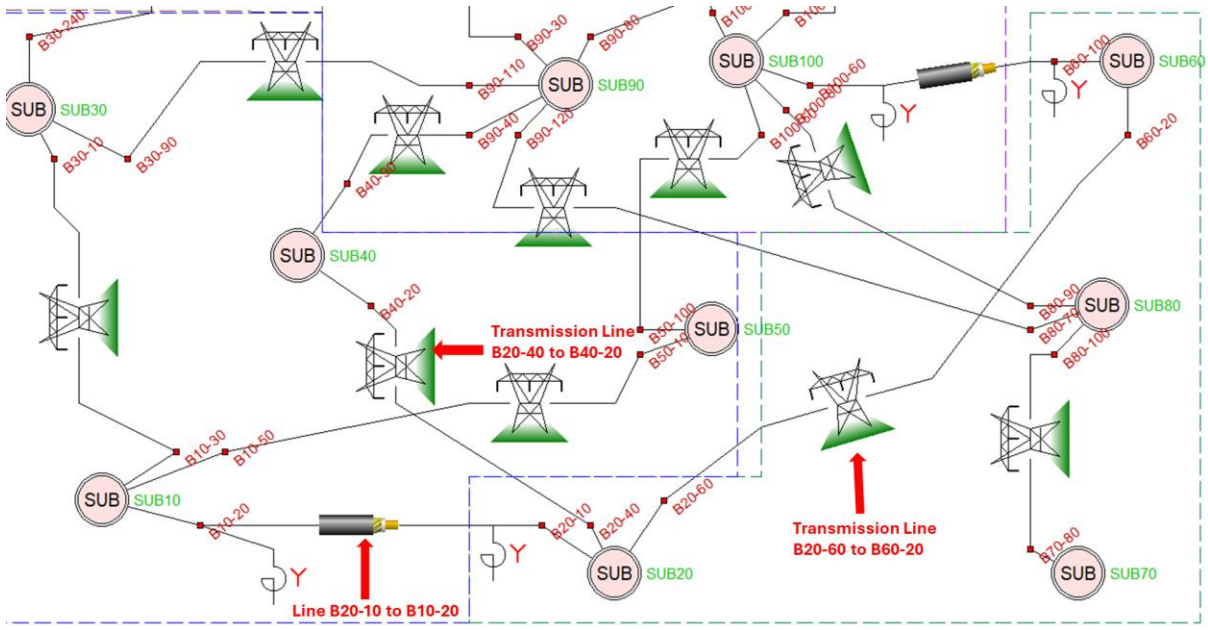


Figure A5.1 Single line diagram of system network connected to Substation-20.

The single line diagram of Substation-20 is shown in Figure 5.2. Substation-20 is a 138 kV substation. It has a breaker and a half arrangement. This substation consists of three 138 kV lines connecting Substation 20 to Substations 20, 40 and 60, four generator/inverter – step-up transformer units, one step-down transformer unit and two substation buses. The substation model is represented with twenty-one (21) three-phase nodes, nineteen (19) circuit breakers, and twenty-eight (28) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-20 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

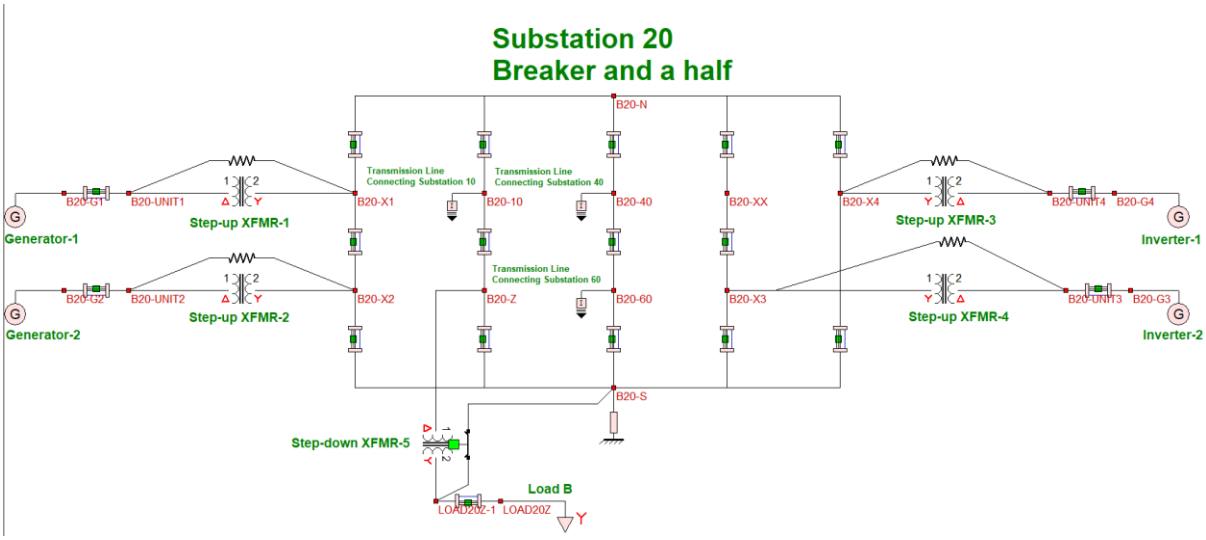


Figure A5.2 Substation-20: Breaker and a Half Configuration, Single Line Diagram

Protection and Control of Substation 20
Description of Substation 20

The substation-20 has a breaker and a half configuration. Figure 5.4 shows the co-model of Substation-20 (power system + protection and control). The protection zones defined in Substation-20 can be seen in the figure. Substation 20 has ten protection zones: (a) four generator/inverter-XFMR unit protection zones, (b) two Bus protection zones, (c) three transmission line protection zones and (d) one transformer protection zone. There are thirty-five MUs in Substation-20. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

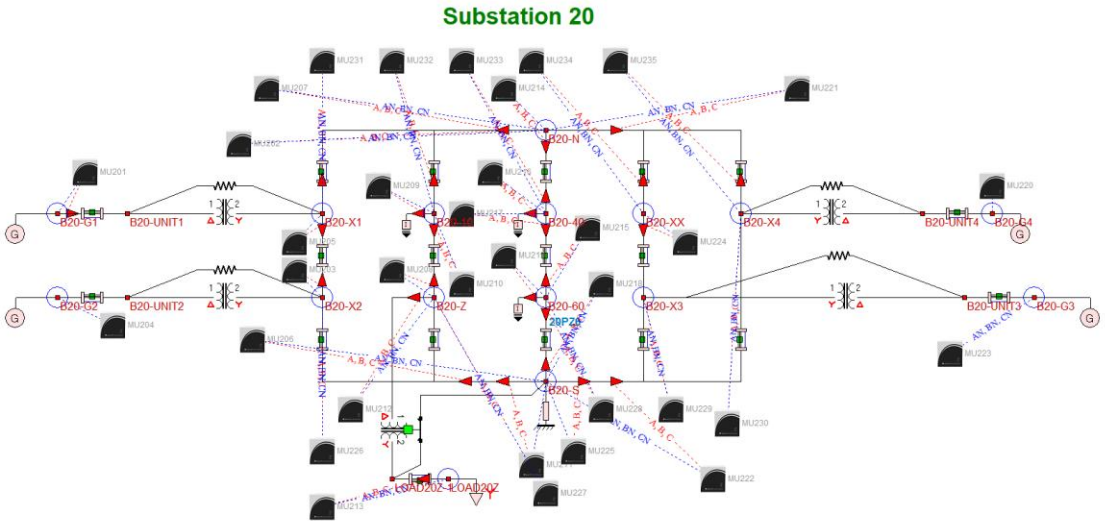


Figure A5.3 Substation 20: Merging Units Location

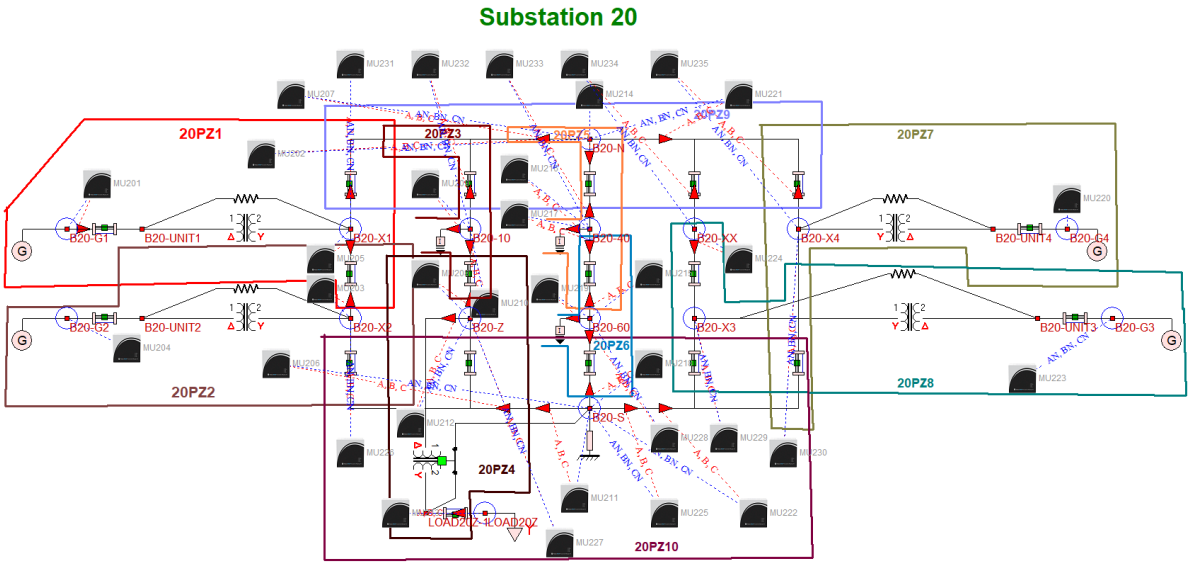


Figure A5.4 Co-model of Substation 20: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The ten protection zones are briefly described below.

1. 20PZ1 protects the generator-XFMR at B20-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

2. 20PZ2 protects the generator-XFMR at B20-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 20PZ3 protects the overhead line B20-10 to B10-20, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 20PZ4 protects the transformer LOAD20Z, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 20PZ5 protects the transmission line B20-40 to B40-20, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 20PZ6 protects the transmission line B20-60 to B60-20, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 20PZ7 protects the inverter-XFMR at B20-G3, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
8. 20PZ8 protects the inverter-XFMR at B20-G4, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
9. 20PZ9 protects the North side Bus B20-N, it has one bus, five circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and nine merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
10. 20PZ10 protects the South side Bus B20-S, it has one bus, five circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and ten merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 20PZ1

This protection zone consists of:

1. A three phase generator that has a 115kV, 100 MVA rating. A step-up XFMR with a setting of 115:138kV, 100 MVA. The 138kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B20-G1 to B20-UNIT1) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B20-N to B20-X1; B20-X2 to B20-X1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B20-N to B20-X1 and B20-X2 to B20-X1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B20-G1 to B20-UNIT1).

Note: As an example, B20-G1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using five merging units namely MU201, MU202, MU003, MU005 and MU231 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 20PZ2

This protection zone consists of:

1. A three phase generator that has a 115kV, 100 MVA rating. A step-up XFMR with a setting of 115:138kV, 100 MVA. The 138kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B20-G2 to B20-UNIT2) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B20-S to B20-X2; B20-X2 to B20-X1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B20-S to B20-X2; B20-X2 to B20-X1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B20-G2 to B20-UNIT2).

Note: As an example, B20-G2 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 2 are collected using five merging units namely MU203, MU204, MU205, MU206 and MU226 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the

current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 20PZ3
This protection zone consists of:

1. The overhead cable/line that is connected between nodes B20-10 to B10-20, the cable is a 138 kV line that is 5000 ft long. The line is modelled as follows:

1. The phase conductors of the line are of the type ABB and size ABB-138KV-1000CMPCU with an kcmil of 1974 kcm.
2. The ground impedance is given as: R =50 ohms and X_c or X_L = 0 ohms.
3. The soil resistivity is 150 ohms-meter.
4. The span length is 5000 ft.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 10 and 20 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B20-N to B20-20 and B20-Z to B20-10 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B20-N to B20-20 and B20-Z to B20-10). One unit collects the voltage and current measurements from the CTs and PTs, at the node B20-10.

For EBP:
An EBP relay monitors the line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU207, MU208, MU209, MU210, and MU232 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 20PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 45 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (LOAD20Z to 1LOAD20Z) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B20-10 to B20-Z; B20-S to B20-Z) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B20-10 to B20-Z; B20-S to B20-Z).one unit collects the voltage and current measurements at node B20-Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present at 1LOAD20Z

Note: As an example, 1LOAD20Z is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU208, MU210, MU211, MU212, MU213 and MU227 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5– 20PZ5
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B20-40 to B40-20, the transmission line is a 138 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 20 and 40 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B20-N to B20-40 and B20-40 to B20-60 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B20-N to B20-40 and B20-40 to B20-60). One unit collects the voltage and current measurements from the CTs and PTs, at the node B20-40.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.

2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU214, MU215, MU216, MU217, and MU233 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 20PZ6
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B20-60 to B60-20, the transmission line is a 138 kV line that is 50 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 20 and 60 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B20-40 to B20-60 and B20-50 to B20-S respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B20-40 to B20-60 and B20-50 to B20-S). One unit collects the voltage and current measurements from the CTs and PTs, at the node B20-60.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU215, MU217, MU218, MU219, and MU228 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 20PZ7

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:138kV, 100 MVA. The 138kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B20-G3 to B20-UNIT3) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B20-S to B20-X3; B20-X3 to B20-XX) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Four Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B20-S to B20-X3), one unit collecting the voltage and current measurements from the CTs and PTs, at the node B20XX of the circuit breaker B20-X3 to B20-XX connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B20-G3 to B20-UNIT3).

Note: As an example, B20-G3 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 7 are collected using four merging units namely MU222, MU224, MU225 and MU229 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 8 – 20PZ8

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:138kV, 100 MVA. The 138kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B20-G4 to B20-UNIT4) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B20-N to B20-X4; B20-S to B20-X4) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B20-N to B20-X4; B20-S to B20-X4). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B20-G4 to B20-UNIT4).

Note: As an example, B20-G4 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 8 are collected using five merging units namely MU220, MU221, MU222, MU230 and MU235 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 9 – 20PZ9

This protection zone consists of:

1. Five Circuit Breakers forms the substation north bus B20-N, namely B20-X1 to B20-N, B20-20 to B20-N, B20-30 to B20-N, B20-XX to B20-N, B20-X4 to B20-N. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Nine Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B20-X1 to B20-N, B20-20 to B20-N, B20-30 to B20-N, B20-XX to B20-N and B20-X4 to B20-N.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 9 are collected using nine merging units namely MU202, MU207, MU214, MU221, MU231, MU232, MU233, MU234 and MU235 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 10 – 20PZ10

This protection zone consists of:

1. Five Circuit Breakers forms the substation north bus B20-S, namely B20-X2 to B20-S, B20-Z to B20-S, B20-50 to B20-S, B20-X3 to B20-S, B20-X4 to B20-S. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Ten Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B20-X2 to B20-S, B20-Z to B20-S, B20-50 to B20-S, B20-X3 to B20-S, B20-X4 to B20-S.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 10 are collected using ten merging units namely MU206, MU211, MU218, MU222, MU225, MU226, MU227, MU228, MU229 and MU230 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-6. Substation-70 System Description

This section of the document describes the Substation-70 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 6.1 shows the single line diagram of the system network model of Substation-70. There is one 138 kV transmission line. This device connects Substation-70 with other substations including Substation 80 (transmission line B70-80 to B80-70) as can be seen in the figure.

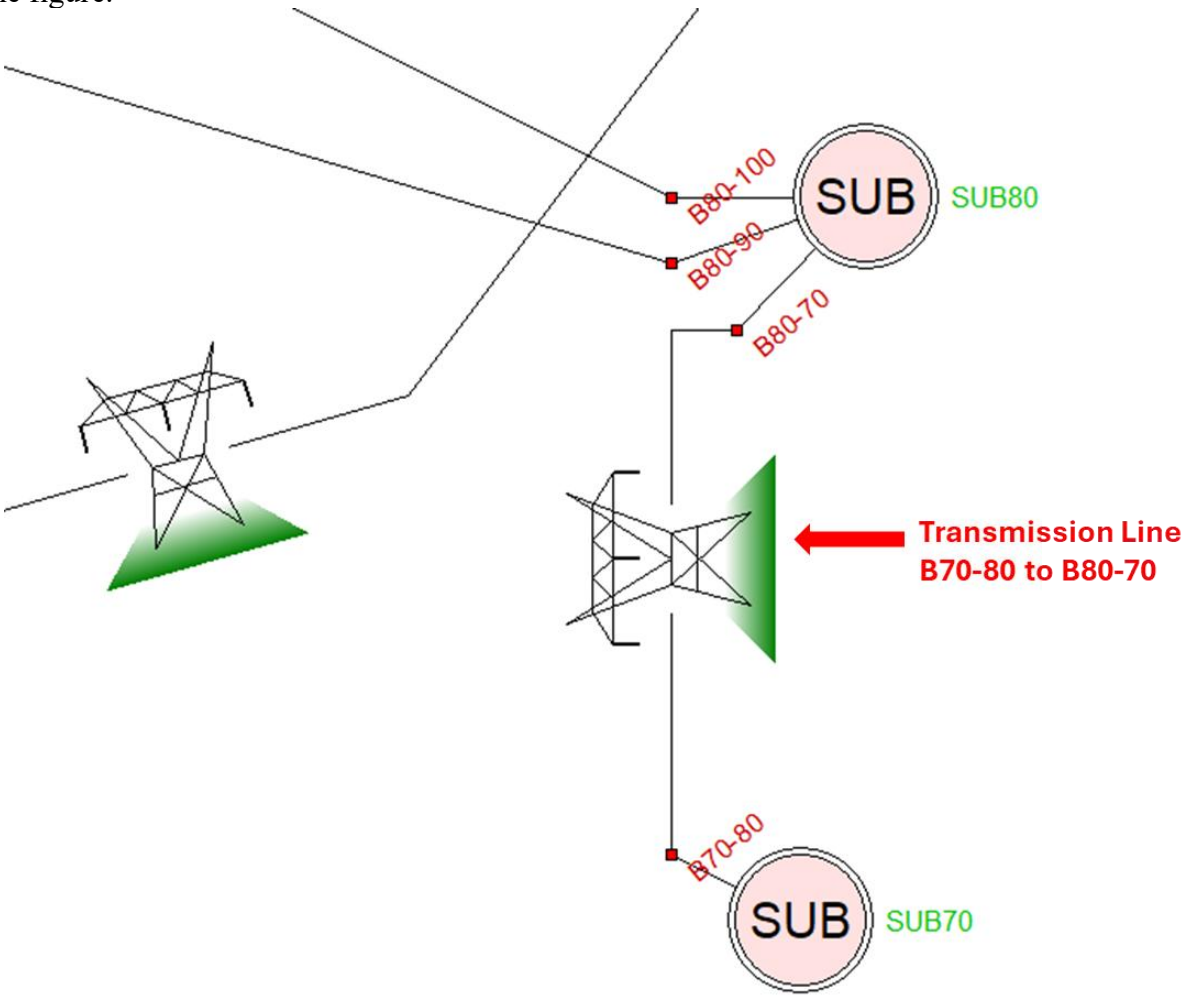


Figure A6.1 Single line diagram of system network connected to Substation-70.

The single line diagram of Substation-70 is shown in Figure 6.2. Substation-70 is a 138 kV substation. It has a ring bus arrangement. This substation consists of one 138 kV line connecting Substation 70 to Substations 80, three generator/inverter-step-up transformer units, one step-down transformer unit and multiple substation buses. The substation model is represented with thirty-six (36) three-phase nodes, nine (9) circuit breakers, and twenty-three (23) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-70 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

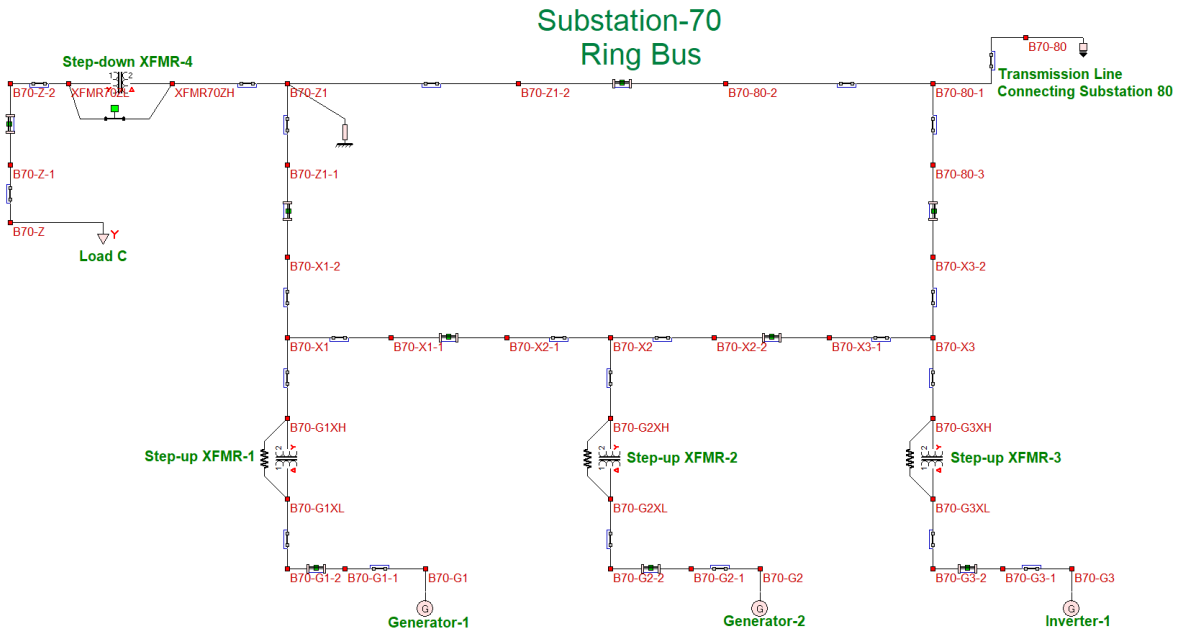


Figure A6.2 Substation-70: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 70
Description of Substation 70

The substation-70 has a ring bus configuration. Figure 6.3 shows the co-model of Substation-70 (power system + protection and control). The protection zones defined in Substation-70 can be seen in the figure. Substation 70 has five protection zones: (a) one transmission line protection zone, (b) one transformer protection zone and (c) three generator/inverter-transformer unit protection zones. There are sixteen MUs in Substation-70. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.
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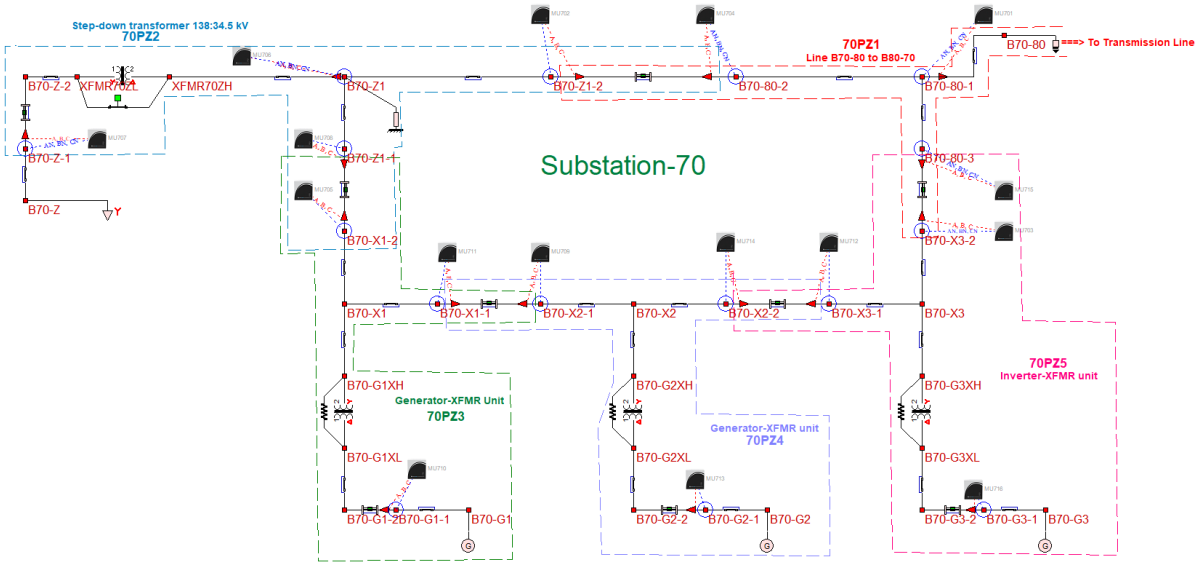


Figure A6.3 Co-model of Substation-70: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The five protection zones are briefly described below.

1. 70PZ1 protects the transmission line B70-80 to B80-70, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 70PZ2 protects the step-down transformer XFMR70ZH, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 70PZ3 protects the generator-XFMR at B70-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 70PZ4 protects the generator-XFMR at B70-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 70PZ5 protects the inverter-XFMR at B70-G3, it has one inverter, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 70PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B70-80 to B80-70, the transmission line is a 138 kV line that is 16 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HEN/SSAC with an Ampacity of 716.4 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 70 and 80 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B70-Z1-2 to B70-80-2 and B70-80-3 to B70-X3-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B70-Z1-2 to B70-80-2 and B70-80-3 to B70-X3-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B70-80-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU701, MU702, MU703, MU704, and MU715 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 70PZ2
This protection zone consists of:

1. A three phase load-XFMR that has a 45 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (B70-Z-1 to B70-Z-2) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B70-Z1-2 to B70-80-2; B70-Z1-1 to B70-X1-2) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B70-Z1-2 to B70-80-2; B70-Z1-1 to B70-X1-2). One unit collecting the voltage and current measurements at node B70-Z1 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B70-Z-1 to B70-Z-2).

Note: As an example, B70-Z-1 is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.

5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 2 are collected using six merging units namely MU702, MU704, MU705, MU706, MU707 and MU708 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 70PZ3

This protection zone consists of:

1. A three phase generator that has a 13.8kV, 20 MVA rating. A step-up XFMR with a setting of 13.8:138kV, 20 MVA. The 138kV is Wye connected and the 13.8kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B70-G1-1 to B70-G1-2) and has a rating of 13.8kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B70-Z1-1 to B70-X1-2; B70-X1-1 to B70-X2-1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B70-Z1-1 to B70-X1-2; B70-X1-1 to B70-X2-1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B70-G1-1 to B70-G1-2).

Note: As an example, B70-G1-1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.

6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 3 are collected using five merging units namely MU705, MU708, MU709, MU710 and MU711 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 70PZ4

This protection zone consists of:

1. A three phase generator that has a 13.8kV, 20 MVA rating. A step-up XFMR with a setting of 13.8:138kV, 20 MVA. The 138kV is Wye connected and the 13.8kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B70-G2-1 to B70-G2-2) and has a rating of 13.8kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B70-X3-1 to B70-X2-2; B70-X1-1 to B70-X2-1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B70-X3-1 to B70-X2-2; B70-X1-1 to B70-X2-1). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B70-G2-1 to B70-G2-2).

Note: As an example, B70-G2-1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 4 are collected using five merging units namely MU709, MU711, MU712, MU713 and MU714 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 70PZ5

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 40 MVA rating. A step-up XFMR with a setting of 34.5:138kV, 40 MVA. The 138kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B70-G3-1 to B70-G3-2) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B70-X3-1 to B70-X2-2; B70-X3-2 to B70-80-3) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B70-X3-1 to B70-X2-2; B70-X3-2 to B70-80-3). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B70-G3-1 to B70-G3-2).

Note: As an example, B70-G3-1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.

4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 5 are collected using five merging units namely MU703, MU712, MU714, MU715 and MU716 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-7. Substation-80 System Description

This section of the document describes the Substation-80 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 7.1 shows the single line diagram of the system network model of Substation-80. There are three 138 kV transmission lines. These devices connect Substation-80 with other substations including Substation 100 (transmission line B80-100 to B100-80), Substation 70 (transmission line B80-70 to B70-80), and Substation 90 (transmission line B80-90 to B90-80) respectively as can be seen in the figure.

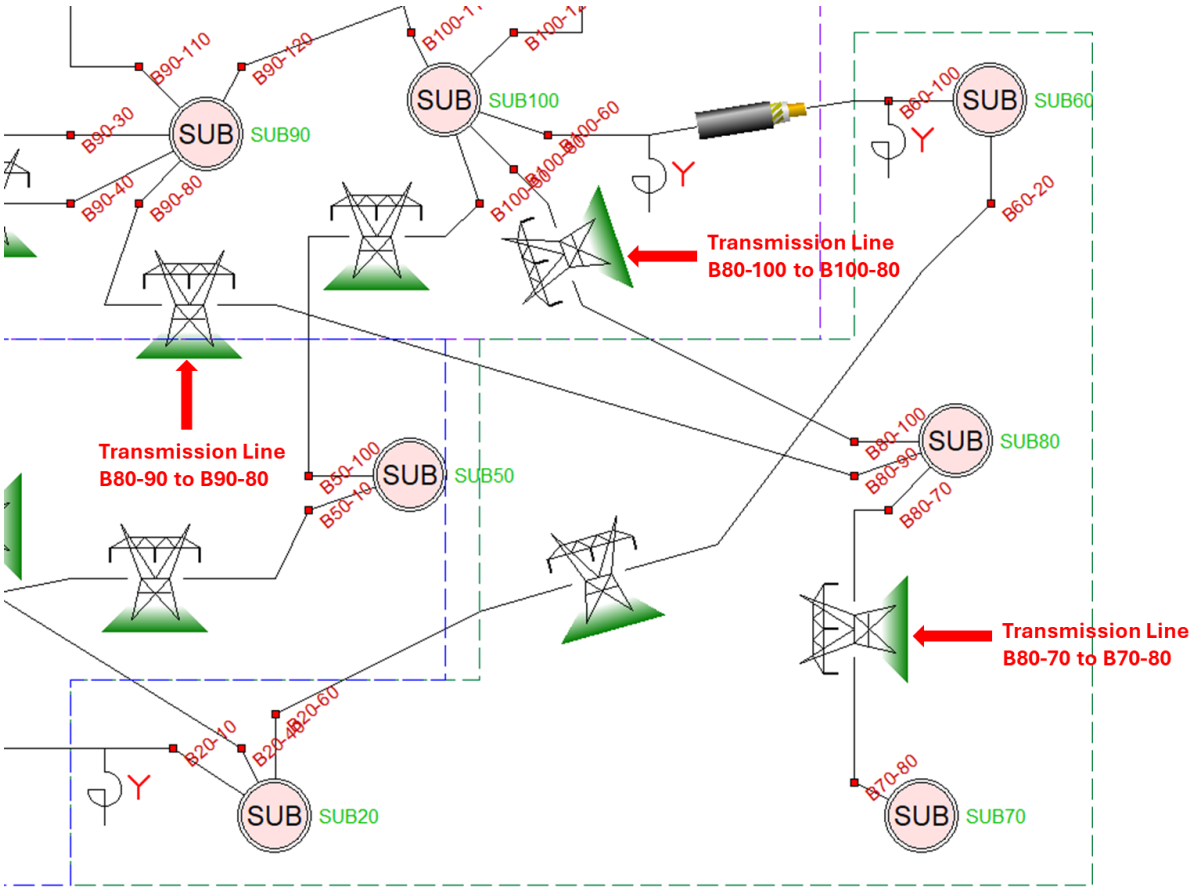


Figure A7.0.2 Single line diagram of system network connected to Substation-80.

The single line diagram of Substation-80 is shown in Figure 8.2. Substation-80 is a 138 kV substation. It has a breaker and a half arrangement. This substation consists of three 138 kV lines connecting Substation 80 to Substations 100, 90 and 70, one step-down transformer unit and multiple substation buses. The substation model is represented with twenty-five (25) three-phase nodes, seven (7) circuit breakers, and eighteen (18) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-80 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

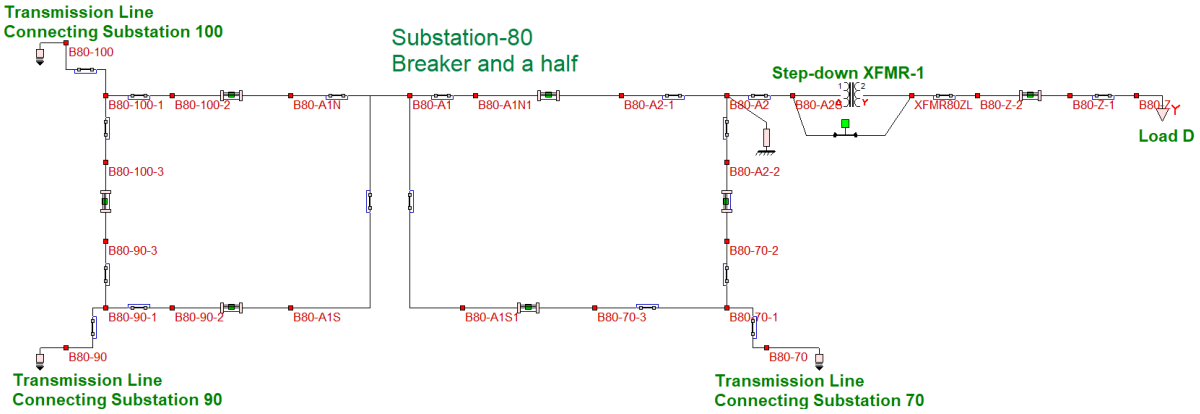


Figure A7.2 Substation-80: Breaker and a half Configuration, Single Line Diagram

Protection and Control of Substation 80
Description of Substation 80

The substation-80 has a breaker and a half configuration. Figure 7.3 shows the co-model of Substation-80 (power system + protection and control). The protection zones defined in Substation-80 can be seen in the figure. Substation 80 has four protection zones: (a) three transmission line protection zones, (b) one transformer protection zone. There are thirteen MUs in Substation-80. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

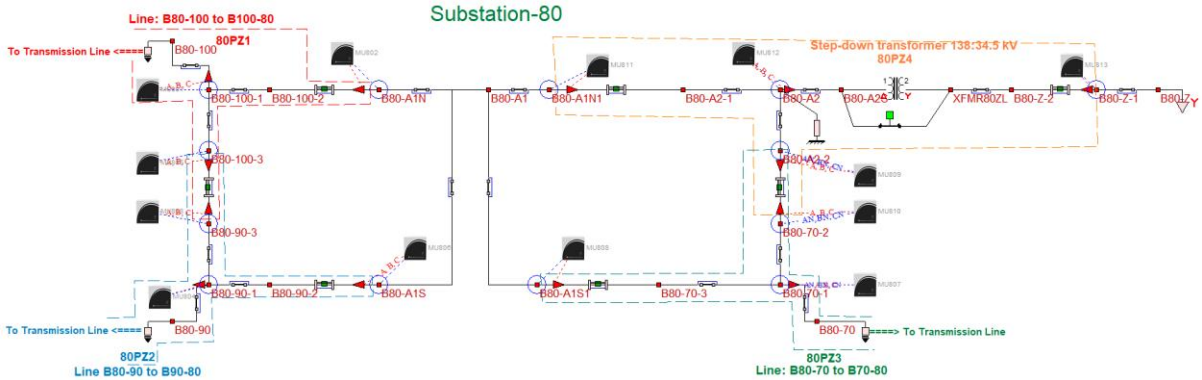


Figure A7.3 Co-model of Substation-80: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The four protection zones are briefly described below.

1. 80PZ1 protects the transmission line B80-100 to B100-80, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 80PZ2 protects the transmission line B80-90 to B90-80, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 80PZ3 protects the transmission line B80-70 to B70-80, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 80PZ4 protects the step-down transformer XFMR80ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 80PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B80-100 to B100-80, the transmission line is a 138 kV line that is 42.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 80 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B80-100-2 to B80-A1N and B80-100-3 to B80-90-3 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on

either side of the circuit breakers (B80-100-2 to B80-A1N and B80-100-3 to B80-90-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B80-100-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using four merging units namely MU801, MU802, MU803 and MU805 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 80PZ2
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B80-90 to B90-80, the transmission line is a 138 kV line that is 42.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 80 and 90 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B80-100-3 to B80-90-3 and B80-90-2 to B80-A1S respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers

(PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B80-100-3 to B80-90-3 and B80-90-2 to B80-A1S). One unit collects the voltage and current measurements from the CTs and PTs, at the node B80-90-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using four merging units namely MU803, MU804, MU805 and MU806 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 80PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B80-70 to B70-80, the transmission line is a 138 kV line that is 16 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HEN/SSAC with an Ampacity of 716.4 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 80 and 70 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B80-A2-2 to B80-70-2 and B80-A1-S1 to B80-70-3 respectively. These circuit breakers have a rated voltage of 138kV

and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B80-A2-2 to B80-70-2 and B80-A1-S1 to B80-70-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B80-70-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using four merging units namely MU807, MU808, MU809 and MU810 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 80PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 50 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (B80-Z-2 to B80-Z-1) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B80-A2-2 to B80-70-2 and B80-A1N1 to B80-A2-1) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These

measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are five Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B80-A2-2 to B80-70-2 and B80-A1N1 to B80-A2-1). One unit collecting the voltage and current measurements at node B80-A2 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B80-Z-2 to B80-Z-1)).

Note: As an example, B80-Z-2 is a node.

For EBP:

An EBP relay monitors the transformer protection zone.

For Legacy Protection:

A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using five merging units namely MU809, MU810, MU811, MU812 and MU813 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-8. Substation-60 System Description

This section of the document describes the Substation-60 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 8.1 shows the single line diagram of the system network model of Substation-60. There are two 138 kV transmission lines. These devices connect Substation-60 with other substations including Substation 20 (transmission line B60-20 to B20-60) and Substation 100 (transmission line B60-100 to B100-60) respectively as can be seen in the figure.

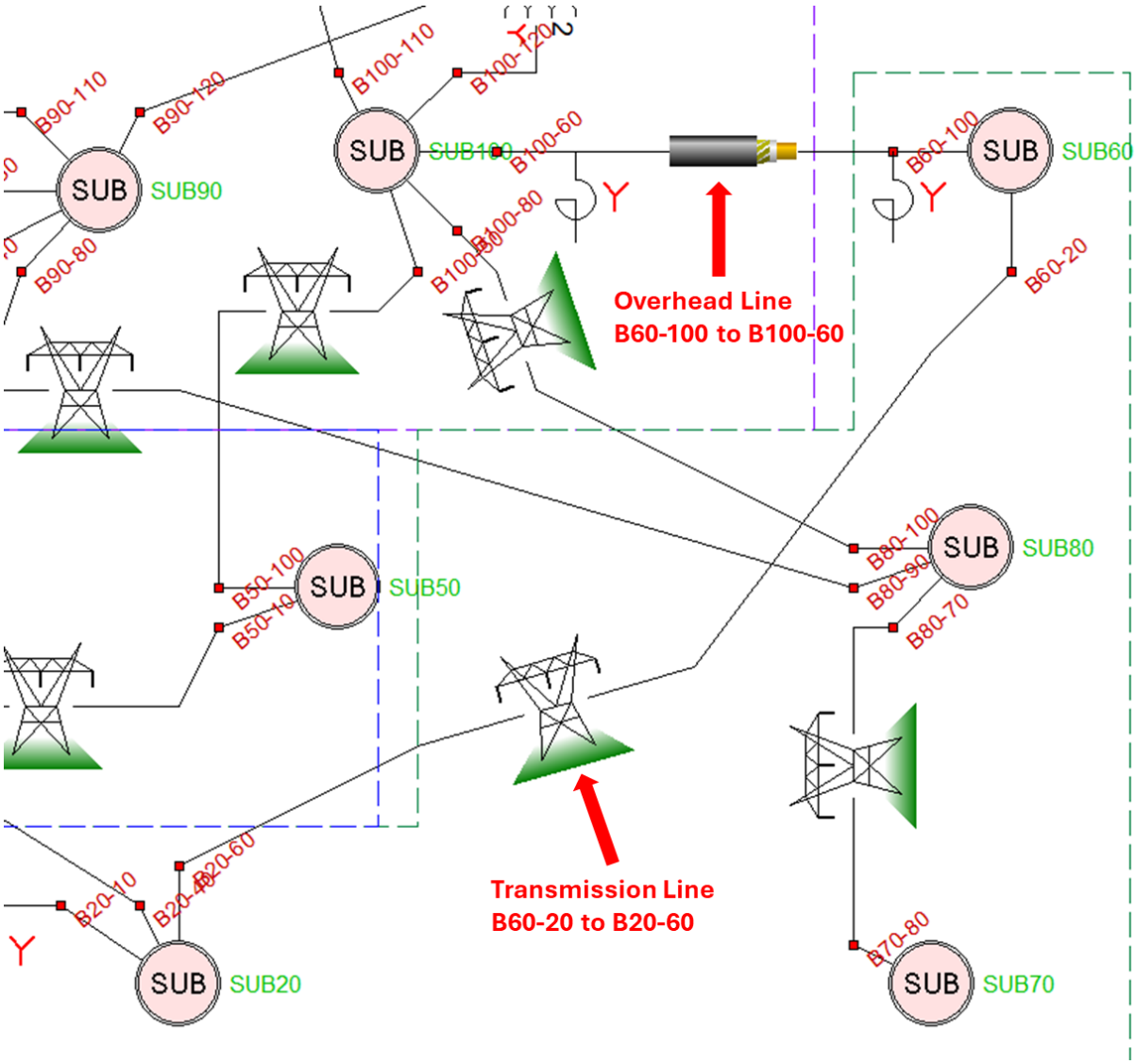


Figure A8.0.3 Single line diagram of system network connected to Substation-60.

The single line diagram of Substation-60 is shown in Figure 8.2. Substation-60 is a 138 kV substation. It has a ring bus arrangement. This substation consists of two 138 kV lines connecting Substation 60 to Substations 20 and 100, one step-down transformer unit and multiple substation buses. The substation model is represented with sixteen (16) three-phase nodes, four (4) circuit breakers, and eleven (11) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-60 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

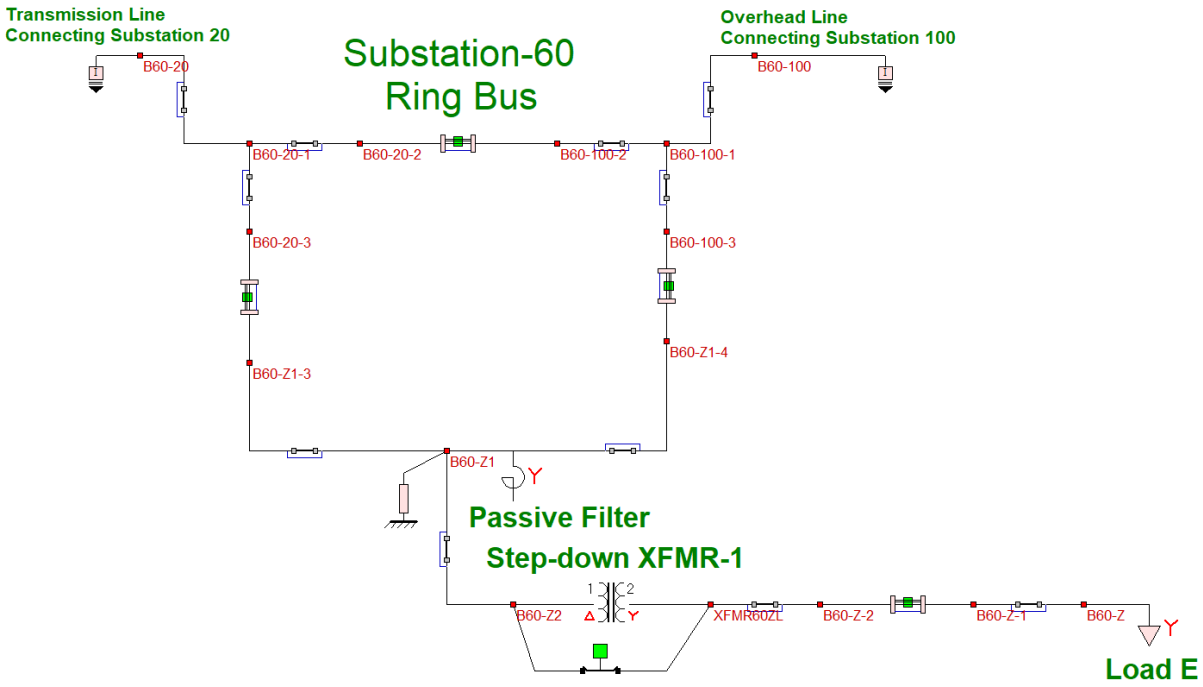


Figure A8.2 Substation-60: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 60
Description of Substation 60

The substation-60 has a ring bus configuration. Figure 8.3 shows the co-model of Substation-60 (power system + protection and control). The protection zones defined in Substation-60 can be seen in the figure. Substation 60 has three protection zones: (a) two line protection zones, (b) one transformer protection zone. There are ten MUs in Substation-60. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

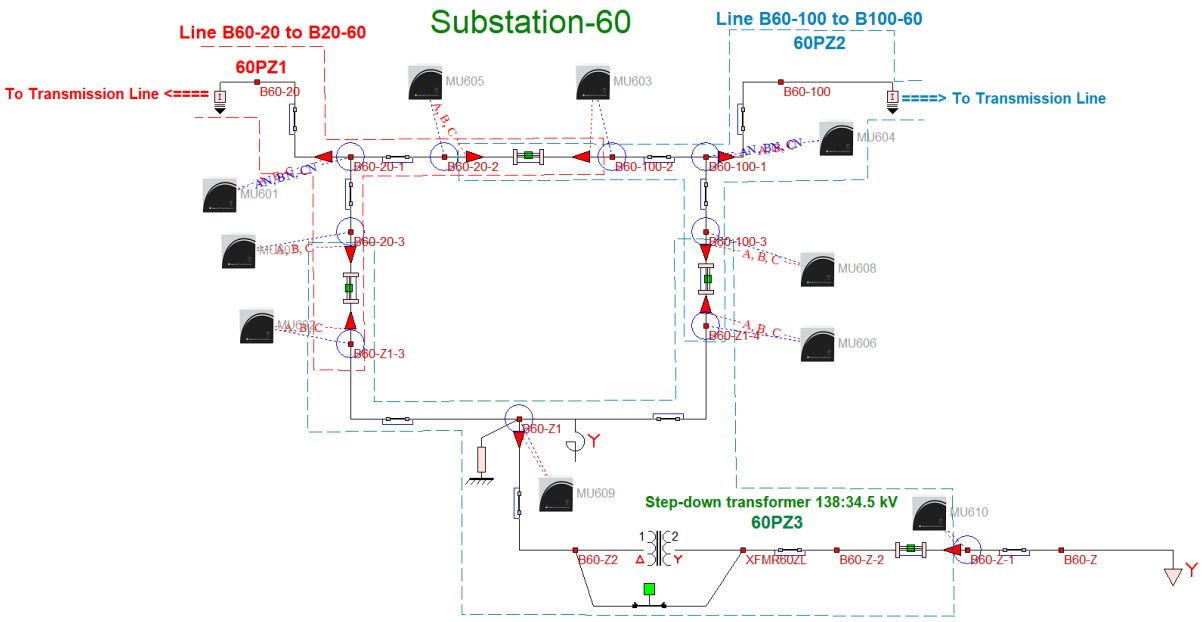


Figure A8.3 Co-model of Substation-60: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The three protection zones are briefly described below.

1. 60PZ1 protects the transmission line B60-20 to B20-60, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 60PZ2 protects the transmission line B60-100 to B100-60, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 60PZ3 protects the step-down transformer XFMR60ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 60PZ1
This protection zone consists of:

This protection zone consists of:

1. The transmission line that is connected between buses B60-20 to B20-60, the transmission line is a 138 kV line that is 50 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 60 and 20 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B60-20-2 to B60-100-2 and nodes B60-20-3 to B60-Z1-3 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B60-20-2 to B60-100-2 and nodes B60-20-3 to B60-Z1-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B60-20-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU601, MU602, MU603, MU605, and MU607 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 60PZ2
This protection zone consists of:

1. The overhead cable/line that is connected between nodes B60-100 to B100-60, the cable is a 138 kV line that is 100000 ft long. The line is modelled as follows:

1. The phase conductors of the line are of the type ABB and size ABB-138KV-1000CMPCU with an kcmil of 1974 kcm.
2. The ground impedance is given as: R =50 ohms and X_c or X_L = 0 ohms.
3. The soil resistivity is 150 ohms-meter.
4. The span length is 100000 ft.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 60 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B60-100-3 to B60-Z1-4 and B60-20-2 to B60-100-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B60-100-3 to B60-Z1-4 and B60-20-2 to B60-100-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B60-100-1.

For EBP:
An EBP relay monitors the line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU603, MU604, MU605, MU606, and MU608 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the

current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 60PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 50 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (B60-Z-1 to B60-Z-2) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B60-100-3 to B60-Z1-4; B60-20-3 to B60-Z1-3) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B60-100-3 to B60-Z1-4; B60-20-3 to B60-Z1-3). One unit collecting the voltage and current measurements at node B60-Z1 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B60-Z-1 to B60-Z-2).

Note: As an example, B60-Z-1 is a node.

4. There is one 10 MVAR capacitor filter connected at node B60-Z1.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU602, MU606, MU607, MU608, MU609 and MU610 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-9. Substation-100 System Description

This section of the document describes the Substation-100 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 9.1 shows the single line diagram of the system network model of Substation-100. There are five 138 kV transmission lines. These devices connect Substation-100 with other substations including Substation 50 (transmission line B100-50 to B50-100), Substation 60 (transmission line B100-60 to B60-100), Substation 80 (transmission line B100-80 to B80-100), Substation 110 (transmission line B100-110 to B110-100) and Substation 120 (transmission line B100-120 to B120-100) respectively as can be seen in the figure.

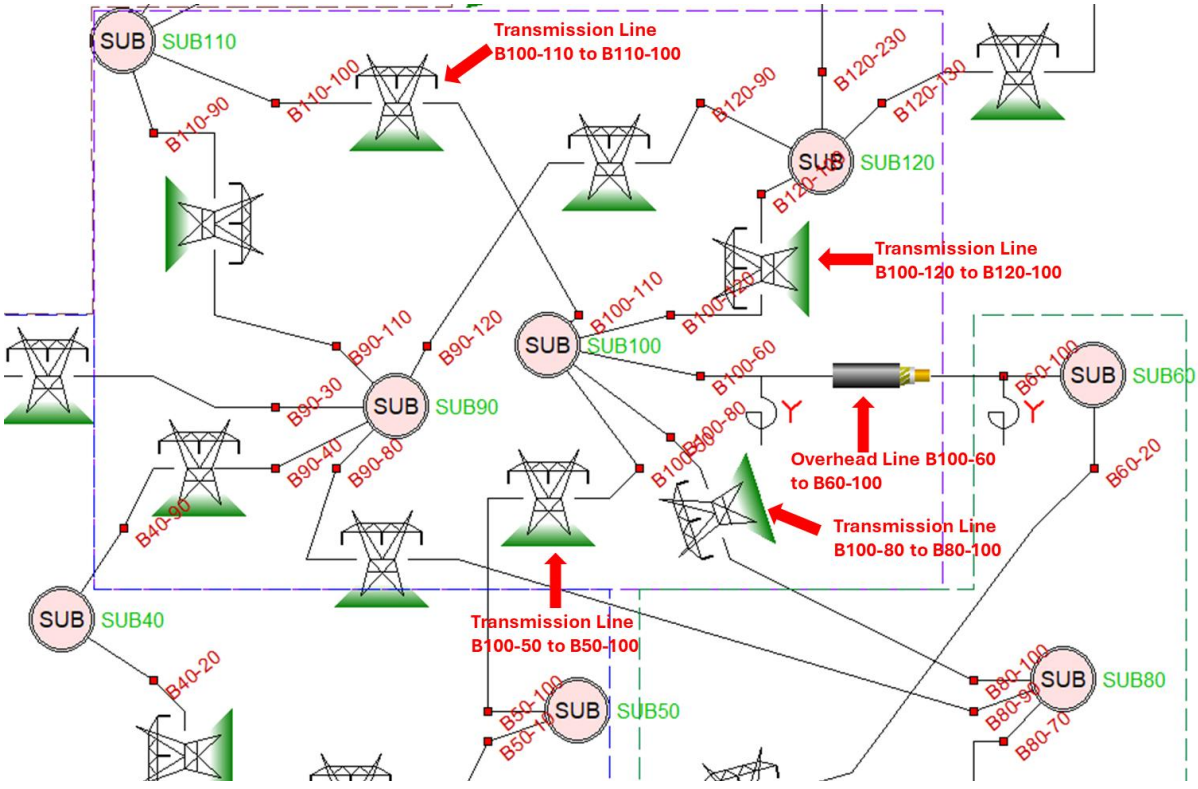


Figure A9.0.4 Single line diagram of system network connected to Substation-100.

The single line diagram of Substation-100 is shown in Figure 9.2. Substation-100 is a 138 kV substation. It has a breaker and a half plus double bus arrangement. This substation consists of five 138 kV lines connecting Substation 100 to Substations 50,60,80,110 and 120, one step-down transformer unit, one Busbar and multiple substation buses. The substation model is represented

with thirty-seven (37) three-phase nodes, eleven (11) circuit breakers, and twenty six (26) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-100 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

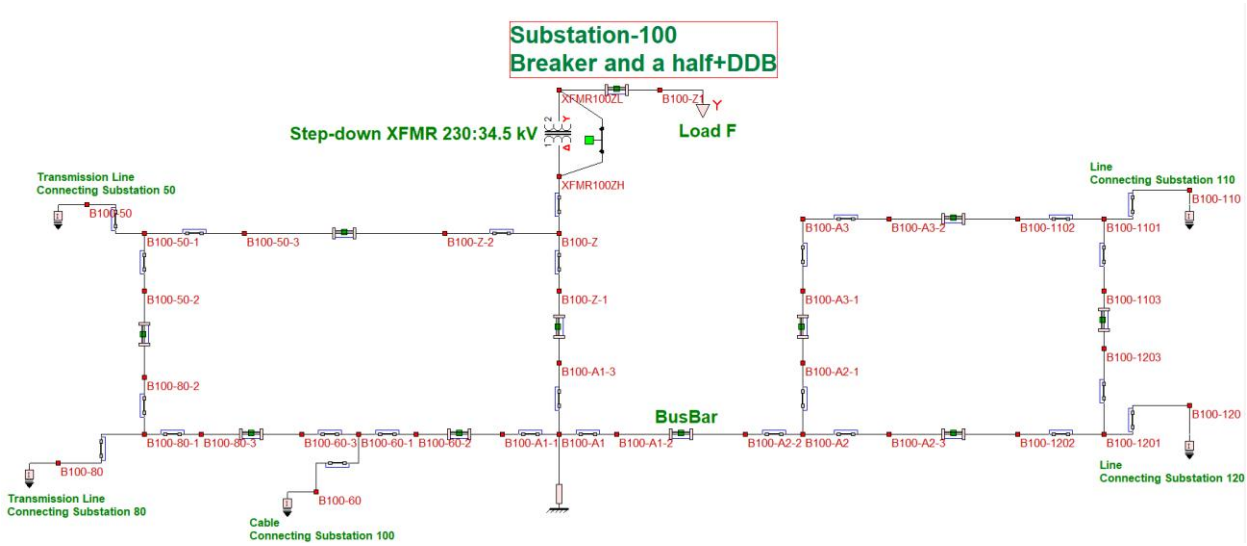


Figure A9.2 Substation-100: Breaker and a half plus double bus Configuration, Single Line Diagram

Protection and Control of Substation 100
Description of Substation 100

The substation-100 has a breaker and a half plus double bus configuration. Figure 9.3 shows the co-model of Substation-100 (power system + protection and control). The protection zones defined in Substation-100 can be seen in the figure. Substation 100 has seven protection zones: (a) five, line protection zones, (b) one transformer protection zone and (c) one Busbar protection zone. There are twenty-five MUs in Substation-100. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

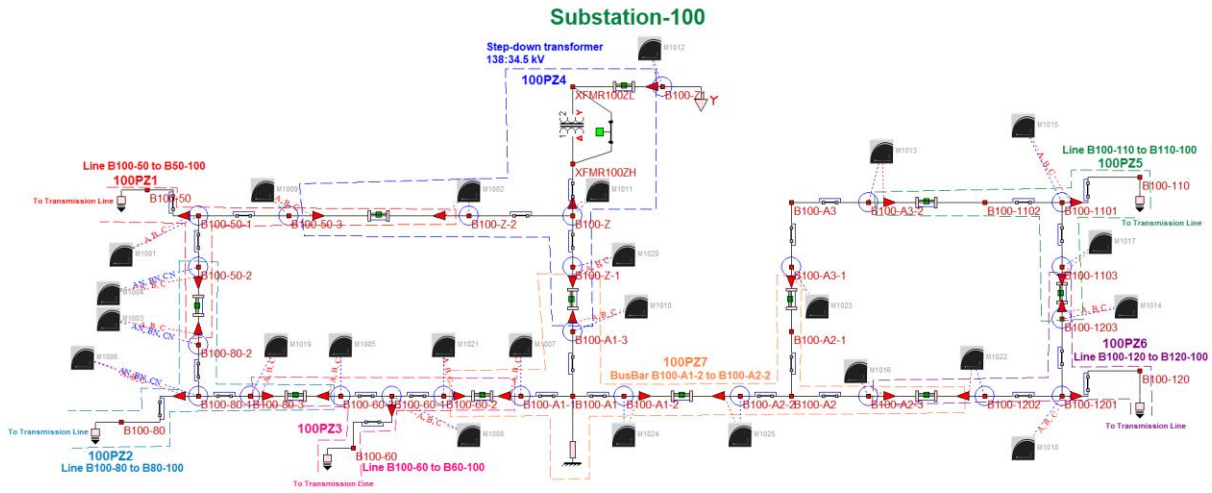


Figure A9.3 Co-model of Substation-100: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 100PZ1 protects the transmission line B100-50 to B50-100, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 100PZ2 protects the transmission line B100-80 to B80-100, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 100PZ3 protects the transmission line B100-60 to B60-100, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 100PZ4 protects the step-down transformer XFMR100ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 100PZ5 protects the transmission line B100-110 to B110-100, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

6. 100PZ6 protects the transmission line B100-120 to B120-100, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 100PZ7 protects the Busbar B100-A1-2 to B100-A2-2, it has one busbar (made up of the circuit breaker B100-A1-2 to B100-A2-2), four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and nine merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 100PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B100-50 to B50-100, the transmission line is a 138 kV line that is 22.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 100 and 50 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B100-50-3 to B100-Z-2 and B100-50-2 to B100-80-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B100-50-3 to B100-Z-2 and B100-50-2 to B100-80-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B100-50-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:

A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU1001, MU1002, MU1003, MU1004, and MU1009 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 100PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B100-80 to B80-100, the transmission line is a 138 kV line that is 42.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 100 and 80 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B100-80-3 to B100-60-3 and B100-50-2 to B100-80-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B100-80-3 to B100-60-3 and B100-50-2 to B100-80-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B100-80-1.

For EBP:

An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU1003, MU1004, MU1005, MU1006, and MU1019 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 100PZ3
This protection zone consists of:

1. The overhead cable/line that is connected between nodes B100-60 to B60-100, the cable is a 138 kV line that is 100000 ft long. The line is modelled as follows:

1. The phase conductors of the line are of the type ABB and size ABB-138KV-1000CMPCU with an kcmil of 1974 kcm.
2. The ground impedance is given as: R =50 ohms and X_c or X_L = 0 ohms.
3. The soil resistivity is 150 ohms-meter.
4. The span length is 100000 ft.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 60 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B100-80-3 to B100-60-3 and B100-60-2 to B100-A1-1 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B100-80-3 to B100-60-3 and B100-60-2 to B100-A1-1). One unit collects the voltage and current measurements from the CTs and PTs, at the node B100-60-1.

For EBP:
An EBP relay monitors the line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU1005, MU1007, MU1008, MU1019, and MU1021 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 100PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 50 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR100ZL to B100-Z1) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B100-50-2 to B100-Z-2; B100-Z-1 to B100-A1-3) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B100-50-2 to B100-Z-2; B100-Z-1 to B100-A1-3). One unit collecting the voltage and current measurements at node B100-Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (XFMR100ZL to B100-Z1).

Note: As an example, XFMR100ZL is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU1002, MU1009, MU1010, MU1011, MU1012 and MU1020 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 100PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B100-110 to B110-100, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 100 and 110 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B100-A3-2 to B100-1102 and B100-1103 to B100-1203 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B100-A3-2 to B100-1102 and B100-1103 to B100-1203). One unit collects the voltage and current measurements from the CTs and PTs, at the node B100-1101.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using four merging units namely MU1013, MU1014, MU1015 and MU1017 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 100PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B100-120 to B120-100, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 100 and 120 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B100-A2-3 to B100-1202 and B100-1103 to B100-1203 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and

Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B100-A2-3 to B100-1202 and B100-1103 to B100-1203). One unit collects the voltage and current measurements from the CTs and PTs, at the node B100-1201.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU1014, MU1016, MU1017, MU1018 and MU1022 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 100PZ7

This protection zone consists of:

1. Five Circuit Breakers, one of the circuit breakers forms the main busbar B100-A1-2 to B100-A2-2, the other breakers are: B100-Z-1 to B100-A1-3, B100-60-2 to B100-A1-1, B100-A3-1 to B100-A2-1 and B100-A2-3 to B100-1202. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, they have one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

3. There are nine Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B100-A1-2 to B100-A2-2, B100-Z-1 to B100-A1-3, B100-60-2 to B100-A1-1, B100-A3-1 to B100-A2-1 and B100-A2-3 to B100-1202.

For EBP: An EBP relay monitors the bus protection zone.

For Legacy protection and control: A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using nine merging units namely MU1007, MU1010, MU1016, MU1020, MU1021, MU1022, MU1023, MU1024 and MU1025 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-10. Substation-90 System Description

This section of the document describes the Substation-90 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 10.1 shows the single line diagram of the system network model of Substation-90. There are five 138 kV transmission lines. These devices connect Substation-90 with other substations including Substation 20 (transmission line B90-30 to B30-90), Substation 40 (transmission line B90-40 to B40-90), Substation 80 (transmission line B90-80 to B80-90), Substation 110 (transmission line B90-110 to B110-90) and Substation 120 (transmission line B90-120 to B120-90) respectively as can be seen in the figure.

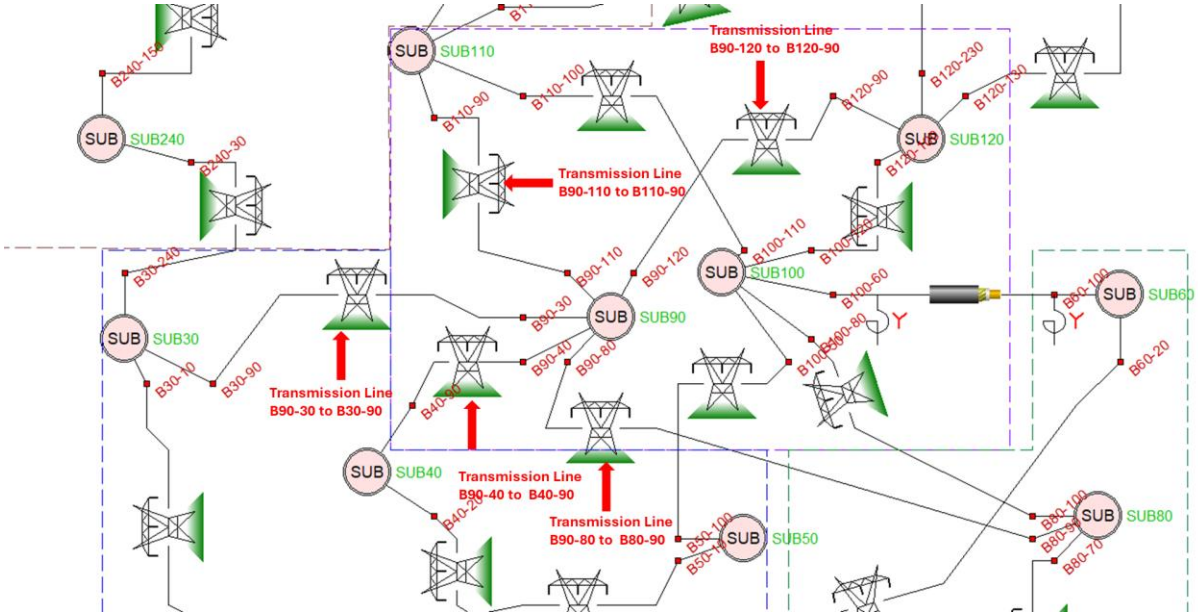


Figure A10.0.5 Single line diagram of system network connected to Substation-90.

The single line diagram of Substation-90 is shown in Figure 10.2. Substation-90 is a 138 kV substation. It has a breaker and a half plus double bus arrangement. This substation consists of five 138 kV lines connecting Substation 90 to Substations 30,40,80,110 and 120, one step-down transformer unit, one Busbar and multiple substation buses. The substation model is represented with thirty-seven (37) three-phase nodes, eleven (11) circuit breakers, and twenty-six (26) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-90 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

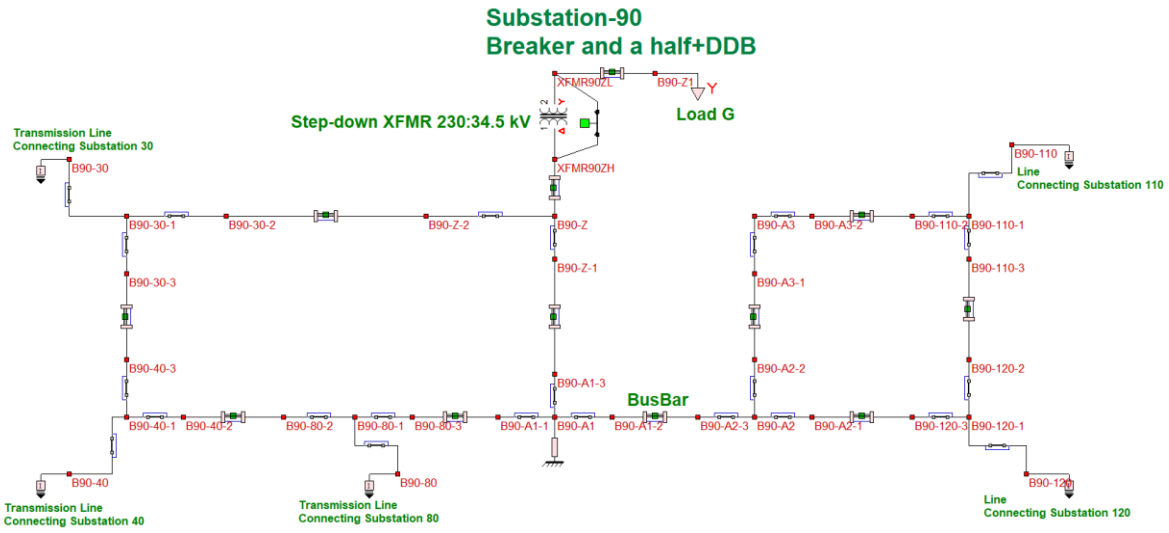


Figure A10.2 Substation-90: Breaker and a half plus double bus Configuration, Single Line Diagram

Protection and Control of Substation 90
Description of Substation 90

The substation-90 has a breaker and a half plus double bus configuration. Figure 10.3 shows the co-model of Substation-90 (power system + protection and control). The protection zones defined in Substation-90 can be seen in the figure. Substation 90 has seven protection zones: (a) five, line protection zones, (b) one transformer protection zone and (c) one Busbar protection zone. There are twenty-five MUs in Substation-90. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

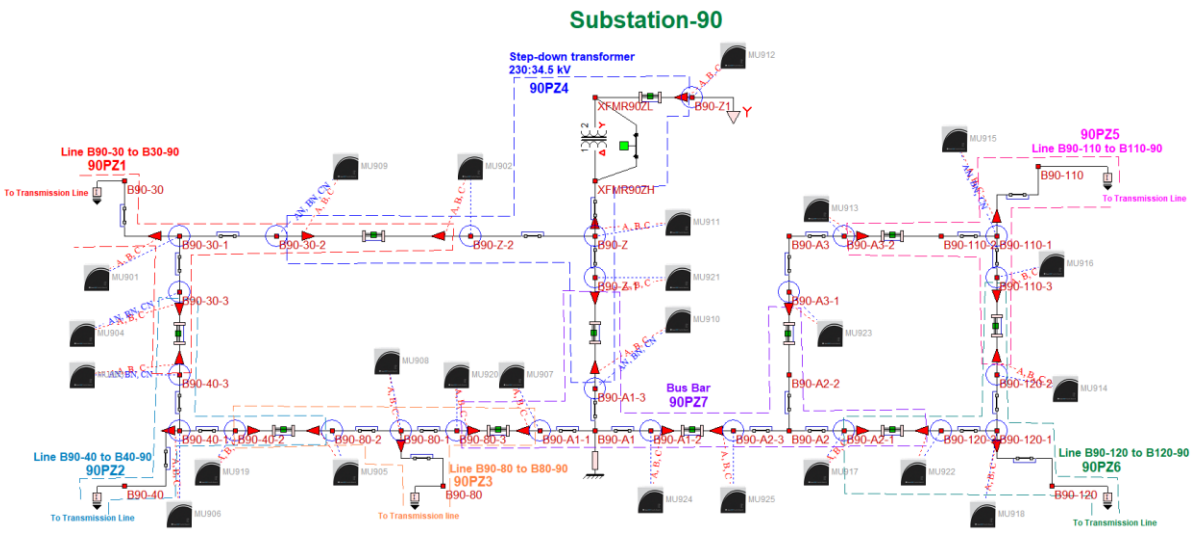


Figure A10.3 Co-model of Substation-90: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 90PZ1 protects the transmission line B90-30 to B30-90, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 90PZ2 protects the transmission line B90-40 to B40-90, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 90PZ3 protects the transmission line B90-80 to B80-90, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 90PZ4 protects the step-down transformer XFMR90ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 90PZ5 protects the transmission line B90-110 to B110-90, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

6. 90PZ6 protects the transmission line B90-120 to B120-90, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 90PZ7 protects the Busbar B90-A1-2 to B90-A2-3, it has one busbar (made up of the circuit breaker B90-A1-2 to B90-A2-3), four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and nine merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 90PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B90-30 to B30-90, the transmission line is a 138 kV line that is 30.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size FLICKER/SSAC with an Ampacity of 690.9 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 90 and 30 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B90-30-2 to B90-Z-2 and B90-30-3 to B90-40-3 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B90-30-2 to B90-Z-2 and B90-30-3 to B90-40-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B90-30-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU901, MU902, MU903, MU904, and MU909 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 90PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B90-40 to B40-90, the transmission line is a 138 kV line that is 26.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 90 and 40 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B90-30-3 to B90-40-3 and B90-40-2 to B90-80-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B90-30-3 to B90-40-3 and B90-40-2 to B90-80-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B90-40-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU903, MU904, MU905, MU906, and MU919 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 90PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B90-80 to B80-90, the transmission line is a 138 kV line that is 42.9 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 90 and 80 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B90-80-3 to B90-A1-1 and B90-40-2 to B90-80-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B90-80-3 to B90-A1-1 and B90-40-2 to B90-80-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B90-80-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

6. 21MG/21MP: Mho ground/phase Distance protection.
1. 21XG/21XP: Quadrilateral ground/phase Distance protection.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU905, MU907, MU908, MU919, and MU920 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 90PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 50 MVA rating. It is a step-down XFMR with a setting of 138:34.5 kV. The 34.5kV is Wye connected and the 138kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR90ZL to B90-Z1) and has a rating of 34.5kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B90-30-2 to B90-Z-2; B90-Z-1 to B90-A1-3) and have a rating of 138kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B90-30-2 to B90-Z-2; B90-Z-1 to B90-A1-3). One unit collecting the voltage and current measurements at node B100-Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (XFMR90ZL to B90-Z1).

Note: As an example, XFMR90ZL is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU902, MU909, MU910, MU911, MU912 and MU921 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 90PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B90-110 to B110-90, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 90 and 110 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B90-A3-2 to B90-110-2 and B90-110-3 to B90-120-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B90-A3-2 to B90-110-2 and B90-110-3 to B90-120-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B90-110-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using four merging units namely MU913, MU914, MU915 and MU916 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 90PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B90-120 to B120-90, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK /SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 90 and 120 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B90-A2-1 to B90-120-3 and B90-110-3 to B90-120-2 respectively. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers

(PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B90-A2-1 to B90-120-3 and B90-110-3 to B90-120-2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B90-120-1.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU914, MU916, MU917, MU918 and MU922 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 90PZ7

This protection zone consists of:

1. Five Circuit Breakers, one of the circuit breakers forms the main busbar B90-A1-2 to B90-A2-3, the other breakers are: B90-Z-1 to B90-A1-3, B90-80-3 to B90-A1-1, B90-A3-1 to B90-A2-2 and B90-A2-1 to B90-120-3. These circuit breakers have a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, they have one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. There are nine Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B90-A1-2 to B90-A2-3, B90-Z-1 to B90-A1-3, B90-80-3 to B90-A1-1, B90-A3-1 to B90-A2-2 and B90-A2-1 to B90-120-3.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using nine merging units namely MU907, MU910, MU917, MU920, MU921, MU922, MU923, MU924 and MU925 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-11. Substation-110 System Description

This section of the document describes the Substation-110 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 11.1 shows the single line diagram of the system network model of Substation-110. There are two 230 kV transmission lines. These devices connect Substation-110 with other substations including Substation 140 (transmission line B110-140 to B140-110) and Substation 130 (transmission line B110-130 to B130-110). In addition, there are two 138 kV lines that are connected to two 138 kV substations namely Substation 90 (transmission line B110-90 to B90-110) and Substation 100 (transmission line B110-100 to B100-110 respectively as can be seen in the figure. It can be noted that Substation-110 acts as an intermediate substation that connects the 138kV portion of the 24 Substation system to the 230 kV side. Therefore, it contains two grid transformers that step-down the voltage from 230 kV to 138 kV, these transformers are connected respectively to the 138 kV transmission lines within the Substation.

The single line diagram of Substation-110 is shown in Figure 11.2. Substation-110 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of two 230 kV lines and two 138 kV lines connecting Substation 110 to Substations 140,130,100 and 90, two step-down grid transformers and multiple substation buses. The substation model is represented with twenty-five (25) three-phase nodes, eight (8) circuit breakers, and sixteen (16) isolation switches that can be used to isolate or control a zone within the substation.

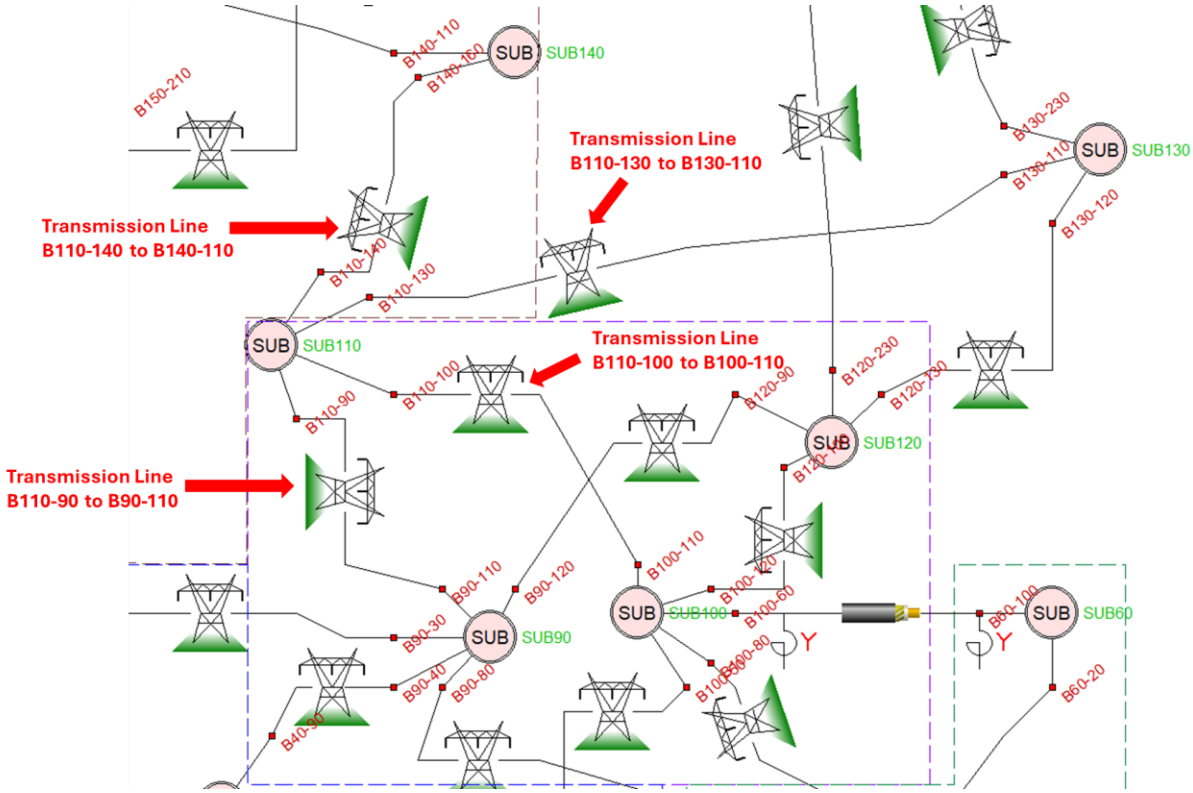


Figure A11.0.6 Single line diagram of network connected to Substation-110.

Note: Substation-110 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

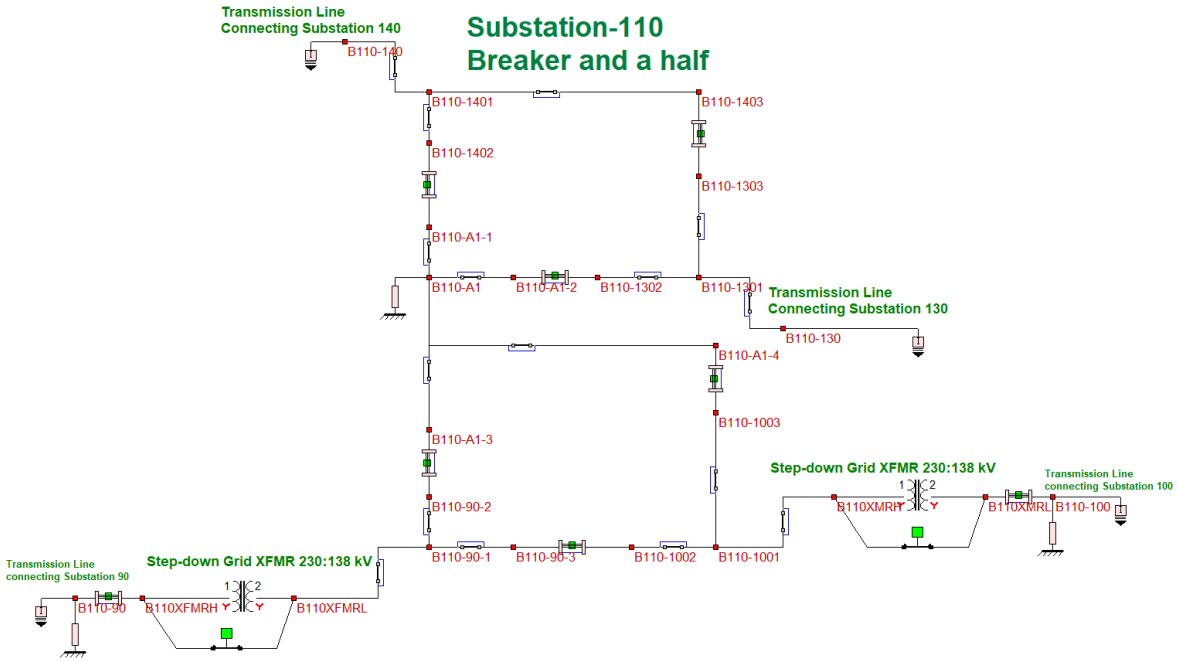


Figure A11.2 Substation-110: Breaker and a half Configuration, Single Line Diagram

Protection and Control of Substation 110
Description of Substation 110

The substation-110 has a breaker and a half configuration. Figure 11.3 shows the co-model of Substation-110 (power system + protection and control). The protection zones defined in Substation-110 can be seen in the figure Substation 110 has six protection zones: (a) four transmission line protection zones, (b) two transformer protection zones. There are sixteen MUs in Substation-110. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

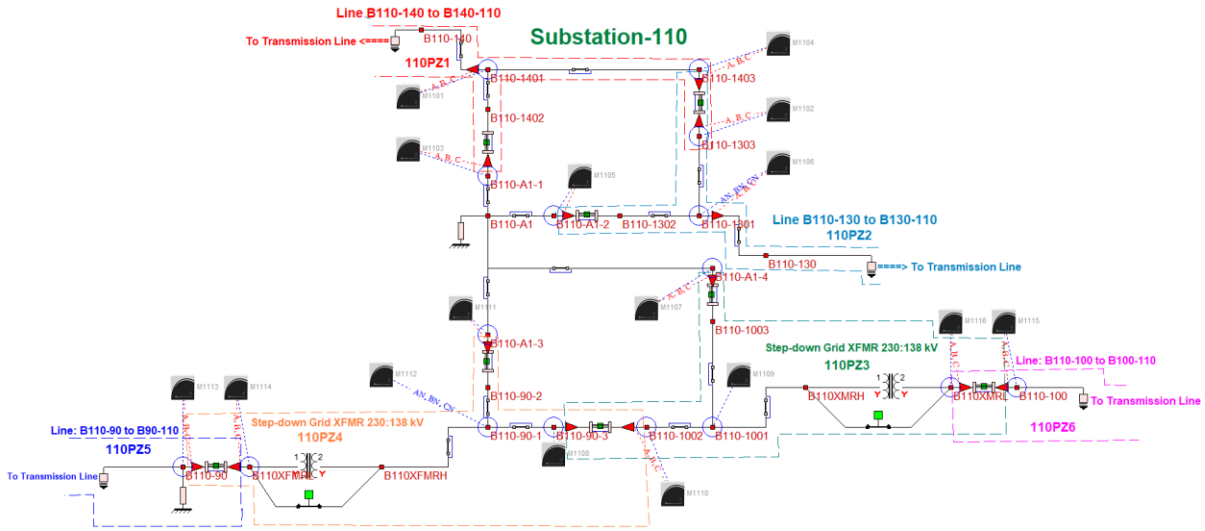


Figure A11.3 Co-model of Substation-110: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The six protection zones are briefly described below.

1. 110PZ1 protects the transmission line B110-140 to B140-110, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 110PZ2 protects the transmission line B110-130 to B130-110, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 110PZ3 protects the step-down transformer B110XMRL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers

(CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

4. 110PZ4 protects the step-down transformer B110XFMRL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 110PZ5 protects the transmission line B110-90 to B90-110, it has one transmission line, one circuit breaker, with two sets of three phase current and voltage transformers (CTs/PTs) and two merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 110PZ6 protects the transmission line B110-100 to B100-110, it has one transmission line, one circuit breaker, with two sets of three phase current and voltage transformers (CTs/PTs) and two merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 110PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B110-140 to B140-110, the transmission line is a 230 kV line that is 29 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 110 and 140 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B110-1402 to B110-A1-1 and B110-1403 to B110-1303 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B110-1402 to B110-A1-1 and B110-1403 to B110-1303). One unit collects the voltage and current measurements from the CTs and PTs, at the node B110-1401.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using four merging units namely MU1101, MU1102, MU1103 and MU1104 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 110PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B110-130 to B130-110, the transmission line is a 230 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 110 and 130 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B110-1302 to B110-A1-2 and B110-1403 to B110-1303 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B110-1302 to B110-A1-2 and B110-1403 to B110-1303). One unit collects the voltage and current measurements from the CTs and PTs, at the node B110-1301.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using four merging units namely MU1102, MU1104, MU1105 and MU1106 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 110PZ3
This protection zone consists of:

1. A three phase grid-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:138 kV. The 138kV is Wye connected and the 230kV is also Wye connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the 138 kV wye terminal of the transformer (B110XMRL to B110-100) and has a rating of 138kV and a 40kA interrupt capability. There are two circuit breakers connected to the 230 kV Wye terminal of the XFMR (B110-A1-4 to B110-1003 and B110-90-3 to B110-1002) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B110-A1-4 to B110-1003 and B110-90-3 to B110-1002). One unit collecting the voltage and current

measurements at node B110-1001 and two units collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B110XMRL to B110-100).

Note: As an example, B110-XMRL is a node.

For EBP:

An EBP relay monitors the transformer protection zone.

For Legacy Protection:

A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU1107, MU1108, MU1109, MU1110, MU1115 and MU1116 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 110PZ4

This protection zone consists of:

1. A three phase grid-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:138 kV. The 138kV is Wye connected and the 230kV is also Wye connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the 138 kV wye terminal of the transformer (B110XFMRL to B110-90) and has a rating of 138kV and a 40kA interrupt capability. There are two circuit breakers connected to the 230 kV Wye terminal of the XFMR (B110-A1-3 to B110-90-2 and B110-90-3 to B110-1002) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B110-A1-3 to B110-90-2 and B110-90-3 to B110-1002). One unit collecting the voltage and current measurements at node B110-90-1 and two units collects the voltage and current measurements

from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B110XFMRL to B110-90).

Note: As an example, B110-XMRL is a node.

For EBP:

An EBP relay monitors the transformer protection zone.

For Legacy Protection:

A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU1108, MU1110, MU1111, MU1112, MU1113 and MU1114 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 110PZ5

This protection zone consists of:

1. The transmission line that is connected between buses B110-90 to B90-110, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 110 and 90 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. One circuit breaker is connected from nodes B110-90 to B110XFMRL. The circuit breaker has a rated voltage of 138kV and interrupt capability of 40kA. The neutral of this breaker is closed. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are two Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker (B110-90 to B110XFMRL).

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using two merging units namely MU1113 and MU1114 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 110PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B110-100 to B100-110, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 110 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. One circuit breaker is connected from nodes B110-100 to B110XMRL. The circuit breaker has a rated voltage of 138kV and interrupt capability of 40kA. The neutral of this breaker is closed. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are two Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker (B110-100 to B110XMRL).

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using two merging units namely MU1115 and MU1116 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-12. Substation-120 System Description

This section of the document describes the Substation-120 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 12.1 shows the single line diagram of the system network model of Substation-120. There are two 230 kV transmission lines. These devices connect Substation-120 with other substations including Substation 130 (transmission line B120-130 to B130-120) and Substation 230 (transmission line B120-230 to B230-120). In addition, there are two 138 kV lines that are connected to two 138 kV substations namely Substation 90 (transmission line B120-90 to B90-120) and Substation 100 (transmission line B120-100 to B100-120 respectively as can be seen in the figure. It can be noted that Substation-120 acts as an intermediate substation that connects the 138kV portion of the 24 Substation system to the 230 kV side. Therefore, it contains two grid transformers that step-down the voltage from 230 kV to 138 kV, these transformers are connected respectively to the 138 kV transmission lines within the Substation.

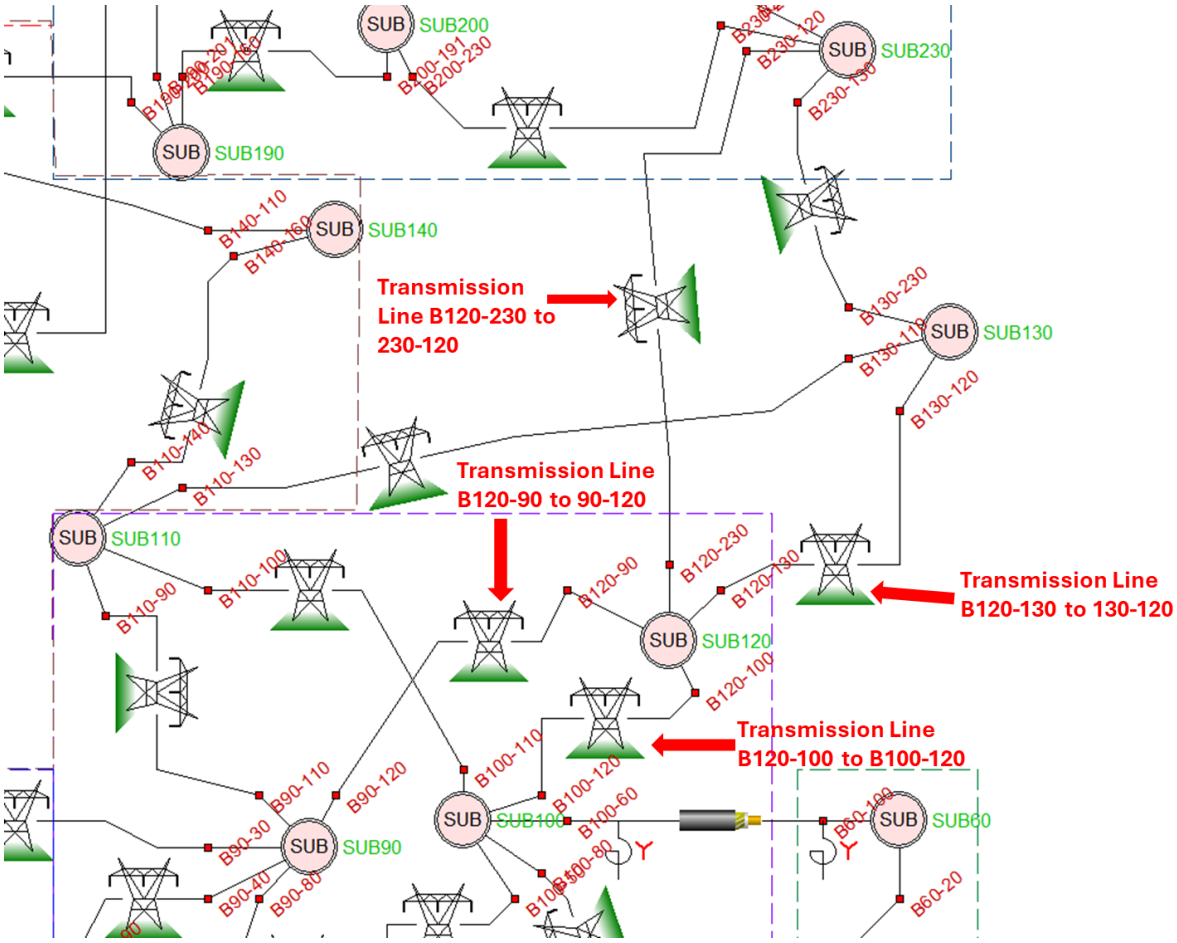


Figure A12.0.7 Single line diagram of network connected to Substation-120.

The single line diagram of Substation-120 is shown in Figure 12.2. Substation-120 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of two 230 kV lines and two 138 kV lines connecting Substation 120 to Substations 130,230,100 and 90, two step-down grid transformers and multiple substation buses. The substation model is represented with twenty-five (25) three-phase nodes, eight (8) circuit breakers, and sixteen (16) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-120 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

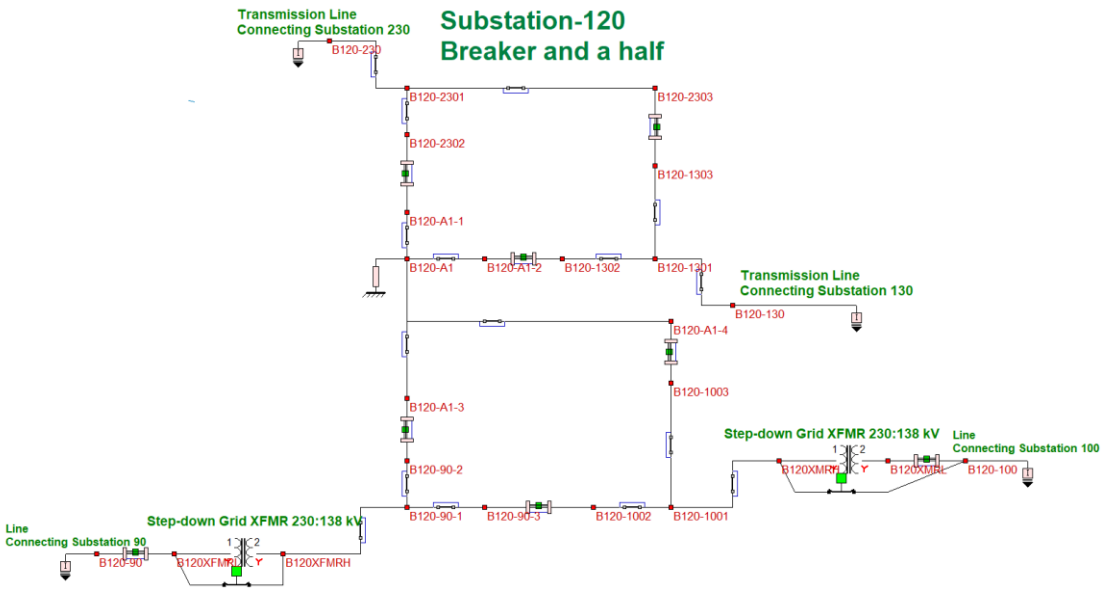


Figure A12.2 Substation-120: Breaker and a half Configuration, Single Line Diagram

Protection and Control of Substation 120
Description of Substation 120

The substation-120 has a breaker and a half configuration. Figure 12.3 shows the co-model of Substation-120 (power system + protection and control). The protection zones defined in Substation-120 can be seen in the figure. Substation 120 has six protection zones: (a) four transmission line protection zones, (b) two transformer protection zones. There are sixteen MUs in Substation-120. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

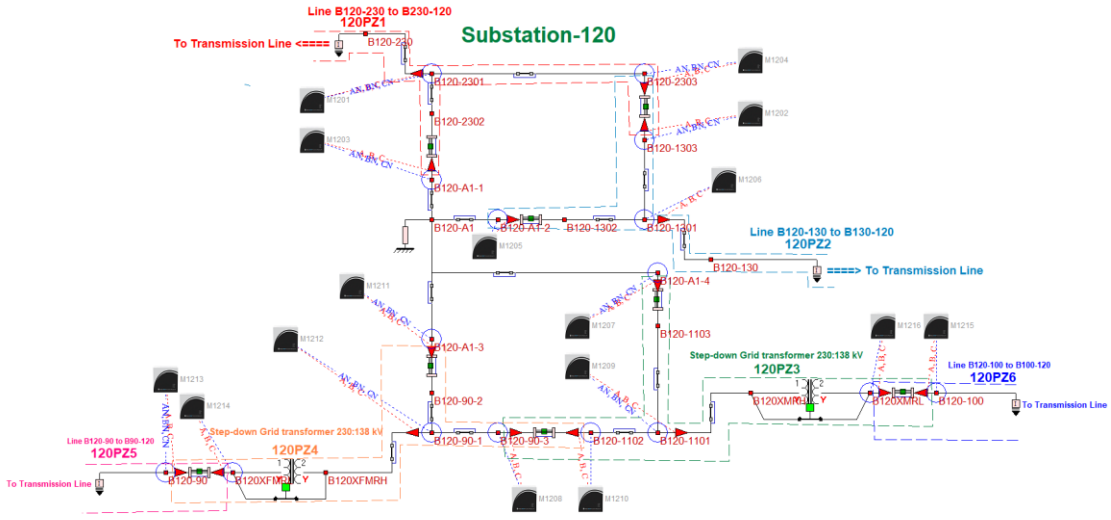


Figure A12.3 Co-model of Substation-120: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The six protection zones are briefly described below.

1. 120PZ1 protects the transmission line B120-230 to B230-120, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 120PZ2 protects the transmission line B120-130 to B130-120, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 120PZ3 protects the step-down transformer B120XMRL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 120PZ4 protects the step-down transformer B120XFMRL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 120PZ5 protects the transmission line B120-90 to B90-120, it has one transmission line, one circuit breaker, with two sets of three phase current and voltage transformers (CTs/PTs) and two merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 120PZ6 protects the transmission line B120-100 to B100-120, it has one transmission line, one circuit breaker, with two sets of three phase current and voltage transformers (CTs/PTs) and two merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 120PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B120-230 to B230-120, the transmission line is a 230 kV line that is 67 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size REDBIRD/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.

5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 120 and 230 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B120-2303 to B120-1303 and B120-2302 to B120-A1-1 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B120-2303 to B120-1303 and B120-2302 to B120-A1-1). One unit collects the voltage and current measurements from the CTs and PTs, at the node B120-2301.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using four merging units namely MU1201, MU1202, MU1203 and MU1204 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 120PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B120-130 to B130-120, the transmission line is a 230 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.

2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 120 and 130 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B120-1302 to B120-A1-2 and B120-2303 to B120-1303 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B120-1302 to B120-A1-2 and B120-2303 to B120-1303). One unit collects the voltage and current measurements from the CTs and PTs, at the node B120-1301.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using four merging units namely MU1202, MU1204, MU1205 and MU1206 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 120PZ3
This protection zone consists of:

1. A three phase grid-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:138 kV. The 138kV is Wye connected and the 230kV is also Wye connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the 138 kV wye terminal of the transformer (B120XMRL to B120-100) and has a rating of 138kV and a 40kA interrupt capability. There are two circuit breakers connected to the 230 kV Wye terminal of the XFMR (B120-A1-4 to B120-1103 and B120-90-3 to B110-1102) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B120-A1-4 to B120-1103 and B120-90-3 to B110-1102). One unit collecting the voltage and current measurements at node B120-1101 and two units collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B120XMRL to B120-100).

Note: As an example, B110-XMRL is a node.

For EBP:

An EBP relay monitors the transformer protection zone.

For Legacy Protection:

A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU1207, MU1208, MU1209, MU1210, MU1215 and MU1216 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 120PZ4

This protection zone consists of:

1. A three phase grid-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:138 kV. The 138kV is Wye connected and the 230kV is also Wye connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the 138 kV wye terminal of the transformer (B120XFMRL to B120-90) and has a rating of 138kV and a 40kA interrupt capability. There are two circuit breakers connected to the 230 kV Wye terminal of the XFMR (B120-A1-3 to B120-90-2 and B120-90-3 to B120-1102) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B120-A1-3 to B120-90-2 and B120-90-3 to B120-1102). One unit collecting the voltage and current measurements at node B120-90-1 and two units collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the wye terminal of the transformer (B120XFMRL to B120-90).

Note: As an example, B110-XMRL is a node.

For EBP: An EBP relay monitors the transformer protection zone.
For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using six merging units namely MU1208, MU1210, MU1211, MU1212, MU1213 and MU1214 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5 – 120PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B120-90 to B90-120, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 120 and 90 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. One circuit breaker is connected from nodes B120-90 to B120XFMRL. The circuit breaker has a rated voltage of 138kV and interrupt capability of 40kA. The neutral of this breaker is closed. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are two Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker (B120-90 to B120XFMRL).

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using two merging units namely MU1213 and MU1214 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 120PZ6
This protection zone consists of:
1. The transmission line that is connected between buses B120-100 to B100-120, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 120 and 100 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. One circuit breaker is connected from nodes B120-100 to B120XMRL. The circuit breaker has a rated voltage of 138kV and interrupt capability of 40kA. The neutral of this breaker is closed. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are two Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker (B120-100 to B120XMRL).

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:
1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using two merging units namely MU1215 and MU1216 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-13. Substation-130 System Description

This section of the document describes the Substation-130 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 13.1 shows the single line diagram of the system network model of Substation-130. There are three 230 kV transmission lines. These devices connect Substation-130 with other substations including Substation 110 (transmission line B130-110 to B110-130), Substation 120 (transmission line B130-120 to B120-130) and Substation 230 (transmission line B130-230 to B230-130) as can be seen in the figure.

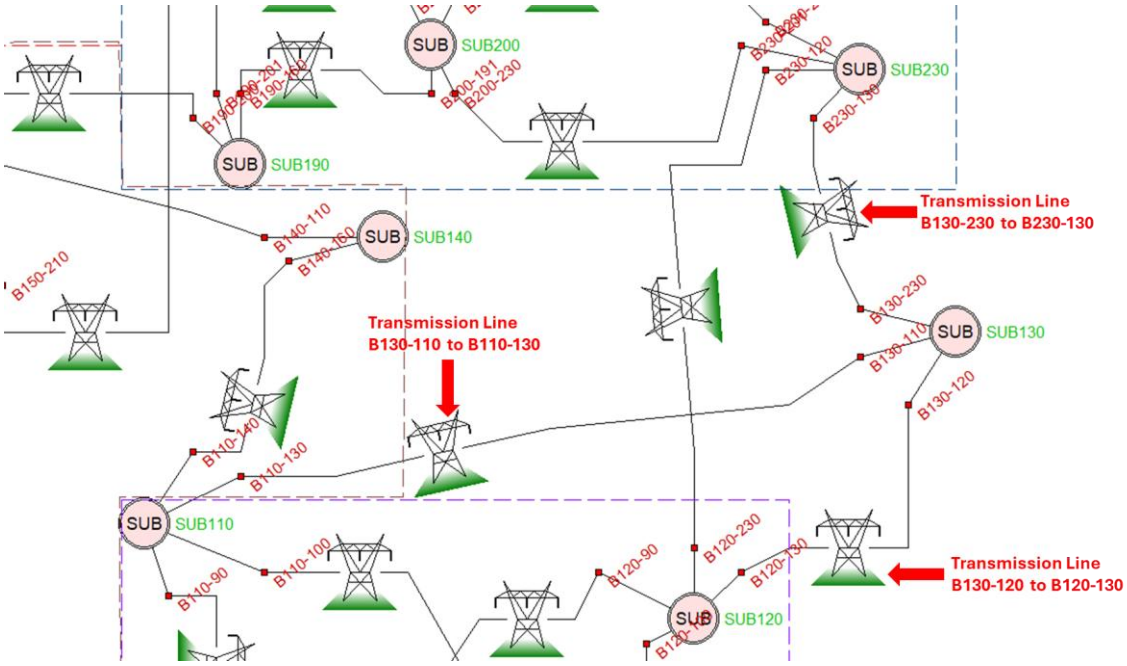


Figure A13.0.8 Single line diagram of system network connected to Substation-130.

The single line diagram of Substation-130 is shown in Figure 13.2. Substation-130 is a 230 kV substation. It has a ring bus arrangement. This substation consists of three 230 kV lines connecting Substation 130 to Substations 110, 120 and 230, three generator/inverter-step-up transformer units, one step-down transformer unit and multiple substation buses. The substation model is represented with thirty-six (36) three-phase nodes, eleven (11) circuit breakers, and twenty-one (21) isolation switches that can be used to isolate or control a zone within the substation. Note: Substation-130 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

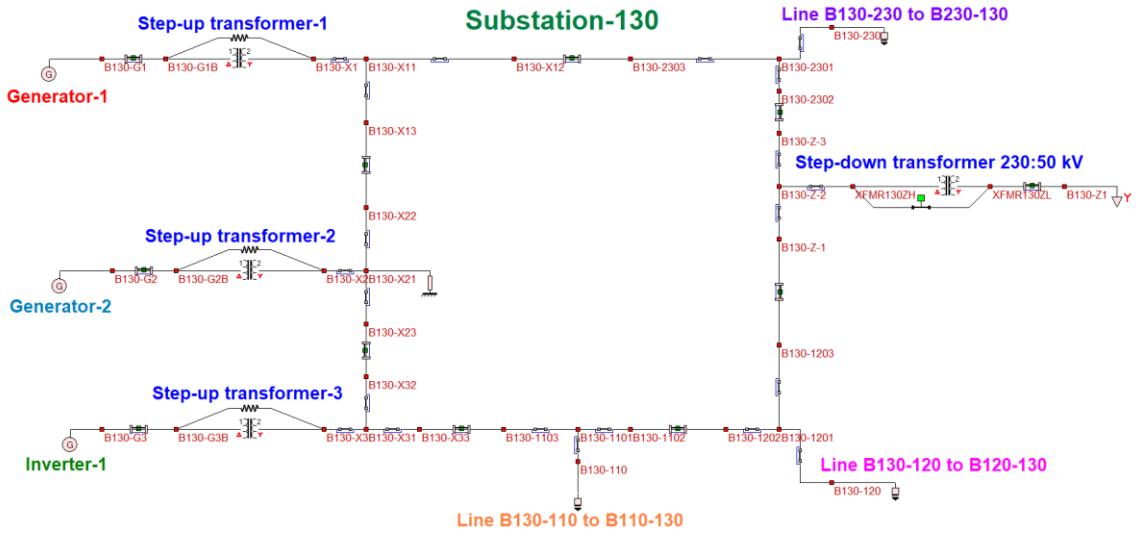


Figure A13.2 Substation-130: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 130
Description of Substation 130

The substation-130 has a ring bus configuration. Figure 13.3 shows the co-model of Substation-130 (power system + protection and control). The protection zones defined in Substation-130 can be seen in the figure. Substation 130 has seven protection zones: (a) three transmission line protection zones, (b) one transformer protection zone and (c) three generator/inverter-transformer unit protection zones. There are twenty-five MUs in Substation-130. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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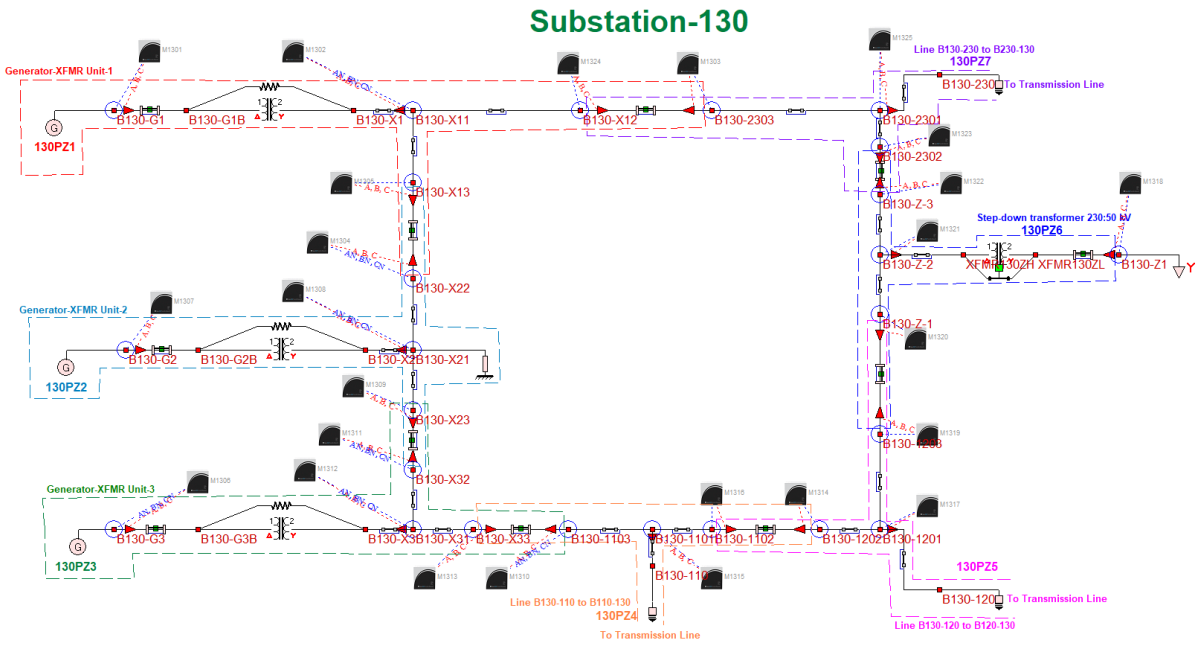


Figure A13.3 Co-model of Substation-130: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 130PZ1 protects the generator-XFMR at B130-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 130PZ2 protects the generator-XFMR at B130-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

3. 130PZ3 protects the inverter-XFMR at B130-G3, it has one inverter, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 130PZ4 protects the transmission line B130-110 to B110-130, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 130PZ5 protects the transmission line B130-120 to B120-130, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 130PZ6 protects the step-down transformer XFMR130ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 130PZ7 protects the transmission line B130-230 to B230-130, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 130PZ1

This protection zone consists of:

1. A three phase generator that has a 115kV, 197 MVA rating. A step-up XFMR with a setting of 115:230kV, 200 MVA. The 230 kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B130-G1 to B130-G1B) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B130-X12 to B130-2303; B130-X13 to B130-X22) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

4. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer

(B130-X12 to B130-2303; B130-X13 to B130-X22).One unit collects the voltage and current measurements from the CTs and PTs at node B130-X11. One unit collects the voltage and current measurements from the CTs and PTs, at node B130-G1.

For EBP: An EBP relay monitors the unit protection zone.

For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using six merging units namely MU1301, MU1302, MU1303, MU1304, MU1305 and MU1324 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 130PZ2

This protection zone consists of:

1. A three phase generator that has a 115kV, 197 MVA rating. A step-up XFMR with a setting of 115:230kV, 200 MVA. The 230 kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B130-G2 to B130-G2B) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B130-X23 to B130-X32; B130-X13 to B130-X22) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B130-X23 to B130-X32; B130-X13 to B130-X22).One unit collects the voltage and current measurements from

the CTs and PTs at node B130-X21. One unit collects the voltage and current measurements from the CTs and PTs, at node B130-G2.

For EBP:

An EBP relay monitors the unit protection zone.

For Legacy Protection:

A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 2 are collected using six merging units namely MU1304, MU1305, MU1307, MU1308, MU1309 and MU1311 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 130PZ3

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 100 MVA. The 230 kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B130-G3 to B130-G3B) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B130-X23 to B130-X32; B130-X33 to B130-1103) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B130-X23 to B130-X32; B130-X33 to B130-1103).One unit collects the voltage and current measurements

from the CTs and PTs at node B130-X31. One unit collects the voltage and current measurements from the CTs and PTs, at node B130-G3.

For EBP:

An EBP relay monitors the unit protection zone.

For Legacy Protection:

A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 3 are collected using six merging units namely MU1306, MU1309, MU1310, MU1311, MU1312 and MU1313 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 130PZ4

This protection zone consists of:

1. The transmission line that is connected between buses B130-110 to B110-130, the transmission line is a 230 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 130 and 110 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B130-X33 to B130-1103 and B130-1102 to B130-1202 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and

Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B130-X33 to B130-1103 and B130-1102 to B130-1202). One unit collects the voltage and current measurements from the CTs and PTs, at the node B130-1101.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU1310, MU1313, MU1314, MU1315, and MU1316 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 5 – 130PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B130-120 to B120-130, the transmission line is a 230 kV line that is 33 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 130 and 120 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B130-1203 to B130-Z-1 and B130-1102 to B130-1202 respectively. These circuit breakers have a rated voltage of

230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B130-1203 to B130-Z-1 and B130-1102 to B130-1202). One unit collects the voltage and current measurements from the CTs and PTs, at the node B130-1201.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU1314, MU1316, MU1317, MU1319, and MU1320 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 130PZ6
This protection zone consists of:

1. A three phase load-XFMR that has a 60 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR130ZL to B130-Z1) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B130-2302 to B130-Z-3; B130-Z-1 to B130-1203) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes.

These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B130-2302 to B130-Z-3; B130-Z-1 to B130-1203).One unit collecting the voltage and current measurements at node B130-Z-2 and one unit collects the voltage and current measurements from the CTs and PTs, at the node B130-Z1.

For EBP: An EBP relay monitors the transformer protection zone.
For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 6 are collected using six merging units namely MU1318, MU1319, MU1320, MU1321, MU1322 and MU1323 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 7 – 130PZ7

This protection zone consists of:

1. The transmission line that is connected between buses B130-230 to B230-130, the transmission line is a 230 kV line that is 60.2 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 130 and 230 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B130-2303 to B130-X12 and B130-2302 to B130-Z-3 respectively. These circuit breakers have a rated voltage of

230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B130-2303 to B130-X12 and B130-2302 to B130-Z-3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B130-2301.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU1303, MU1322, MU1323, MU1324 and MU1325 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-14. Substation-230 System Description

This section of the document describes the Substation-230 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 14.1 shows the single line diagram of the system network model of Substation-230. There are four 230 kV transmission lines. These devices connect Substation-230 with other substations including Substation 200 (transmission line B230-201 to B200-231 and B230-202 to B200-232), Substation 120 (transmission line B230-120 to B120-230) and Substation 130 (transmission line B230-130 to B130-230) as can be seen in the figure.

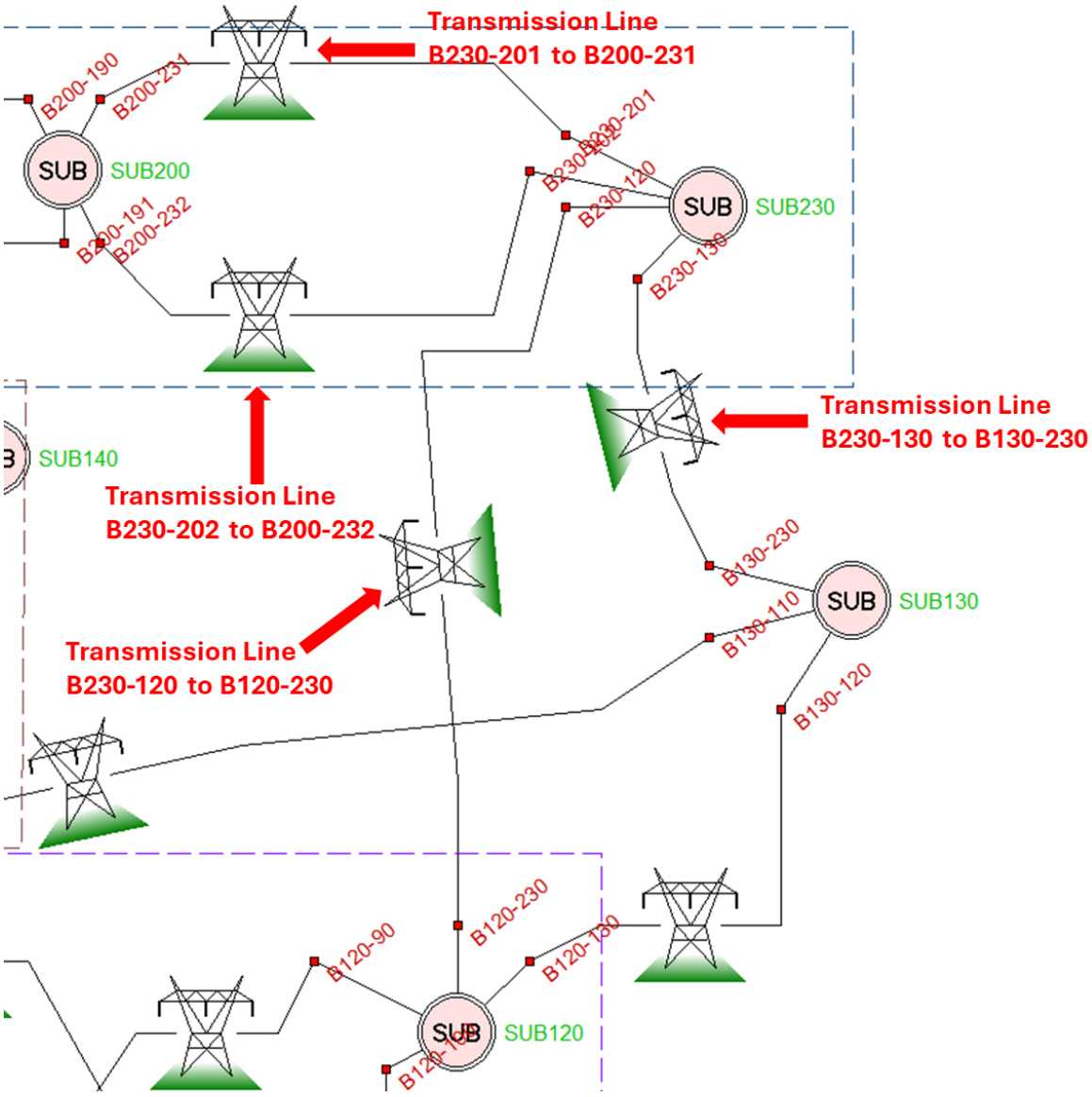


Figure A14.0.9 Single line diagram of system network connected to Substation-230.

The single line diagram of Substation-230 is shown in Figure 14.2. Substation-230 is a 230 kV substation. It has a ring bus arrangement. This substation consists of four 230 kV lines connecting Substation 230 to Substations 200, 120 and 130, three generator/inverter-step-up transformer units and multiple substation buses. The substation model is represented with thirty-four (34) three-phase nodes, ten (10) circuit breakers, and twenty-one (21) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-230 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

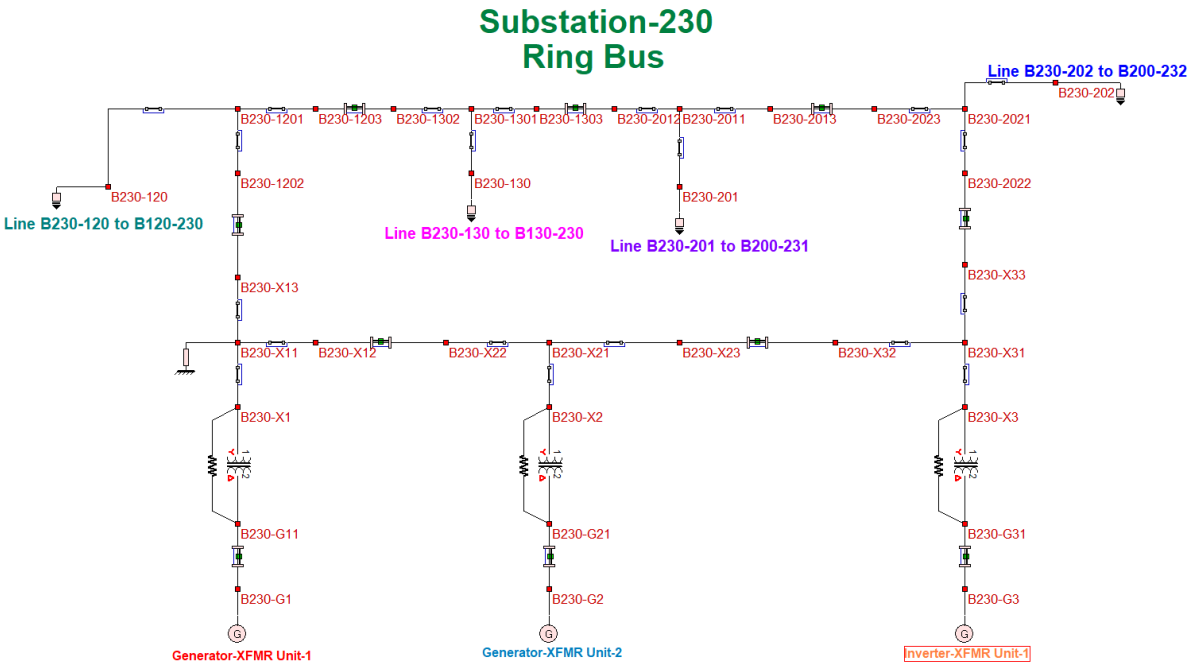


Figure A14.2 Substation-230: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 230
Description of Substation 230

The substation-230 has a ring bus configuration. Figure 14.3 shows the co-model of Substation-230 (power system + protection and control). The protection zones defined in Substation-230 can be seen in the figure. Substation 230 has seven protection zones: (a) four transmission line protection zones and (b) three generator/inverter-transformer unit protection zones. There are twenty-four MUs in Substation-230. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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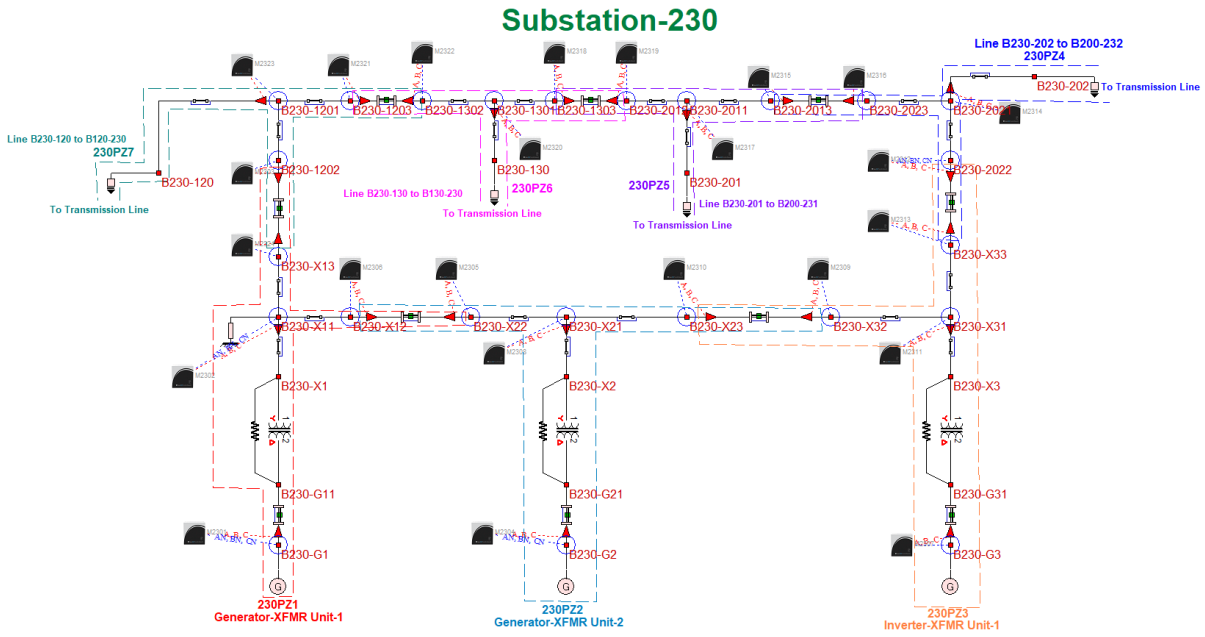


Figure A14.3 Co-model of Substation-230: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 230PZ1 protects the generator-XFMR at B230-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 230PZ2 protects the generator-XFMR at B230-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 230PZ3 protects the inverter-XFMR at B230-G3, it has one inverter, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 230PZ4 protects the transmission line B230-202 to B200-232, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 230PZ5 protects the transmission line B230-201 to B200-231, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

6. 230PZ6 protects the transmission line B230-130 to B130-230, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 230PZ7 protects the transmission line B230-120 to B120-230, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 230PZ1

This protection zone consists of:

1. A three phase generator that has a 115kV, 155 MVA rating. A step-up XFMR with a setting of 115:230kV, 155 MVA. The 230 kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B230-G1 to B230-G11) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B230-X13 to B230-1202; B230-X12 to B230-X22) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

4. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B230-X13 to B230-1202; B230-X12 to B230-X22).One unit collects the voltage and current measurements from the CTs and PTs at node B230-X11. One unit collects the voltage and current measurements from the CTs and PTs, at node B230-G1.

For EBP: An EBP relay monitors the unit protection zone.

For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using six merging units namely MU2301, MU2302, MU2303, MU2305, MU2306 and MU2324 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 230PZ2

This protection zone consists of:

1. A three phase generator that has a 115kV, 155 MVA rating. A step-up XFMR with a setting of 115:230kV, 155 MVA. The 230 kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B230-G2 to B230-G21) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B230-X23 to B230-X32; B230-X12 to B230-X22) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B230-X23 to B230-X32; B230-X12 to B230-X22) One unit collects the voltage and current measurements from the CTs and PTs at node B230-X21. One unit collects the voltage and current measurements from the CTs and PTs, at node B230-G2.

For EBP:

An EBP relay monitors the unit protection zone.

For Legacy Protection:

A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 2 are collected using six merging units namely MU2304, MU2305, MU2306, MU2308, MU2309 and MU2310 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 230PZ3

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 100 MVA. The 230 kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B230-G3 to B230-G31) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B230-X23 to B230-X32; B230-X33 to B230-2022) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B230-X23 to B230-X32; B230-X33 to B230-2022).One unit collects the voltage and current measurements from the CTs and PTs at node B130-X31. One unit collects the voltage and current measurements from the CTs and PTs, at node B230-G3.

For EBP:

An EBP relay monitors the unit protection zone.

For Legacy Protection:

A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 3 are collected using six merging units namely MU2307, MU2309, MU2310, MU2311, MU2312 and MU2313 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 230PZ4
This protection zone consists of:

1. The transmission line that is connected between buses B230-202 to B200-232, the transmission line is a 230 kV line that is 15 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 230 and 200 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B230-X33 to B230-2022 and B230-2023 to B230-2013 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B230-X33 to B230-2022 and B230-2023 to B230-2013). One unit collects the voltage and current measurements from the CTs and PTs, at the node B230-2021.

For EBP: An EBP relay monitors the transmission line protection zone.

For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU2312, MU2313, MU2314, MU2315, and MU2316 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 5 – 230PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B230-201 to B200-231, the transmission line is a 230 kV line that is 15 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 230 and 200 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B230-1303 to B230-2012 and B230-2023 to B230-2013 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B230-1303 to B230-2012 and B230-2023 to B230-2013). One unit collects the voltage and current measurements from the CTs and PTs, at the node B230-2011.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU2315, MU2316, MU2317, MU2318, and MU2319 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 230PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B230-130 to B130-230, the transmission line is a 230 kV line that is 60.2 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 130 and 230 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B230-1303 to B230-2012 and B230-1203 to B230-1302 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B230-1303 to B230-2012 and B230-1203 to B230-1302). One unit collects the voltage and current measurements from the CTs and PTs, at the node B230-1301.

For EBP: An EBP relay monitors the transmission line protection zone.

For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU2318, MU2319, MU2320, MU2321 and MU2322 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 230PZ7

This protection zone consists of:

1. The transmission line that is connected between buses B230-120 to B120-230, the transmission line is a 230 kV line that is 67 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size REDBIRD/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 230 and 120 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B230-1203 to B230-1302 and B230-1202 to B130-X13 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on

either side of the circuit breakers (B230-1203 to B230-1302 and B230-1202 to B130-X13). One unit collects the voltage and current measurements from the CTs and PTs, at the node B230-1201.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU2303, MU2321, MU2322, MU2323, and MU2324 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-15. Substation-200 System Description

This section of the document describes the Substation-200 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 15.1 shows the single line diagram of the system network model of Substation-200. There are four 230 kV transmission lines. These devices connect Substation-200 with other substations including Substation 190 (transmission line B200-191 to B190-201 and B200-192 to B190-202) and Substation 230 (transmission line B200-231 to B230-201 and B200-232 to B230-202) as can be seen in the figure.

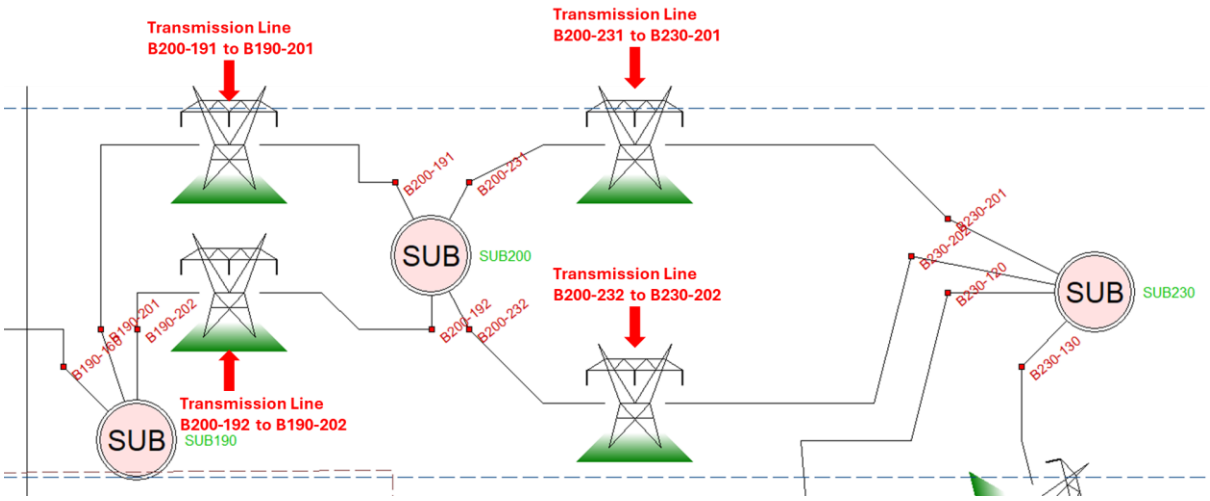


Figure A15.0.10 Single line diagram of system network connected to Substation-200.

The single line diagram of Substation-200 is shown in Figure 15.2. Substation-200 is a 230 kV substation. It has a ring bus arrangement. This substation consists of four 230 kV lines connecting Substation 200 to Substations 190 and 230, one step-down transformer unit and multiple substation buses. The substation model is represented with twenty-two (22) three-phase nodes, six (6) circuit breakers, and fifteen (15) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-200 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

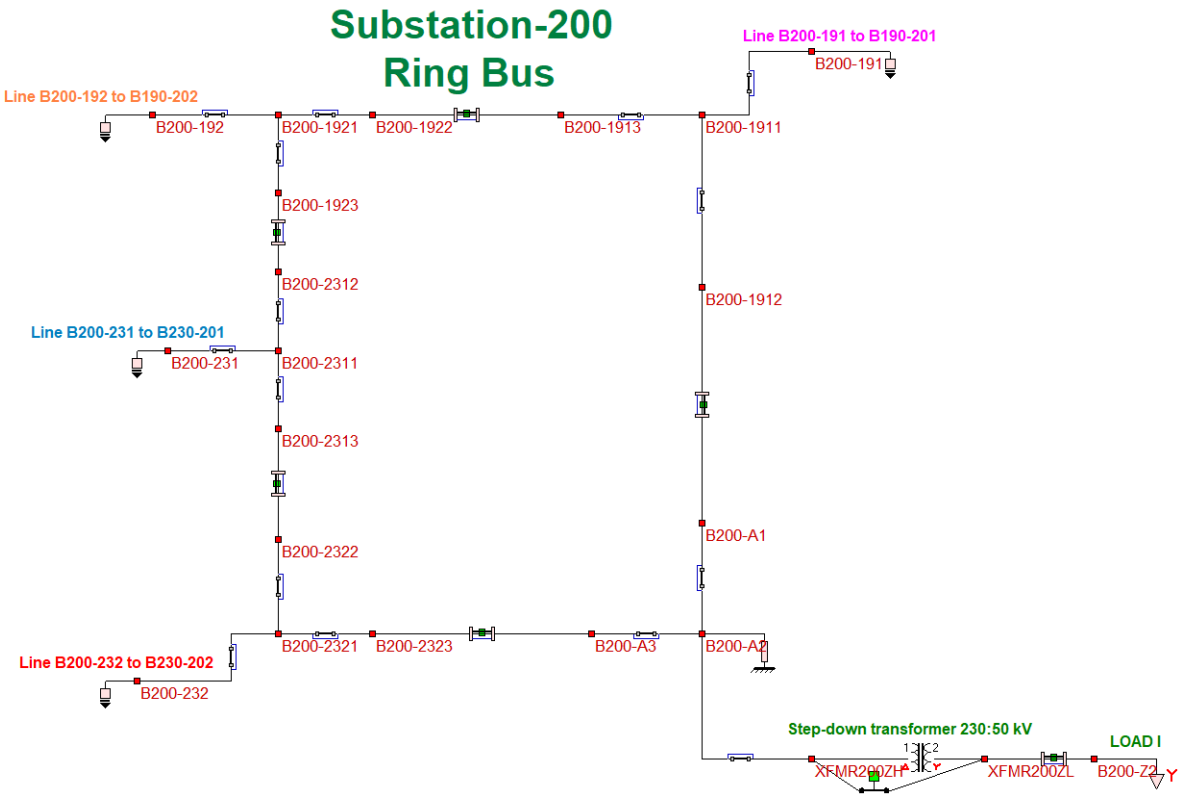


Figure A15.2 Substation-200: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 200
Description of Substation 200

The substation-200 has a ring bus configuration. Figure 15.3 shows the co-model of Substation-200 (power system + protection and control). The protection zones defined in Substation-200 can be seen in the figure. Substation 200 has five protection zones: (a) four transmission line protection zones and (b) one transformer protection zone. There are sixteen MUs in Substation-200. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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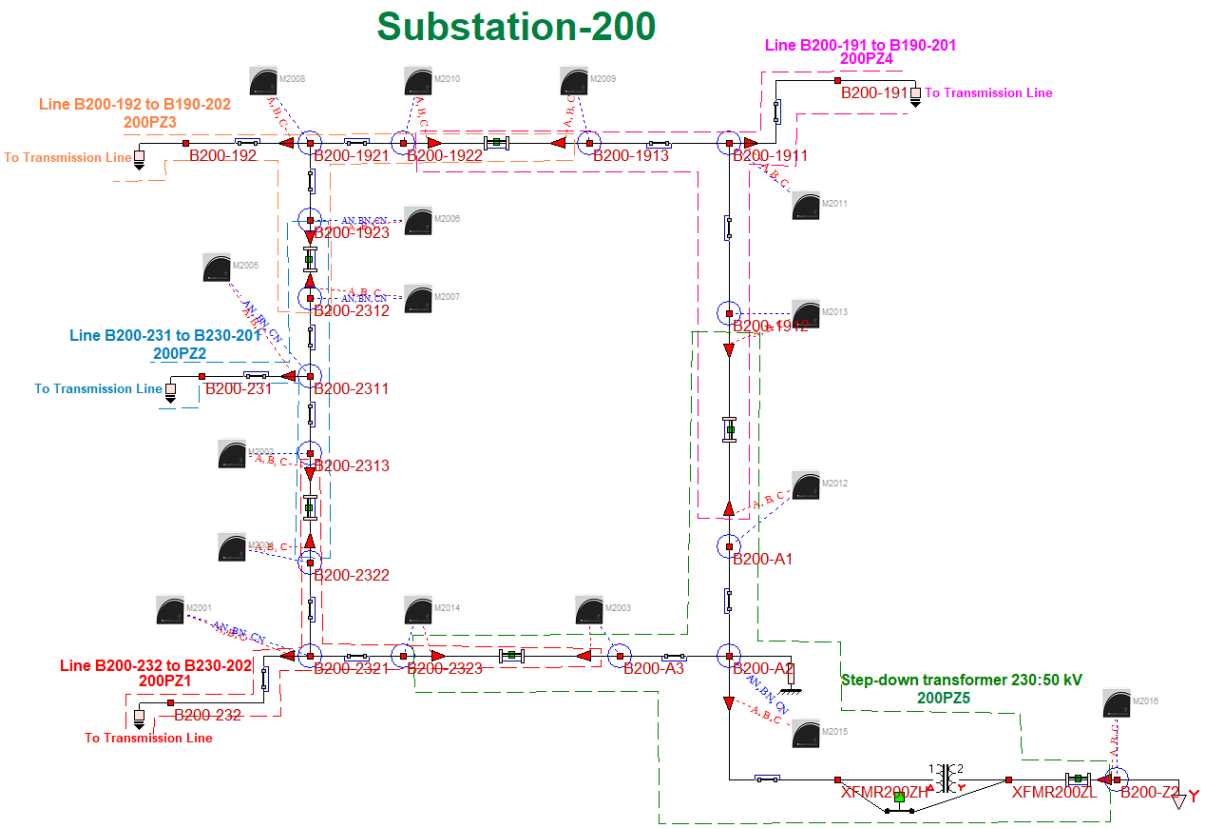


Figure A15.3 Co-model of Substation-200: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The five protection zones are briefly described below.

1. 200PZ1 protects the transmission line B200-232 to B230-202, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 200PZ2 protects the transmission line B200-231 to B230-201, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 200PZ3 protects the transmission line B200-192 to B190-202, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

4. 200PZ4 protects the transmission line B200-191 to B190-201, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 200PZ5 protects the step-down transformer XFMR200ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 200PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B200-232 to B230-202, the transmission line is a 230 kV line that is 15 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 230 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B200-2313 to B200-2322 and B200-2323 to B200-A3 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B200-2313 to B200-2322 and B200-2323 to B200-A3). One unit collects the voltage and current measurements from the CTs and PTs, at the node B200-2321.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU2001, MU2002, MU2003, MU2004, and MU2014 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 200PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B200-231 to B230-201, the transmission line is a 230 kV line that is 15 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 230 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B200-2313 to B200-2322 and B200-1923 to B200-2312 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B200-2313 to B200-2322 and B200-1923 to B200-2312). One unit collects the voltage and current measurements from the CTs and PTs, at the node B200-2311.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

6. 21MG/21MP: Mho ground/phase Distance protection.
1. 21XG/21XP: Quadrilateral ground/phase Distance protection.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU2002, MU2004, MU2005, MU2006, and MU2007 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 200PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B200-192 to B190-202, the transmission line is a 230 kV line that is 27.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B200-1922 to B200-1913 and B200-1923 to B200-2312 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B200-1922 to B200-1913 and B200-1923 to B200-2312). One unit collects the voltage and current measurements from the CTs and PTs, at the node B200-1921.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
5. 21XG/21XP: Quadrilateral ground/phase Distance protection.
6. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
7. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
8. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU2006, MU2007, MU2008, MU2009, and MU2010 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 200PZ4
This protection zone consists of:

1. The transmission line that is connected between buses B200-191 to B190-201, the transmission line is a 230 kV line that is 27.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B200-1922 to B200-1913 and B200-1912 to B200-A1 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B200-1922 to B200-1913 and B200-1912 to B200-A1). One unit collects the voltage and current measurements from the CTs and PTs, at the node B200-1911.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU2009, MU2010, MU2011, MU2012, and MU2013 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 5 – 200PZ5
This protection zone consists of:

1. A three phase load-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR200ZL to B200-Z2) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B200-1912 to B200-A1; B200-2323 to B200-A3) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B200-1912 to B200-A1; B200-2323 to B200-A3).One unit collecting the voltage and current measurements at node B200-A2 and one unit collects the voltage and current measurements from the CTs and PTs, at the node B200-Z2.

For EBP: An EBP relay monitors the transformer protection zone.

For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.

2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 6 are collected using six merging units namely MU2003, MU2012, MU2013, MU2014, MU2015 and MU2016 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-16. Substation-190 System Description

This section of the document describes the Substation-190 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 16.1 shows the single line diagram of the system network model of Substation-190. There are three 230 kV transmission lines. These devices connect Substation-190 with other substations including Substation 200 (transmission line B190-201 to B200-191 and B190-202 to B200-192) and Substation 160 (transmission line B190-160 to B160-190) as can be seen in the figure.

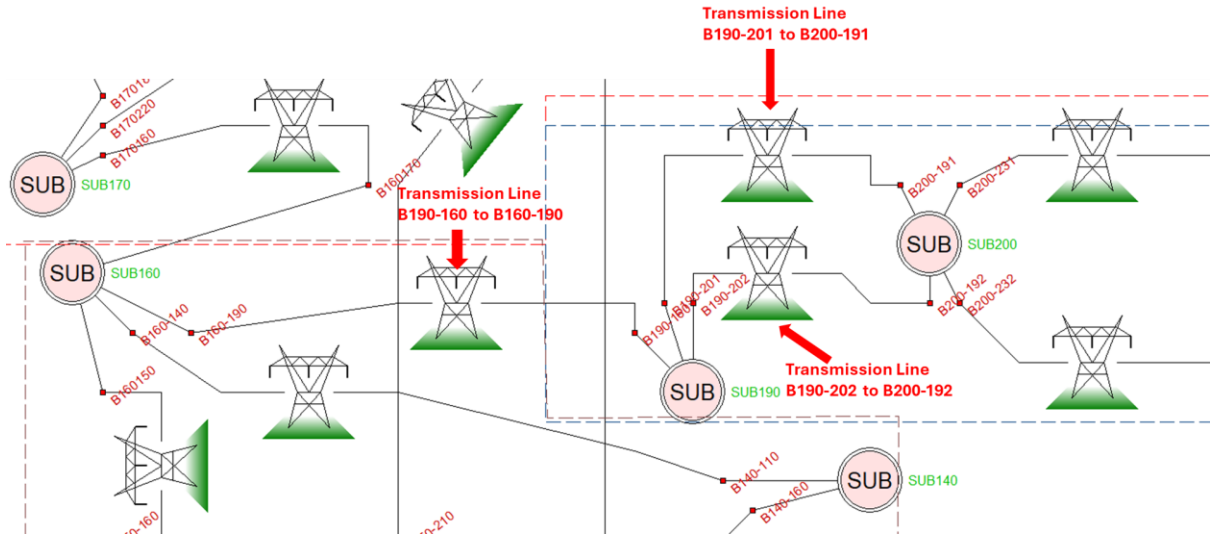


Figure A16.0.11 Single line diagram of system network connected to Substation-190.

The single line diagram of Substation-190 is shown in Figure 16.2. Substation-190 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of three 230 kV lines connecting Substation 190 to Substations 200 and 160, one step-down transformer unit and multiple substation buses. The substation model is represented with twenty-three (23) three-phase nodes, six (6) circuit breakers, and sixteen (16) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-190 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

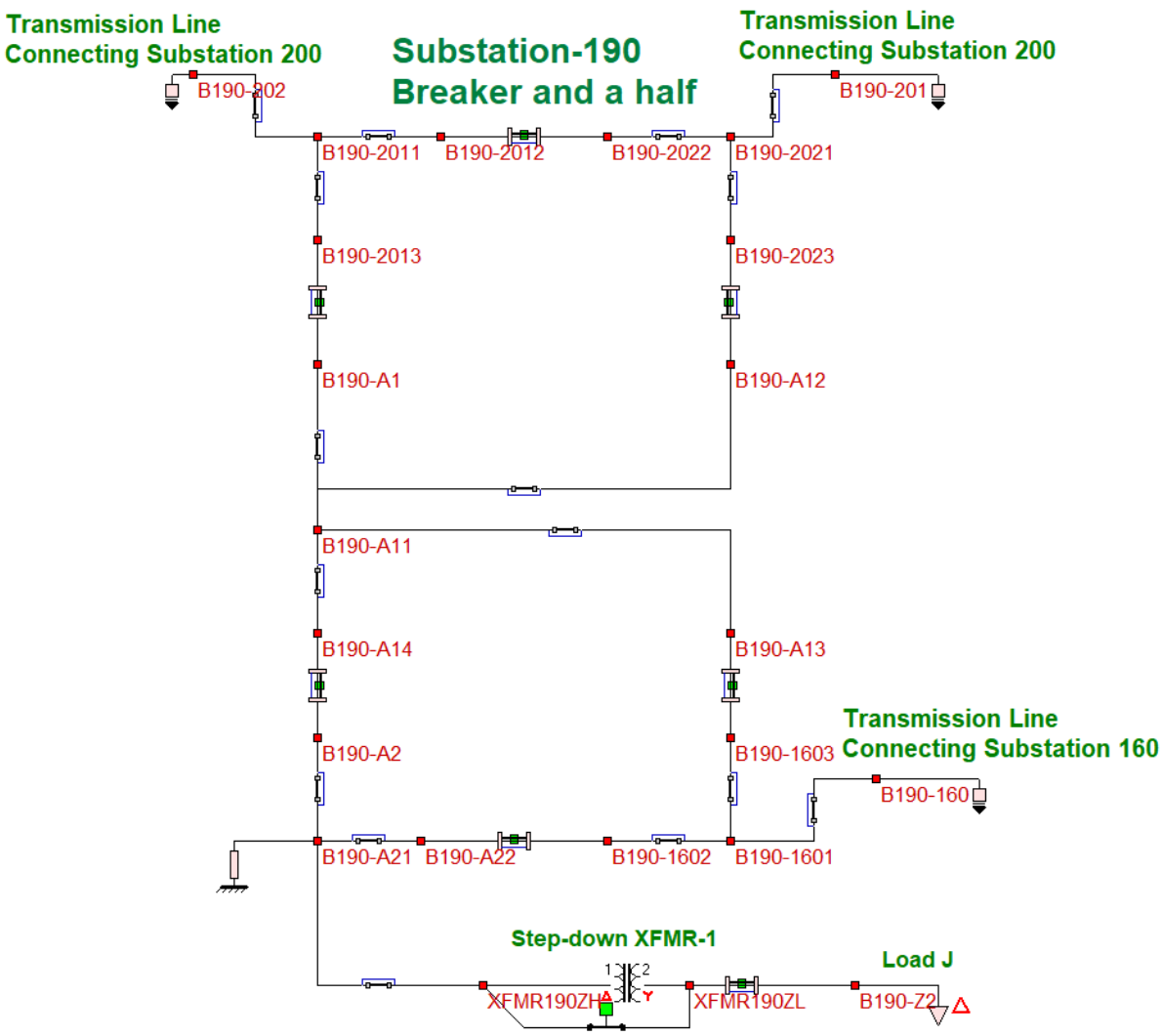


Figure A16.2 Substation-190: Breaker and a half Configuration, Single Line Diagram

Protection and Control of Substation 190
Description of Substation 190

The substation-190 has a breaker and a half configuration. Figure 16.3 shows the co-model of Substation-190 (power system + protection and control). The protection zones defined in Substation-190 can be seen in the figure. Substation 190 has four protection zones: (a) three transmission line protection zones and (b) one transformer protection zone. There are thirteen MUs in Substation-190. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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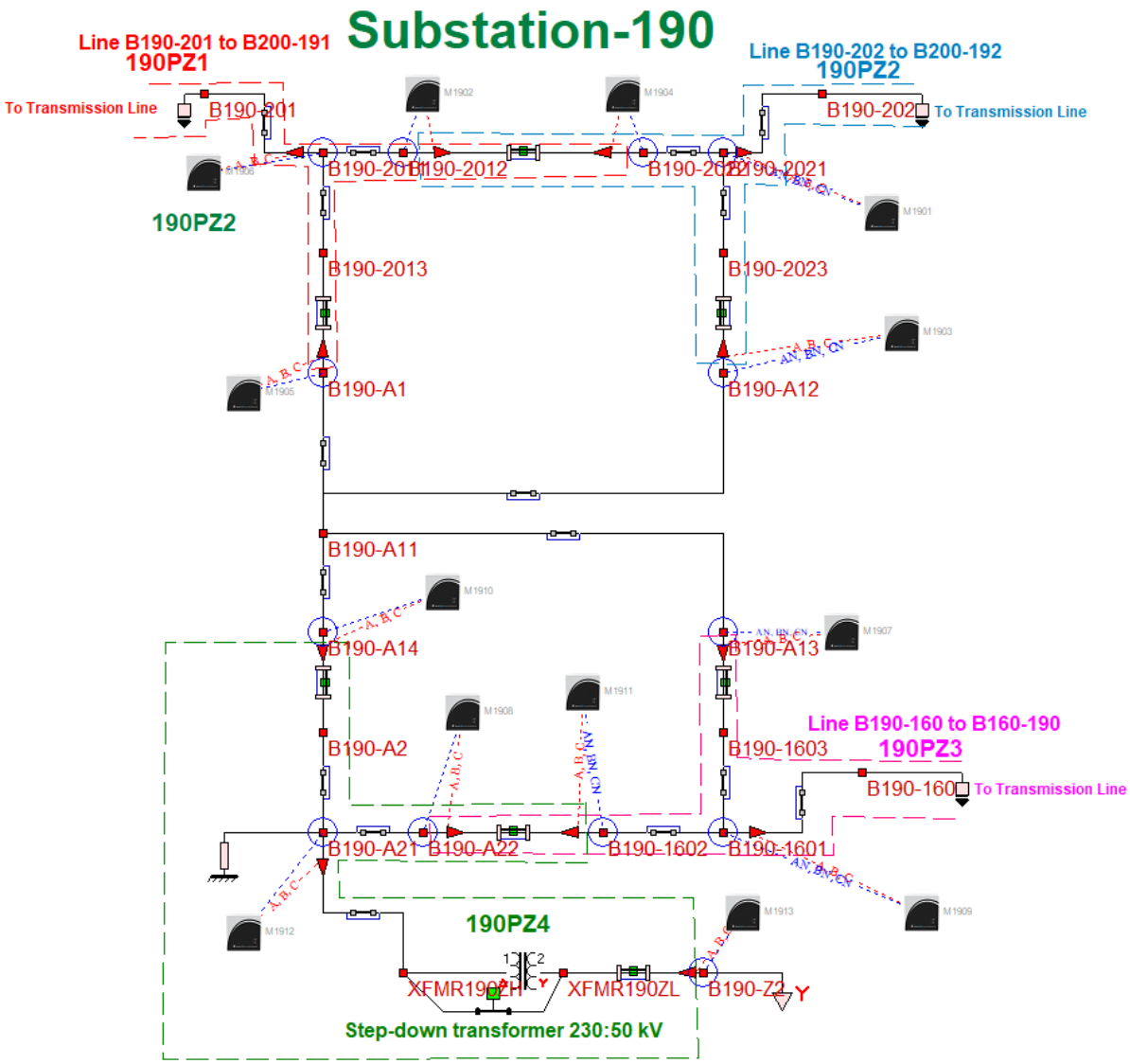


Figure A16.3 Co-model of Substation-190: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The four protection zones are briefly described below.

1. 190PZ1 protects the transmission line B190-201 to B200-191, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 190PZ2 protects the transmission line B190-202 to B200-192, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

3. 190PZ3 protects the transmission line B190-160 to B160-190, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 190PZ4 protects the step-down transformer XFMR190ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 190PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B190-201 to B200-191, the transmission line is a 230 kV line that is 27.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B190-2012 to B190-2022 and B190-2013 to B190-A1 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B190-2012 to B190-2022 and B190-2013 to B190-A1). One unit collects the voltage and current measurements from the CTs and PTs, at the node B190-2011.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.

2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using four merging units namely MU1902, MU1904, MU1905 and MU1906 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 190PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B190-202 to B200-192, the transmission line is a 230 kV line that is 27.5 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 200 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B190-2012 to B190-2022 and B190-2023 to B190-A12 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B190-2012 to B190-2022 and B190-2023 to B190-A12 respectively). One unit collects the voltage and current measurements from the CTs and PTs, at the node B190-2021.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using four merging units namely MU1901, MU1902, MU1903 and MU1904 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 190PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B190-160 to B160-190, the transmission line is a 230 kV line that is 16 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 160 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B190-1602 to B190-A22 and B190-1603 to B190-A13 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B190-1602 to B190-A22 and B190-1603 to B190-A13). One unit collects the voltage and current measurements from the CTs and PTs, at the node B190-1601.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using four merging units namely MU1907, MU1908, MU1909 and MU1911 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 190PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR190ZL to B190-Z2) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B190-1602 to B190-A22; B190-A14 to B190-A2) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are five Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B190-1602 to B190-A22; B190-A14 to B190-A2).One unit collecting the voltage and current measurements at node B190-A21 and one unit collects the voltage and current measurements from the CTs and PTs, at the node B190-Z2.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.

2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 6 are collected using five merging units namely MU1908, MU1910, MU1911, MU1912 and MU1913 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-17. Substation-140 System Description

This section of the document describes the Substation-140 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 17.1 shows the single line diagram of the system network model of Substation-140. There are two 230 kV transmission lines. These devices connect Substation-140 with other substations including Substation 160 (transmission line B140-160 to B160-140) and Substation 110 (transmission line B140-110 to B110-140) as can be seen in the figure.

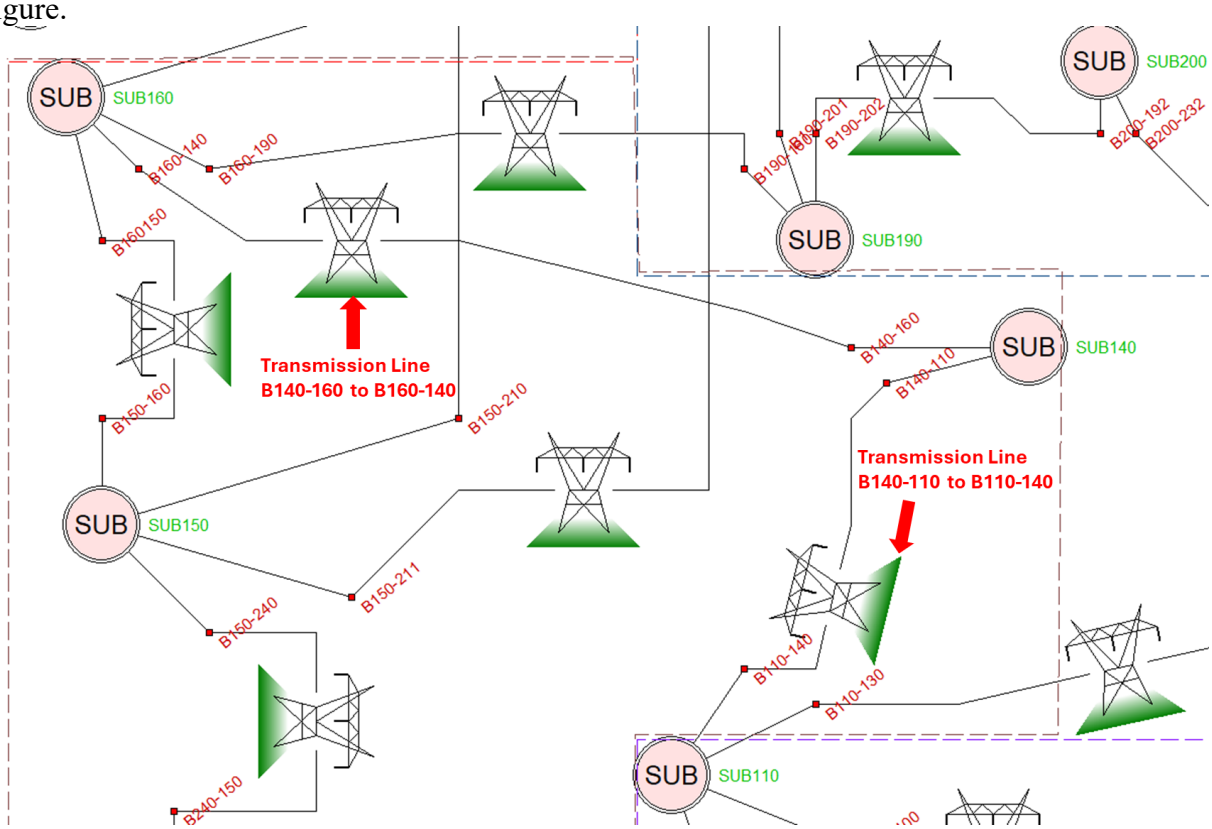


Figure A17.0.12 Single line diagram of system network connected to Substation-140.

The single line diagram of Substation-140 is shown in Figure 17.2. Substation-140 is a 230 kV substation. It has a ring bus arrangement. This substation consists of two 230 kV lines connecting Substation 140 to Substations 160 and 110, one 45MWp PV farm, one step-down transformer unit and multiple substation buses. The substation model is represented with twenty (20) three-phase nodes, six (6) circuit breakers, and twelve (12) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-140 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

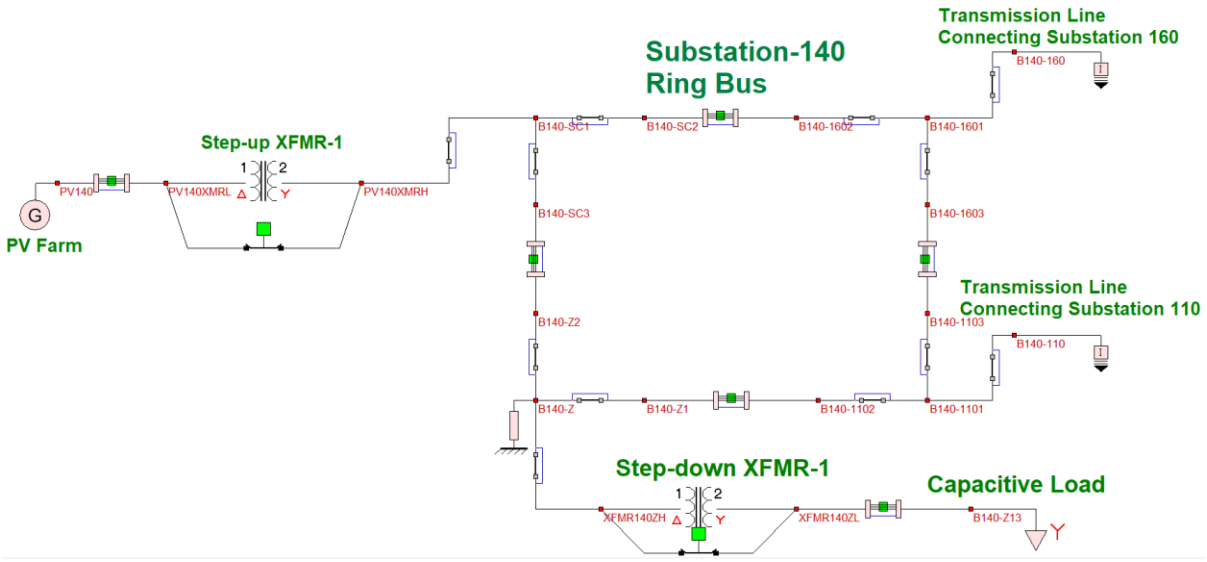


Figure A17.2 Substation-140: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 140
Description of Substation 140

The substation-140 has a breaker and a half configuration. Figure 17.3 shows the co-model of Substation-140 (power system + protection and control). The protection zones defined in Substation-140 can be seen in the figure. Substation 140 has four protection zones: (a) two transmission line protection zones, (b) one inverter-transformer unit protection zone and (c) one transformer protection zone. There are fourteen MUs in Substation-140. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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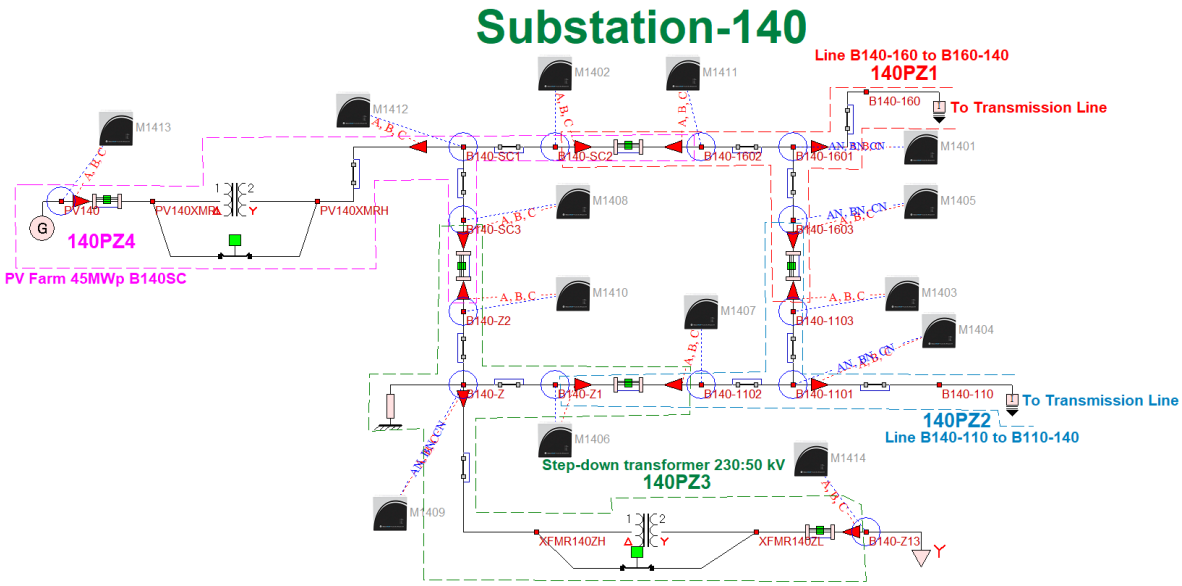


Figure A17.3 Co-model of Substation-140: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The four protection zones are briefly described below.

1. 140PZ1 protects the transmission line B140-160 to B160-140, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 140PZ2 protects the transmission line B140-110 to B110-140, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 140PZ3 protects the step-down transformer XFMR140ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 140PZ4 protects the inverter-XFMR at PV140, it has one inverter, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 140PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B140-160 to B160-140, the transmission line is a 230 kV line that is 27 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 140 and 160 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B140-SC2 to B140-1602 and B140-1603 to B140-1103 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B140-SC2 to B140-1602 and B140-1603 to B140-1103). One unit collects the voltage and current measurements from the CTs and PTs, at the node B140-1601.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU1401, MU1402, MU1403, MU1405 and MU1411 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 140PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B140-110 to B110-140, the transmission line is a 230 kV line that is 29 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 140 and 110 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B140-Z1 to B140-1102 and B140-1603 to B140-1103 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B140-Z1 to B140-1102 and B140-1603 to B140-1103). One unit collects the voltage and current measurements from the CTs and PTs, at the node B140-1101.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU1403, MU1404, MU1405, MU1406 and MU1407 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 140PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 200 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR140ZL to B140-Z13) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B140-SC3 to B140-Z2; B140-Z1 to B140-1102) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B140-SC3 to B140-Z2; B140-Z1 to B140-1102).One unit collecting the voltage and current measurements at node B140-Z and one unit collects the voltage and current measurements from the CTs and PTs, at the node B140-Z13.

For EBP: An EBP relay monitors the transformer protection zone.
For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using five merging units namely MU1406, MU1407, MU1408, MU1409, MU1410 and MU1414 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 140PZ4

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 45 MWp rating. A step-up XFMR with a setting of 34.5:230kV, 45 MVA. The 230 kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (PV140 to PV140XMRL) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B140-SC3 to B140-Z2; B140-SC2 to B140-1602) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B140-SC3 to B140-Z2; B140-SC2 to B140-1602).One unit collects the voltage and current measurements from the CTs and PTs at node B140-SC1. One unit collects the voltage and current measurements from the CTs and PTs, at node PV140.

For EBP:

An EBP relay monitors the unit protection zone.

For Legacy Protection:

A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 4 are collected using six merging units namely MU1402, MU1408, MU1410, MU1411, MU1412 and MU1413 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-18. Substation-240 System Description

This section of the document describes the Substation-240 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 18.1 shows the single line diagram of the system network model of Substation-240. There is one 230 kV transmission line, and one 138 kV transmission line. These devices connect Substation-240 with other substations including Substations 150 (transmission line B240-150 to B150-240) and 30 (transmission line B24030 to B30240)

respectively as can be seen in the figure. It can be noted that Substation-240 acts as an intermediate substation that connects the 138kV portion of the 24 Substation system to the 230 kV side. Therefore, it contains a grid transformer that steps down the voltage from 230 kV to 138 kV, this transformer is connected to the 138 kV transmission line within the Substation.

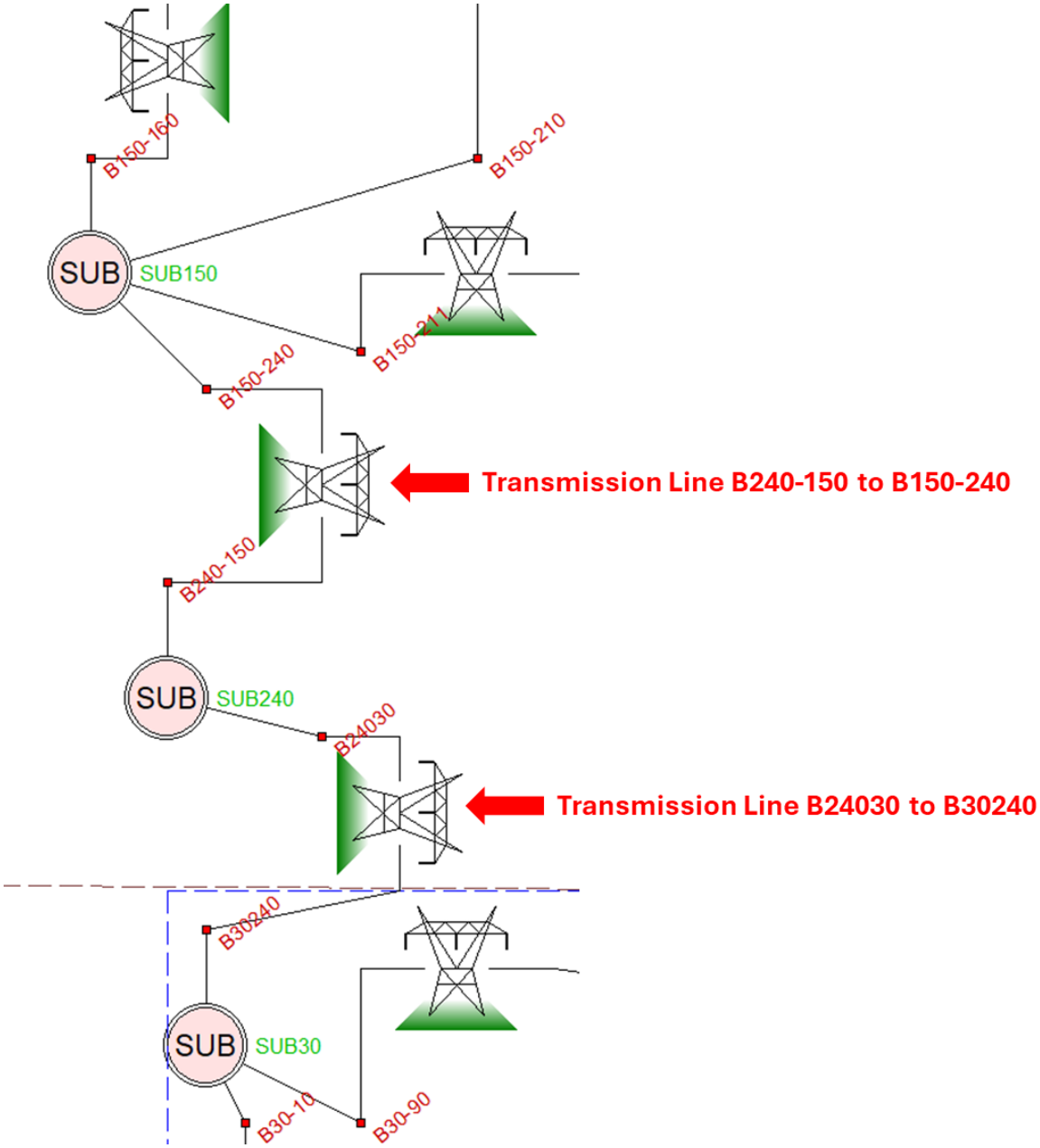


Figure A18.0.13 Single line diagram of network connected to Substation-240.

The single line diagram of Substation-240 is shown in Figure 18.2. Substation-240 is a 230 kV substation. It has a ring bus arrangement. This substation consists of one 230 kV transmission line connecting Substations 240 and 150, one 230:138 kV step-down grid XFMR, one 138 kV transmission line connecting substation 240 and substation 30 and two 230 kV buses. The

substation model is represented with ten (10) three-phase nodes, three (3) circuit breakers, and six (6) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-240 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

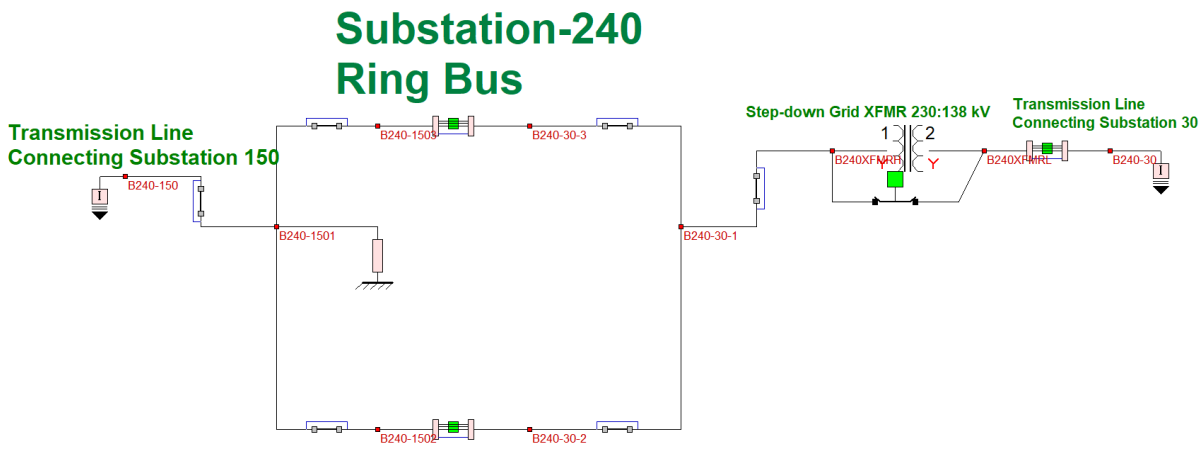


Figure A18.2 Substation-240: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 240
Description of Substation 240

The substation-240 has a ring bus configuration. Figure 18.3 shows the co-model of Substation-240 (power system + protection and control). The protection zones defined in Substation-240 can be seen in the figure. Substation-240 has three defined protection zones: (a) two transmission line protection zones and (b) one transformer protection zone. There are eight MUs in Substation-240. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

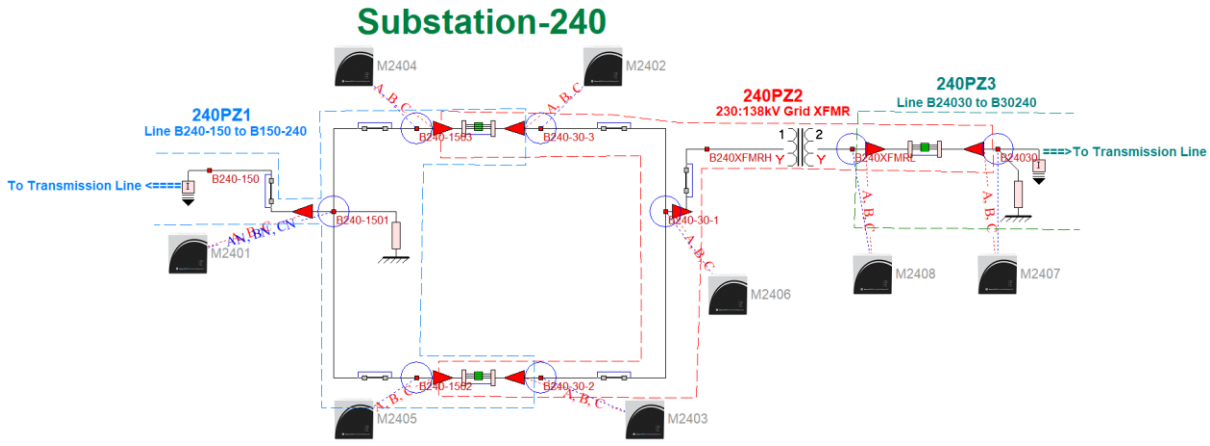


Figure A18.3 Co-model of Substation-240: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The three protection zones are briefly described below.

1. 240PZ1 protects the transmission line B240-150 to B150-240, it has one transmission line, two circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and five merging units in total taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.
2. 240PZ2 protects the step-down transformer B240XFMRL, it has one 230:138 kV step-down XFMR, three circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and seven merging units taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.
3. 240PZ3 protects the transmission line B24030 to B30240, it has one transmission line, one circuit breaker with two sets of three phase current and voltage transformers (CT/PT) and two merging units in total taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.

Protection Zone 1 – 240PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B240-150 to B150-240, the transmission line is a 230 kV line that is 36 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 150 and 240 respectively) measuring the voltages and currents at the ends of the transmission line, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B240-1503 to B240-30-3and B240-1502 to B240-30-2 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. Five Merging Units in total, one measures the three phase voltages and currents on the transmission line from the CTs and PTs present at node B240-1501, four units measure the voltages and currents from the CTs and PTs on both the sides of each of the circuit breakers B240-1503 to B240-30-3and B240-1502 to B240-30-2 respectively.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU2401, MU2402, MU2403, MU2404 and MU2405 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 240PZ2
This protection zone consists of:

1. A three phase Grid-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:138 kV. The 138kV is Wye connected and the 230kV is also Wye connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B240-1503 to B240-30-3 and B240-1502 to B240-30-2 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units. Additionally, one 138 kV circuit breaker is connected at B240XFMRL and B24030, connecting the low side of the transformer to the 138 kV transmission line (which connects substations 240 and 30). This breaker also has two sets of three phase CTs and PTs on either side measuring three phase currents and voltages.

3. Seven Merging Units in total, one measures the three phase voltages and currents on the high side of the XFMR at node B240-30-1 from the CTs and PTs present. Four units measure the voltages and currents from the CTs and PTs present on both the sides of each of the 230 kV circuit breakers B240-1503 to B240-30-3and B240-1502 to B240-30-2 respectively. Finally, two units

measure the voltages and currents from the CTs and PTs present on both the sides of the circuit breaker B240XFMRL to B24030.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 2 are collected using seven merging units namely MU2402, MU2403, MU2404, MU2405, MU2406, MU2407 and MU2408 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 240PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B24030 to B30240, the transmission line is a 138 kV line that is 17.7178 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size HAWK/SSAC with an Ampacity of 699 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 150 and 240 respectively) measuring the voltages and currents at the ends of the transmission line, these values are fed to the Merging Units.

2. One circuit breaker is present in the protection zone 240PZ3 namely the breaker connected between nodes B240XFMRL to B24030. The circuit breaker has a rated voltage of 138kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Additionally, the circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. Twp Merging Units in total, two units measure the voltages and currents from the CTs and PTs on both the sides of the circuit breaker B240XFMRL to B24030.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using two merging units, namely MU2407 and MU2408 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

A-19. Substation-150 System Description

This section of the document describes the Substation-150 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 19.1 shows the single line diagram of the system network model of Substation-150. There are four 230 kV transmission lines. These devices connect Substation-150 with other substations including Substation 210 (transmission line B150-211 to B210-151 and B150-212 to B210-152), Substation 240 (transmission line B150-240 to B240-150), and Substation 160 (transmission line B150-160 to B160-150) respectively as can be seen in the figure.

The single line diagram of Substation-150 is shown in Figure 19.2. Substation-150 is a 230 kV substation. It has a breaker and a half plus double bus arrangement. This substation consists of four 230 kV lines connecting Substation 150 to Substations 210, 240 and 160, six generator/inverter – step-up transformer units, one step-down transformer unit and two substation buses. The substation model is represented with thirty-two (32) three-phase nodes, twenty-eight (28) circuit breakers, and forty-two (42) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-150 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

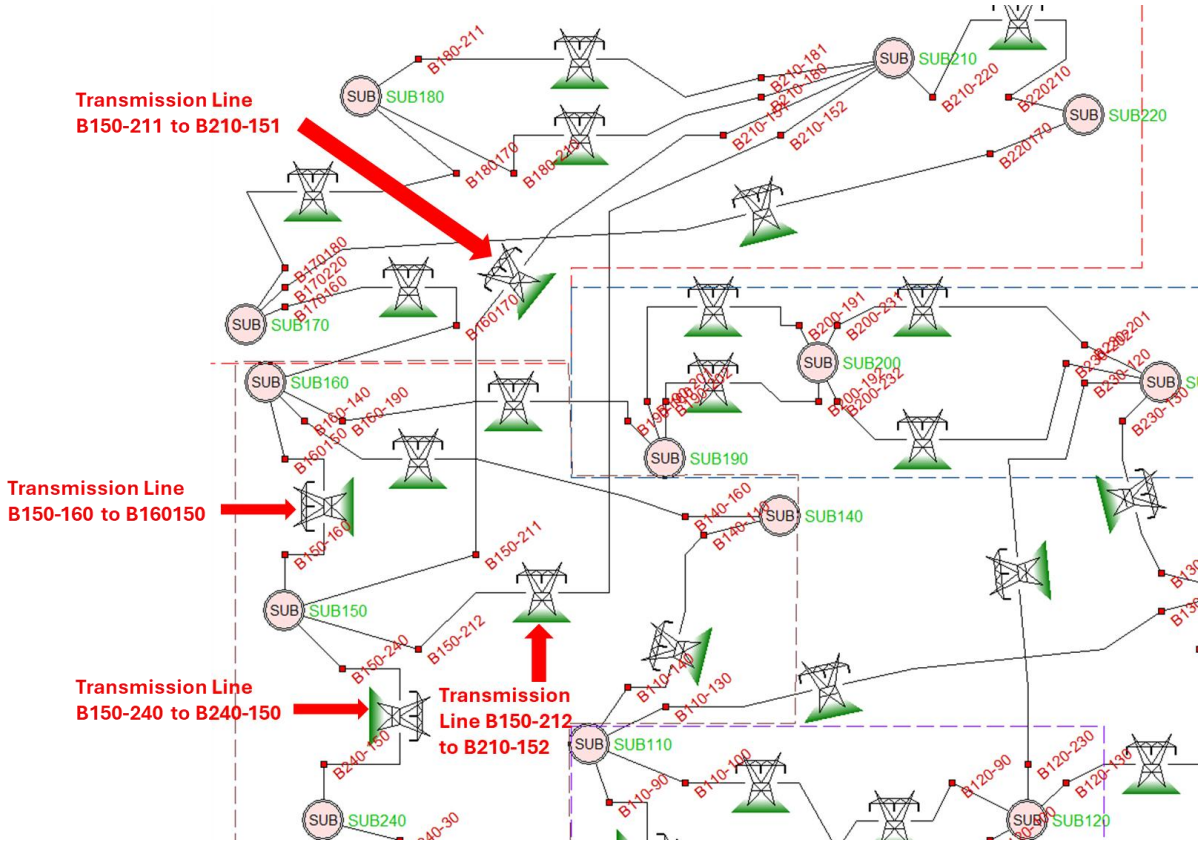


Figure A19.0.14 Single line diagram of system network connected to Substation-150.

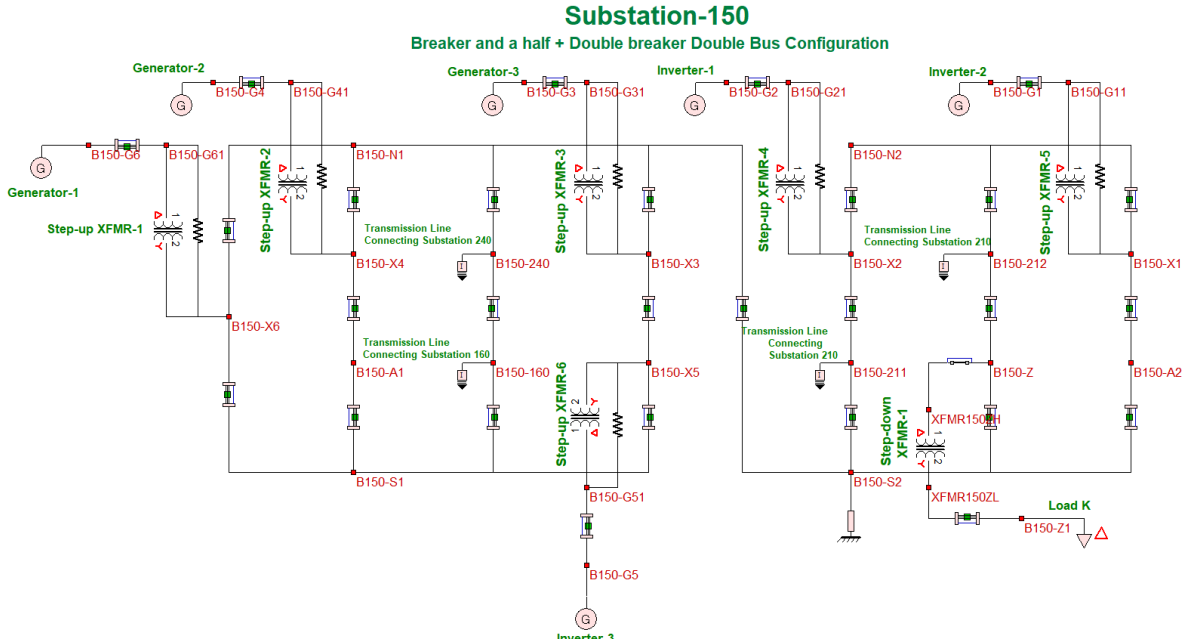


Figure A19.2 Substation-150: Breaker and a Half plus Double bus Configuration, Single Line Diagram

Protection and Control of Substation 150
Description of Substation 150

The substation-150 has a breaker and a half plus double bus configuration. Figure 19.4 shows the co-model of Substation-150 (power system + protection and control). The protection zones defined in Substation-150 can be seen in the figure 19.5. Substation 150 has fourteen protection zones: (a) six generator/inverter-XFMR unit protection zones, (b) three Bus protection zones, (c) four transmission line protection zones and (d) one transformer protection zone. There are forty-eight MUs in Substation-150. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

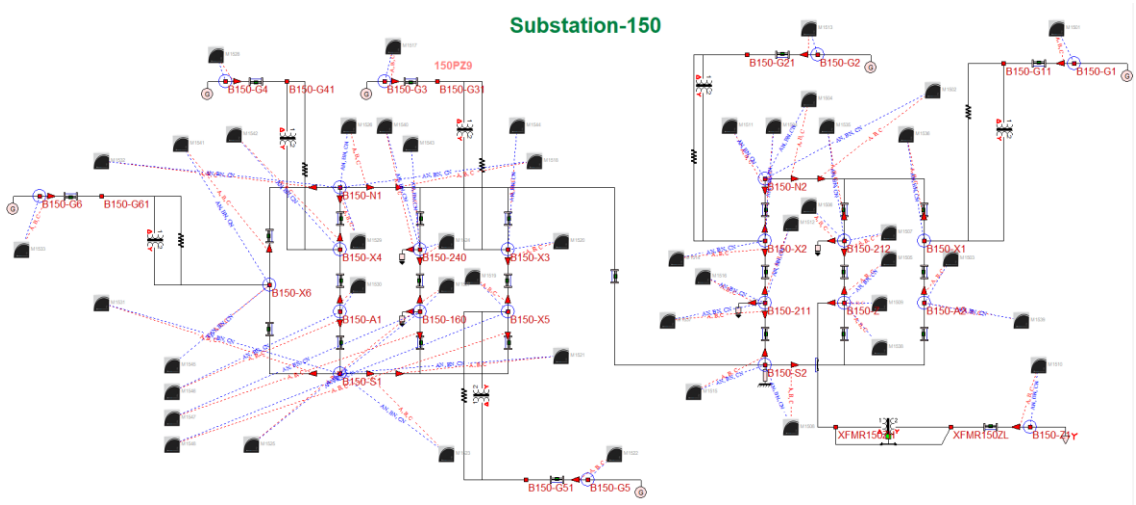


Figure A19.3 Substation-150: Merging Units Location

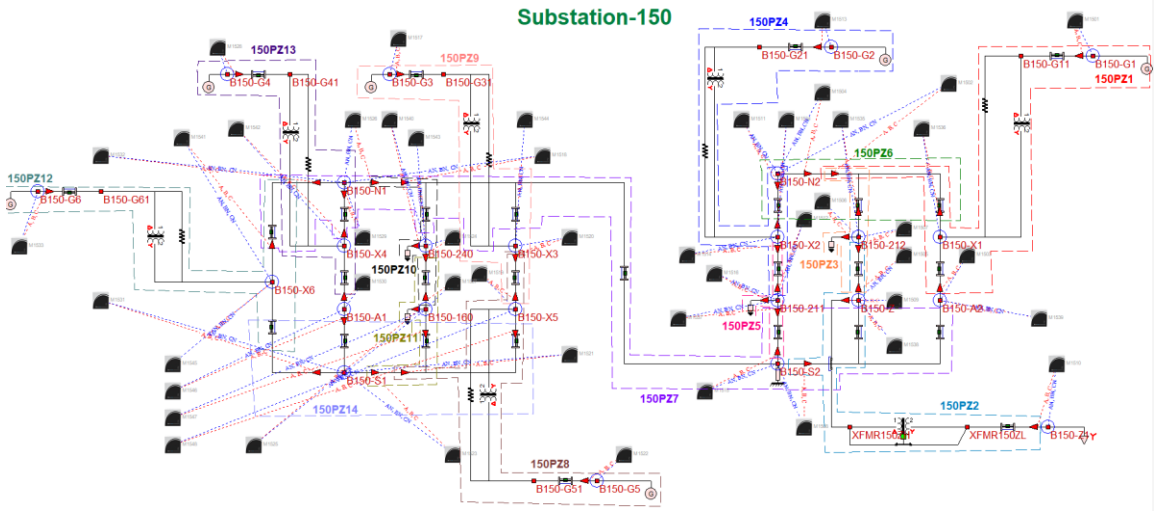


Figure A19.4 Co-model of Substation-150: Merging Units and Relays (Protection zones).

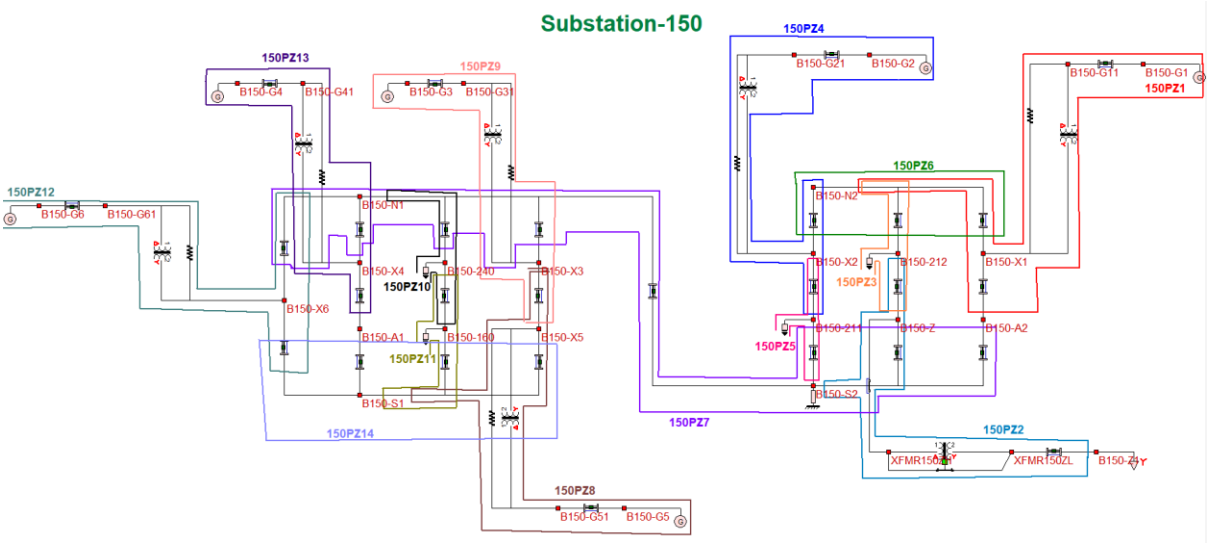


Figure A19.5 Substation-150 Defined Protection Zones

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The fourteen protection zones are briefly described below.

1. 150PZ1 protects the inverter-XFMR at B150-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and four merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 150PZ2 protects the transformer XFMR150ZL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 150PZ3 protects the transmission line B150-212 to B210-152, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 150PZ4 protects the inverter-XFMR at B150-G2, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 150PZ5 protects the transmission line B150-211 to B210-151, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage

transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

6. 150PZ6 protects the North side Bus B150-N2, it has one bus, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 150PZ7 protects the B150-N1 to B150-S2 bus, it has one bus, eight circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and thirteen merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
8. 150PZ8 protects the inverter-XFMR at B150-G5, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
9. 150PZ9 protects the generator-XFMR at B150-G3, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
10. 150PZ10 protects the transmission line B150-240 to B240-150, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
11. 150PZ11 protects the transmission line B150-160 to B160-150, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
12. 150PZ12 protects the generator-XFMR at B150-G6, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
13. 150PZ13 protects the generator-XFMR at B150-G4, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
14. 150PZ14 protects the South side Bus B150-S1, it has one bus, four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and seven merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 150PZ1

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 100 MVA. The 230kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G1 to B150-G11) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-N2 to B150-X1; B150-X1 to B150-A2) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Four Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B150-N2 to B150-X1), one unit collecting the voltage and current measurements from the CTs and PTs, at the node B150-A2 of the circuit breaker B150-X1 to B150-A2 connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G1 to B150-G11).

Note: As an example, B150-G1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using four merging units namely MU1501, MU1502, MU1503 and MU1536 respectively. Measurements are collected from six sets of

instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 150PZ2
This protection zone consists of:

1. A three phase load-XFMR that has a 60 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR150ZL to B150-Z1) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B150-212 to B150-Z; B150-S2 to B150-Z) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B150-212 to B150-Z; B150-S2 to B150-Z).one unit collects the voltage and current measurements at node B150-Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present at B150-Z1

Note: As an example, B150-Z1 is a node.

For EBP: An EBP relay monitors the transformer protection zone.
For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 2 are collected using six merging units namely MU1505, MU1507, MU1508, MU1509, MU1510 and MU1538 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The

locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3– 150PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B150-212 to B210-152, the transmission line is a 230 kV line that is 34 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B150-N2 to B150-212 and B150-212 to B150-Z respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B150-N2 to B150-212 and B150-212 to B150-Z). One unit collects the voltage and current measurements from the CTs and PTs, at the node B150-212.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU1504, MU1505, MU1506, MU1507 and MU1535 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 150PZ4

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 100 MVA. The 230kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G2 to B150-G21) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-N2 to B150-X2; B150-X2 to B150-211) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B150-N2 to B150-X2),two units collecting the voltage and current measurements from the CTs and PTs, at both the nodes of the circuit breaker B150-X2 to B150-211connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G2 to B150-G21).

Note: As an example, B150-G2 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 4 are collected using five merging units namely MU1511, MU1512, MU1513, MU1514 and MU1534 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5– 150PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B150-211 to B210-151, the transmission line is a 230 kV line that is 34 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B150-X2 to B150-211 and B150-211 to B150-S2 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B150-X2 to B150-211 and B150-211 to B150-S2). One unit collects the voltage and current measurements from the CTs and PTs, at the node B150-211.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:

A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU1512, MU1514, MU1515, MU1516 and MU1537 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6 – 150PZ6

This protection zone consists of:

1. Three Circuit Breakers forms the substation north bus B150-N2, namely B150-X2 to B150-N2, B150-212 to B150-N2, B150-X1 to B150-N2. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Six Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B150-X2 to B150-N2, B150-212 to B150-N2, B150-X1 to B150-N2.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 6 are collected using six merging units namely MU1502, MU1504, MU1511, MU1534, MU1535 and MU1536 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 7 – 150PZ7

This protection zone consists of:

1. Three Circuit Breakers forms the substation bus B150-N1 to B150-S2, namely B150-211 to B150-S2, B150-Z to B150-S2, B150-A2 to B150-S2, B150-X3 to B150-N1, B150-X4 to B150-N1, B150-X6 to B150-N1, B150-240 to B150-N1. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Thirteen Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B150-211 to B150-S2, B150-Z to B150-S2, B150-A2 to B150-S2, B150-X3 to B150-N1, B150-X4 to B150-N1, B150-X6 to B150-N1, B150-240 to B150-N1.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using thirteen merging units namely MU1508, MU1515, MU1516, MU1518, MU1526, MU1529, MU1532, MU1538, MU1539, MU1541, MU1542, MU1543 and MU1544 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 8 – 150PZ8

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 100 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 100 MVA. The 230kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G5 to B150-G51) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-X3 to B150-X5; B150-X5 to B150-S1) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B150-X3 to B150-X5),two units collecting the voltage and current measurements from the CTs and PTs, at both the nodes of the circuit breaker B150-X5 to B150-S1 connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G5 to B150-G51).

Note: As an example, B150-G5 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 8 are collected using five merging units namely MU1519, MU1520, MU1521, MU1522 and MU1548 respectively. Measurements are collected from six sets

of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 9 – 150PZ9

This protection zone consists of:

1. A three phase generator that has a 115kV, 155 MVA rating. A step-up XFMR with a setting of 115:230kV, 155 MVA. The 230kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G3 to B150-G31) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-X3 to B150-X5; B150-N1 to B150-X3) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B150-X3 to B150-X5; B150-N1 to B150-X3). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G3 to B150-G31).

Note: As an example, B150-G3 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 9 are collected using five merging units namely MU1517, MU1518, MU1519, MU1520 and MU1544 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 10– 150PZ10
This protection zone consists of:

1. The transmission line that is connected between buses B150-240 to B240-150, the transmission line is a 230 kV line that is 36 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 240 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B150-240 to B150-N1 and B150-240 to B150-160 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B150-240 to B150-N1 and B150-240 to B150-160). One unit collects the voltage and current measurements from the CTs and PTs, at the node B150-240.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 10 are collected using five merging units namely MU1524, MU1526, MU1527, MU1540 and MU1543 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 11– 150PZ11
This protection zone consists of:

1. The transmission line that is connected between buses B150-160 to B160-150, the transmission line is a 230 kV line that is 12 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 240 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B150-240 to B150-160 and B150-S1 to B150-160 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B150-240 to B150-160 and B150-S1 to B150-160). One unit collects the voltage and current measurements from the CTs and PTs, at the node B150-160.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.

4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 10 are collected using five merging units namely MU1523, MU1524, MU1525, MU1527 and MU1547 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 12 – 150PZ12

This protection zone consists of:

1. A three phase generator that has a 115kV, 155 MVA rating. A step-up XFMR with a setting of 115:230kV, 155 MVA. The 230kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G6 to B150-G61) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-X6 to B150-S1; B150-N1 to B150-X6) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B150-X6 to B150-S1; B150-N1 to B150-X6). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G6 to B150-G61).

Note: As an example, B150-G6 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 12 are collected using five merging units namely MU1531, MU1532, MU1533, MU1541 and MU1545 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 13 – 150PZ13

This protection zone consists of:

1. A three phase generator that has a 115kV, 155 MVA rating. A step-up XFMR with a setting of 115:230kV, 155 MVA. The 230kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B150-G4 to B150-G41) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B150-X4 to B150-A1; B150-N1 to B150-X4) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Four Merging Units collecting measurements within the protection zone, three units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B150-A1; B150-N1 to B150-X4). One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B150-G4 to B150-G41).

Note: As an example, B150-G4 is a node.

For EBP: An EBP relay monitors the unit protection zone.
For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.

5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 13 are collected using four merging units namely MU1528, MU1529, MU1530 and MU1542 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 14 – 150PZ14

This protection zone consists of:

1. Three Circuit Breakers forms the substation South bus B150-S1, namely B150-160 to B150-S1, B150-X5 to B150-S1, B150-X6 to B150-S1, B150-A1 to B150-S1. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Seven Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B150-160 to B150-S1, B150-X5 to B150-S1, B150-X6 to B150-S1, B150-A1 to B150-S1.
For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 14 are collected using seven merging units namely MU1521, MU1523, MU1531, MU1545, MU1546, MU1547 and MU1548 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents.

The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-20. Substation-160 System Description

This section of the document describes the Substation-160 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 20.1 shows the single line diagram of the system network model of Substation-160. There are four 230 kV transmission lines. These devices connect Substation-160 with other substations including Substation 140 (transmission line B160-140 to B140-160), Substation 170 (transmission line B160-170 to B170-160), Substation 190 (transmission line B160-190 to B190-160) and Substation 150 (transmission line B160150 to B150-160) respectively as can be seen in the figure.

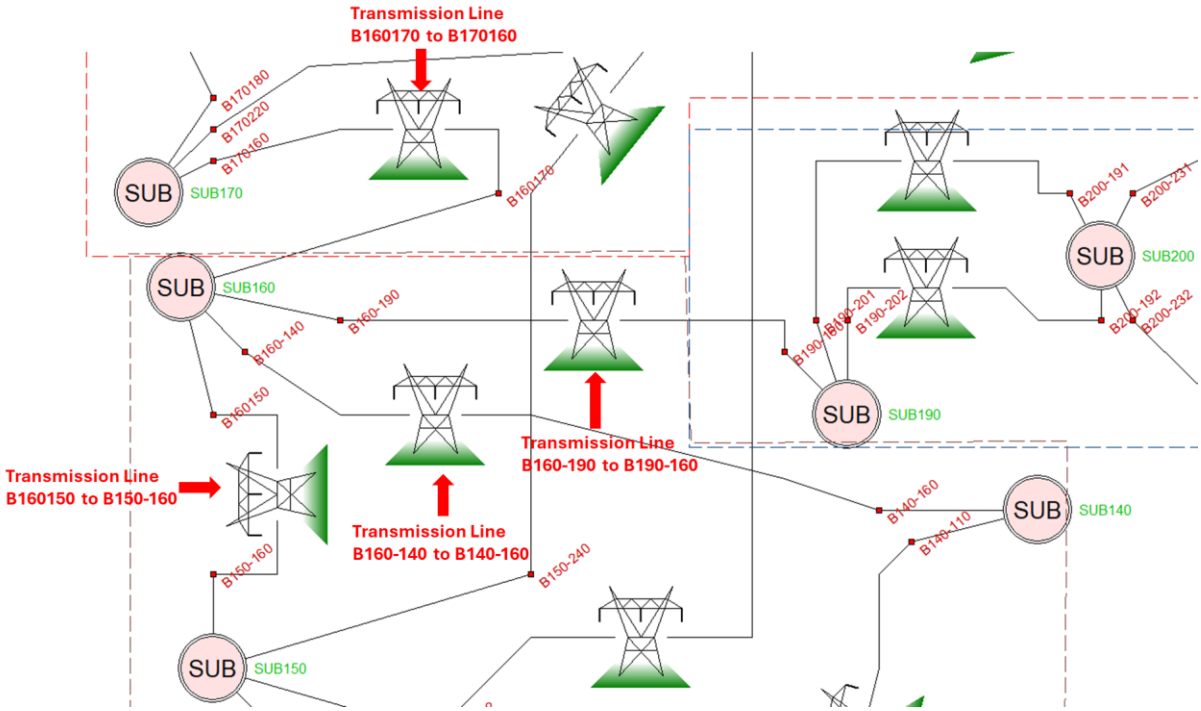


Figure A20.0.15 Single line diagram of system network connected to Substation-160.

The single line diagram of Substation-160 is shown in Figure 20.2. Substation-160 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of four 230 kV lines connecting Substation 160 to Substations 170, 140, 190 and 150, one inverter – step-up transformer unit, one step-down transformer unit and two substation buses. The substation model is represented with twelve (12) three-phase nodes, ten (10) circuit breakers, and eighteen (18) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-160 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

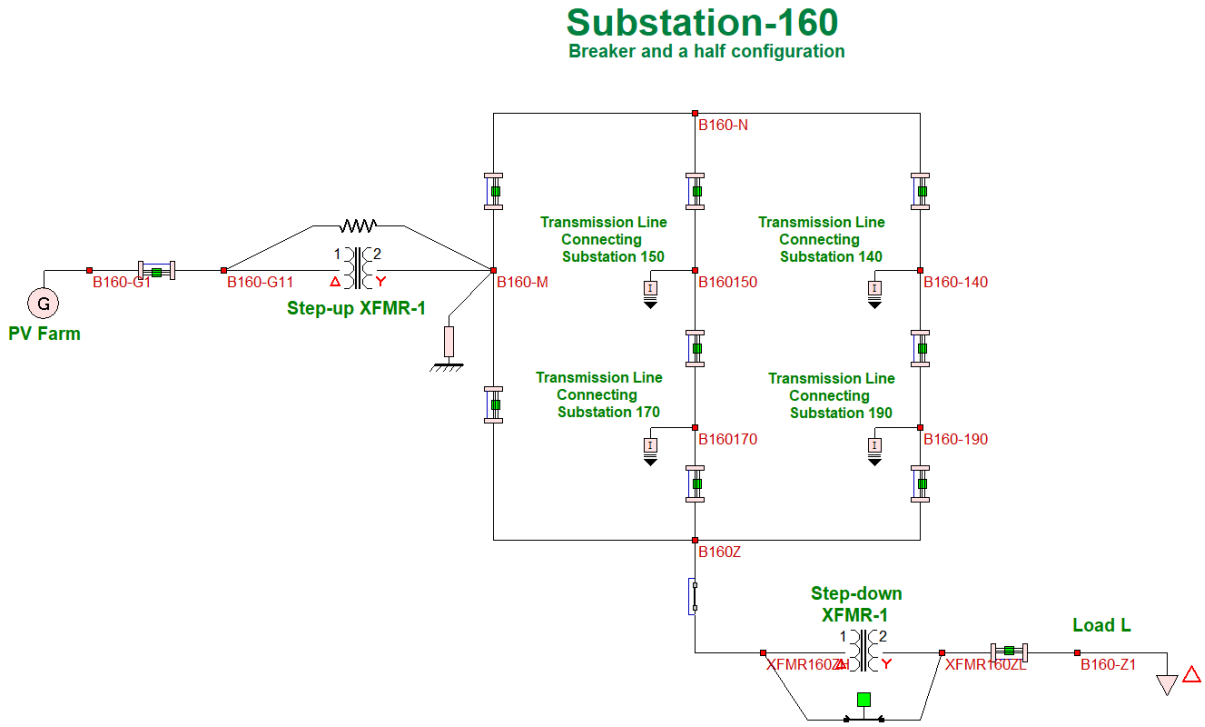


Figure A20.2 Substation-160: Breaker and a Half Configuration, Single Line Diagram

Protection and Control of Substation 160
Description of Substation 160

The substation-160 has a breaker and a half configuration. Figure 20.4 shows the co-model of Substation-160 (power system + protection and control). The protection zones defined in Substation-160 can be seen in the figure 20.5. Substation 160 has seven protection zones: (a) one inverter-XFMR unit protection zone, (b) one Bus protection zone, (c) four transmission line protection zones and (d) one transformer protection zone. There are twenty-three MUs in Substation-160. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

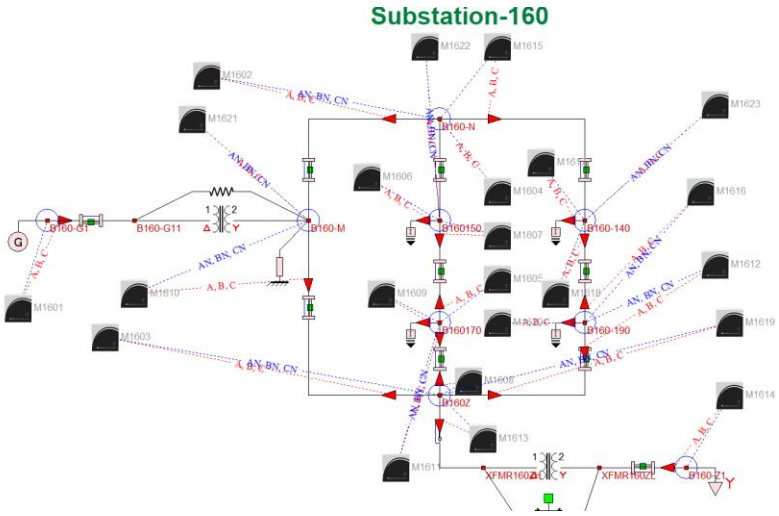


Figure A20.3 Substation-160: Merging Units Location

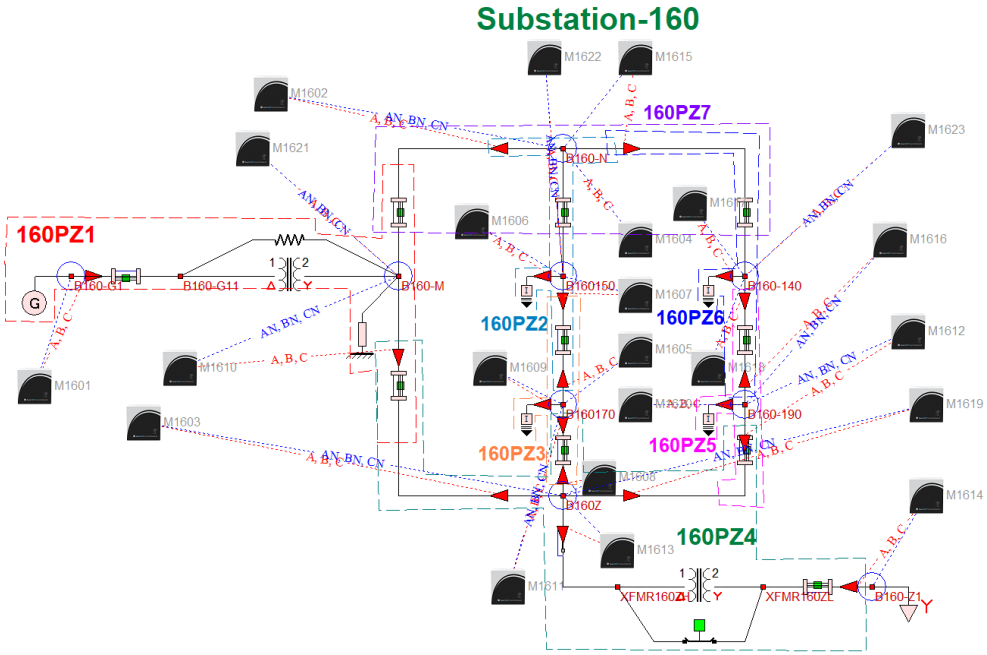


Figure A20.4 Co-model of Substation-160: Merging Units and Relays (Protection zones).

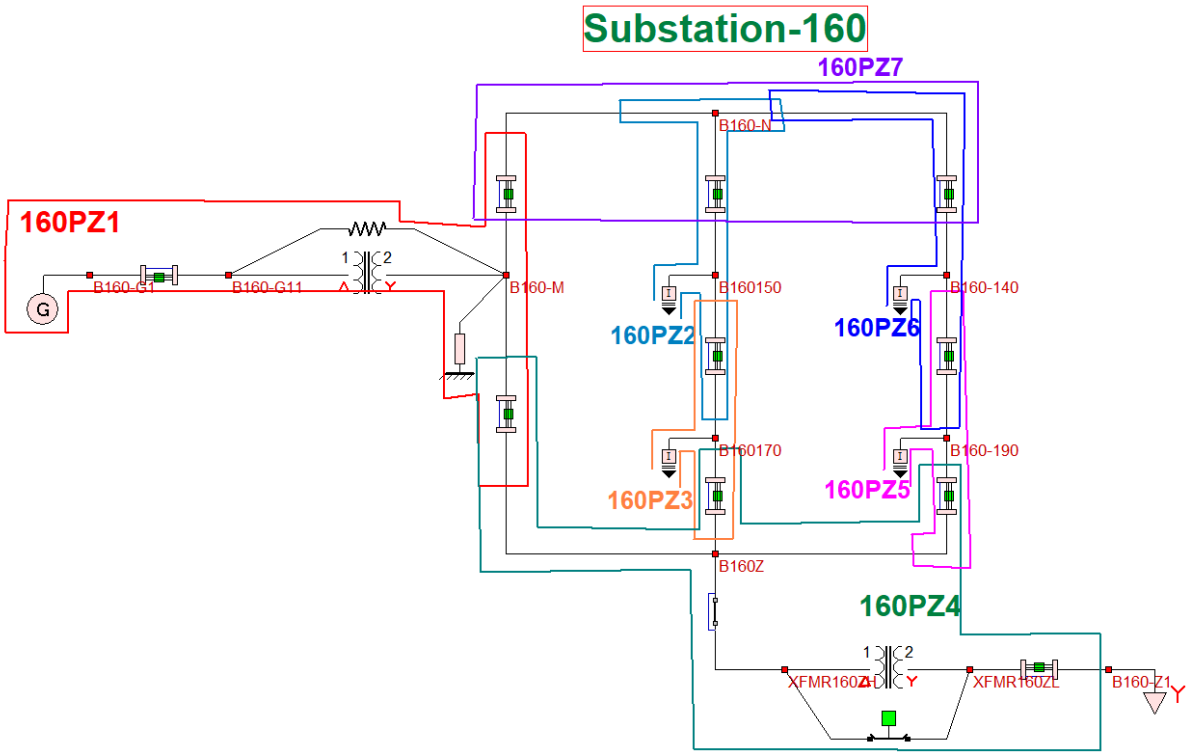


Figure A20.5 Substation-160 Defined Protection Zones

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 160PZ1 protects the inverter-XFMR at B160-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 160PZ2 protects the transmission line B160150 to B150-160, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 160PZ3 protects the transmission line B160170 to B170160, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 160PZ4 protects the transformer XFMR160ZL, it has one step-down XFMR, four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs)

each and eight merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

5. 160PZ5 protects the transmission line B160-190 to B190-160, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 160PZ6 protects the transmission line B160-140 to B140-160, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 160PZ7 protects the North side Bus B160-N, it has one bus, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 160PZ1

This protection zone consists of:

1. A three phase inverter that has a 34.5kV, 175 MVA rating. A step-up XFMR with a setting of 34.5:230kV, 175 MVA. The 230kV is Wye connected and the 34.5kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B160-G1 to B160-G11) and has a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B160-N to B160-M; B160-M to B160Z) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B160-N to B160-M), two units collecting the voltage and current measurements from the CTs and PTs, present on both the nodes of the circuit breaker B160-M to B160-Z connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B160-G1 to B160-G11).

Note: As an example, B160-G1 is a node.

For EBP: An EBP relay monitors the unit protection zone.

For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using five merging units namely MU1601, MU1602, MU1603, MU1610 and MU1621 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2– 160PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B160150 to B150-160, the transmission line is a 230 kV line that is 12 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 160 and 150 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B160-N to B160150 and B160150 to B160170 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on

either side of the circuit breakers (B160-N to B160150 and B160150 to B160170). One unit collects the voltage and current measurements from the CTs and PTs, at the node B160150.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU1604, MU1605, MU1606, MU1607 and MU1622 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3– 160PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B160170 to B170160, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 160 and 170 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B160Z to B160170 and B160150 to B160170 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B160Z to B160170 and B160150 to B160170). One unit collects the voltage and current measurements from the CTs and PTs, at the node B160170.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU1605, MU1607, MU1608, MU1609 and MU1611 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 160PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 60 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are four circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR160ZL to B160-Z1) and has a rating of 50kV and a 10kA interrupt capability. There are three circuit breakers connected to the delta terminal of the XFMR (B160-M to B160Z; B160170 to B160Z; B160-190 to B160Z) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are eight Merging Units collecting measurements within the protection zone, six units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B160-M to B160Z; B160170 to B160Z; B160-190 to B160Z).One unit collects the voltage and current measurements at node B160Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present at B160-Z1

Note: As an example, B160-Z1 is a node.

For EBP: An EBP relay monitors the transformer protection zone.
For Legacy Protection: A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using eight merging units namely MU1603, MU1608, MU1610, MU1611, MU1612, MU1613, MU1614 and MU1619 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5– 160PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B160-190 to B190-160, the transmission line is a 230 kV line that is 16 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 160 and 190 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B160-140 to B160-190 and B160-190 to B160Z respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B160-140 to B160-190 and B160-190 to B160Z). One unit collects the voltage and current measurements from the CTs and PTs, at the node B160170.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU1612, MU1616, MU1618, MU1619 and MU1620 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6– 160PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B160-140 to B140-160, the transmission line is a 230 kV line that is 27 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 160 and 140 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B160-140 to B160-190 and B160-140 to B160-N respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B160-140 to B160-190 and B160-140 to B160-N). One unit collects the voltage and current measurements from the CTs and PTs, at the node B160-140.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU1615, MU1616, MU1617, MU1618 and MU1623 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 160PZ7

This protection zone consists of:

1. Three Circuit Breakers forms the substation north bus B160-N, namely B160-N to B160-M, B160150 to B160-N, B160-140 to B160-N. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Six Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B160-N to B160-M, B160150 to B160-N, B160-140 to B160-N.
For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.

3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using six merging units namely MU1602, MU1604, MU1615, MU1621, MU1622 and MU1623 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-21. Substation-170 System Description

This section of the document describes the Substation-170 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 21.1 shows the single line diagram of the system network model of Substation-170. There are three 230 kV transmission lines connected to Substation-170. These lines connect Substation-170 with other substations including Substations 180 (transmission line B170180 to B180170),220 (transmission line B170220 to B220170), and 160 (transmission line B170160 to B160170), respectively as can be seen in the figure.

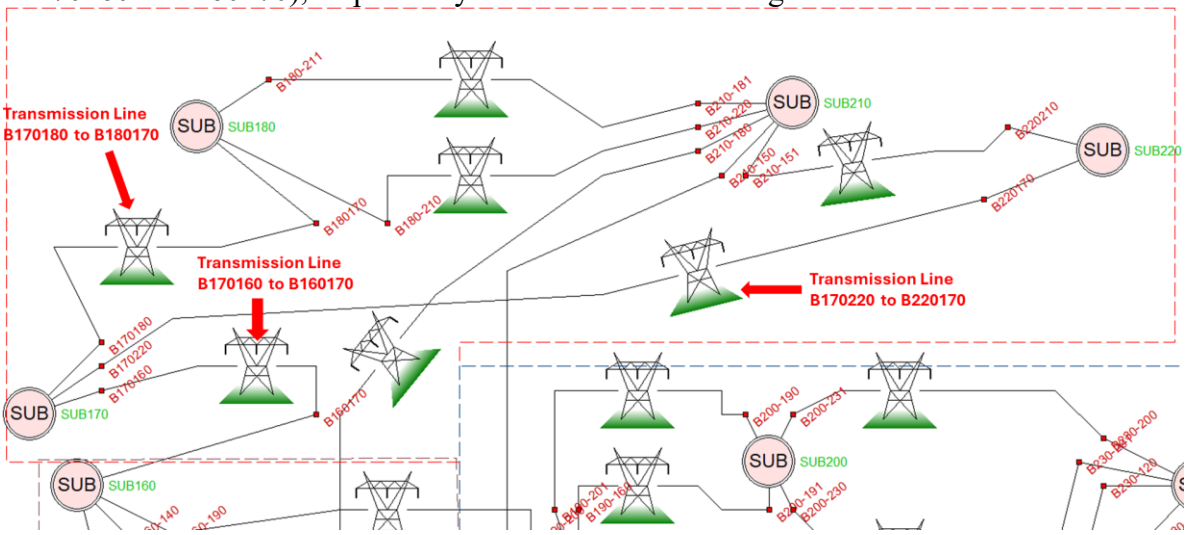


Figure A21.0.16 Single line diagram of network connected to Substation-170.

The single line diagram of Substation-170 is shown in Figure 1.3. Substation-170 is a 230 kV substation. It has a ring bus arrangement. This substation consists of three 230 kV primary power lines, one 35 kV Distribution network and four 230 kV buses. The substation model is represented with sixteen (16) three-phase nodes, four (4) circuit breakers, and twelve (12) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-170 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

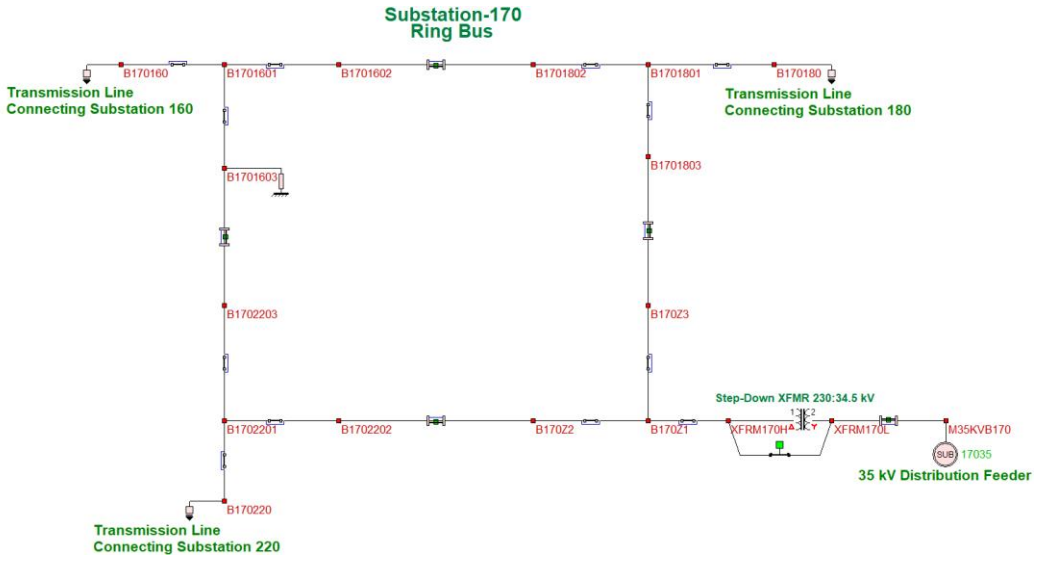


Figure A21.2 Substation-170: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 170
Description of Substation 170

The substation-170 has a ring bus configuration. Figure 21.3 shows the co-model of Substation-170 (power system + protection and control). The protection zones defined in Substation-170 can be seen in the figure. Substation-170 has four defined protection zones: (a) three transmission line protection zones and (b) one transformer protection zone. There are thirteen MUs in Substation-170. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

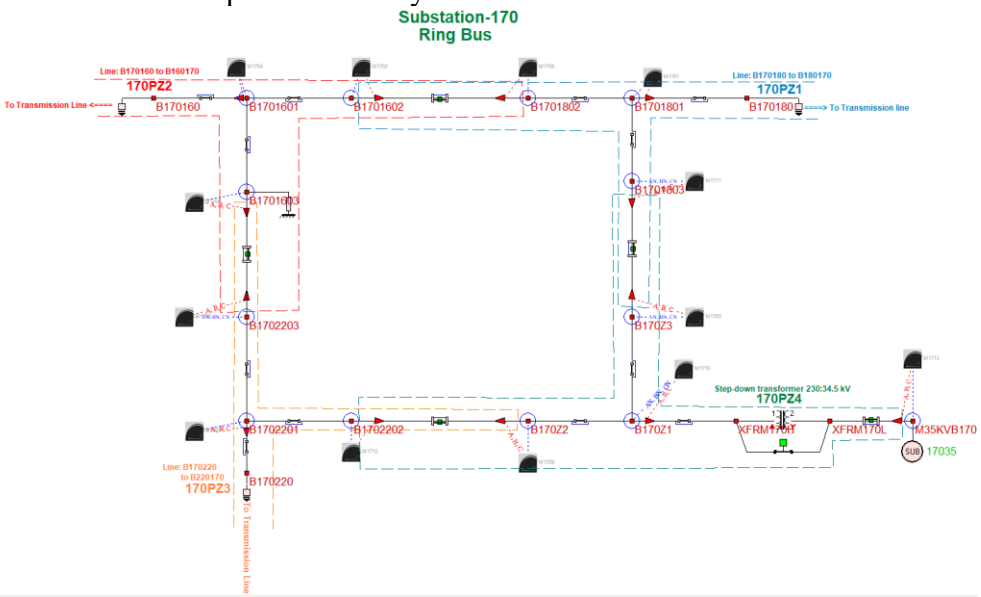


Figure A21.3 Co-model of Substation-170: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The six protection zones are briefly described below.

1. 170PZ1 protects the transmission line B170180 to B180170, it has one transmission line, two circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and five merging units in total taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.
2. 170PZ2 protects the transmission line B170160 to B160170, it has one transmission line, two circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and five merging units in total taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.
3. 170PZ3 protects the transmission line B170220 to B220170, it has one transmission line, two circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and five merging units in total taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.
4. 170PZ4 protects the step-down transformer XFRM170L, it has one 230:34.5 kV step-down XMFR, three circuit breakers each with two sets of three phase current and voltage transformers (CT/PT) and six merging units taking measurements from the CTs and PTs present in the protection zone. A protective relay is used to protect the protection zone.

Protection Zone 1 – 170PZ1
This protection zone consists of:

1. The transmission line that is connected between buses B170180 to B180170, the transmission line is a 230 kV line that is 10 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 170 and 180 respectively) measuring the voltages and currents at the ends of the transmission line, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B1701602 to B1701802 and B1701803 to B170Z3 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two

sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. Five Merging Units in total, one measures the three phase voltages and currents on the transmission line from the CTs and PTs present at node B1701801, four units measure the voltages and currents from the CTs and PTs on both the sides of each of the circuit breakers B1701602 to B1701802 and B1701803 to B170Z3 respectively.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 1 are collected using five merging units namely MU1701, MU1702, MU1703, MU1705 and MU1711 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 2 – 170PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B170160 to B160170, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 170 and 160 respectively) measuring the voltages and currents at the ends of the transmission line, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B1701602 to B1701802 and B1701603 to B1702203 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. Five Merging Units in total, one measures the three phase voltages and currents on the transmission line from the CTs and PTs present at node B1701601, four units measure the voltages and currents from the CTs and PTs on both the sides of each of the circuit breakers B1701602 to B1701802 and B1701603 to B1702203 respectively.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU1702, MU1704, MU1705, MU1706 and MU1708 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 170PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B170220 to B220170, the transmission line is a 230 kV line that is 73 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2FLYCATCHER/SSAC with an Ampacity of 1076.6 A.
2. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
3. The soil resistivity is 100 ohms-meter.
4. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the transmission line (present in Substations 170 and 220 respectively) measuring the voltages and currents at the ends of the transmission line, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B1702202 to B170Z2 and B1701603 to B1702203 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. Five Merging Units in total, one measures the three phase voltages and currents on the transmission line from the CTs and PTs present at node B1702201, four units measure the voltages and currents from the CTs and PTs on both the sides of each of the circuit breakers B1702202 to B170Z2 and B1701603 to B1702203 respectively.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU1706, MU1707, MU1708, MU1709 and MU1712 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 170PZ4
This protection zone consists of:

1. A three phase distribution-XFMR that has a 200 MVA rating. It is a step-down XFMR with a setting of 230:34.5 kV. The 34.5kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. Two circuit breakers that form the substation buses B1701803 to B170Z3 and B1702202 to B170Z2 respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units. Additionally, one 34.5 kV circuit breaker is connected at XFRM170L and M35KVB170 connecting the low side of the transformer to the 34.5 kV Distribution network. This breaker also has two sets of three phase CTs and PTs on either side measuring three phase currents and voltages.

3.There are Six Merging Units in total, one measures the three phase voltages and currents on the high side of the XFMR at node B170Z1 from the CTs and PTs present. Four units measure the voltages and currents from the CTs and PTs present on both the sides of each of the 230 kV circuit breakers B1701803 to B170Z3 and B1702202 to B170Z2 respectively. Finally, one unit measures the voltages and currents from the CTs and PTs present on the side of the circuit breaker XFRM170L to M35KVB170.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using seven merging units namely MU1703, MU1709, MU1710, MU1711, MU1712 and MU1713 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-22. Substation-180 System Description

This section of the document describes the Substation-180 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 22.1 shows the single line diagram of the system network model of Substation-180. There are three 230 kV transmission lines. These devices connect Substation-160 with other substations including Substation 170 (transmission line B180170 to B170180), Substation 210 (transmission line B180-211 to B210-181 and transmission line B180-212 to B210-182) respectively as can be seen in the figure.

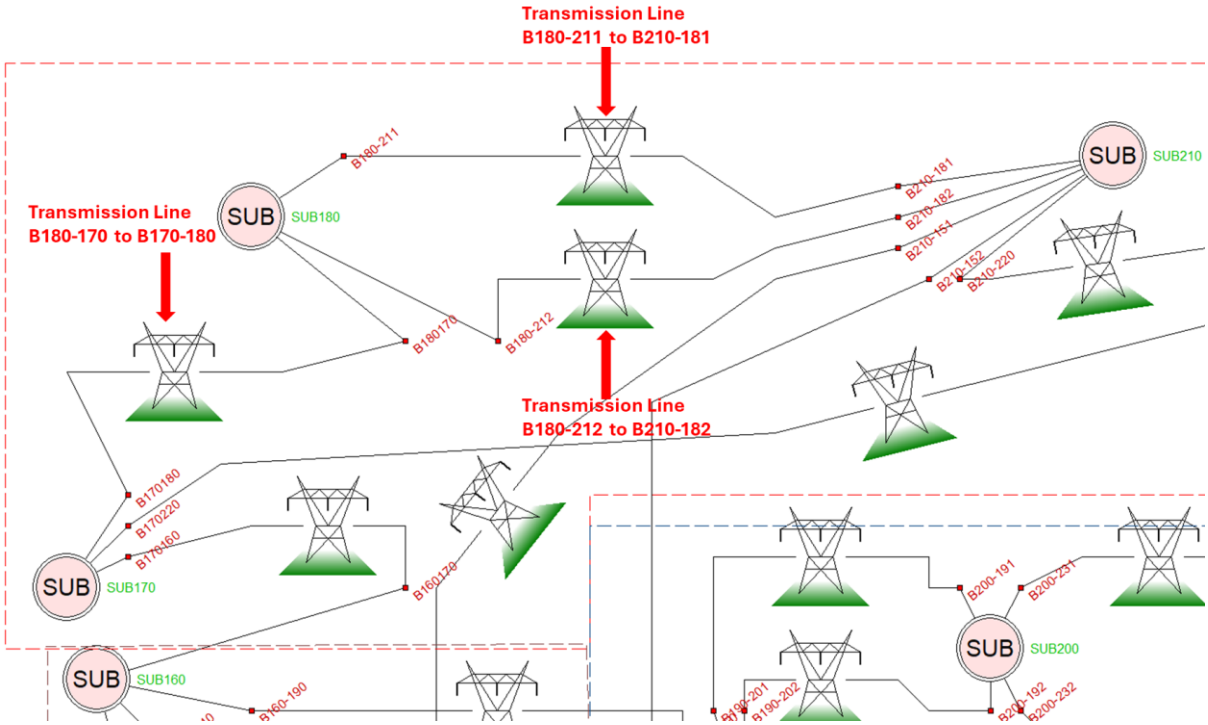


Figure A22.0.17 Single line diagram of system network connected to Substation-180.

The single line diagram of Substation-180 is shown in Figure 22.2. Substation-180 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of three 230 kV lines connecting Substation 180 to Substations 170 and 210, one generator–step-up transformer unit, two step-down transformer units and two substation buses. The substation model is represented with fifteen (15) three-phase nodes, eleven (11) circuit breakers, and nineteen (19) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-180 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

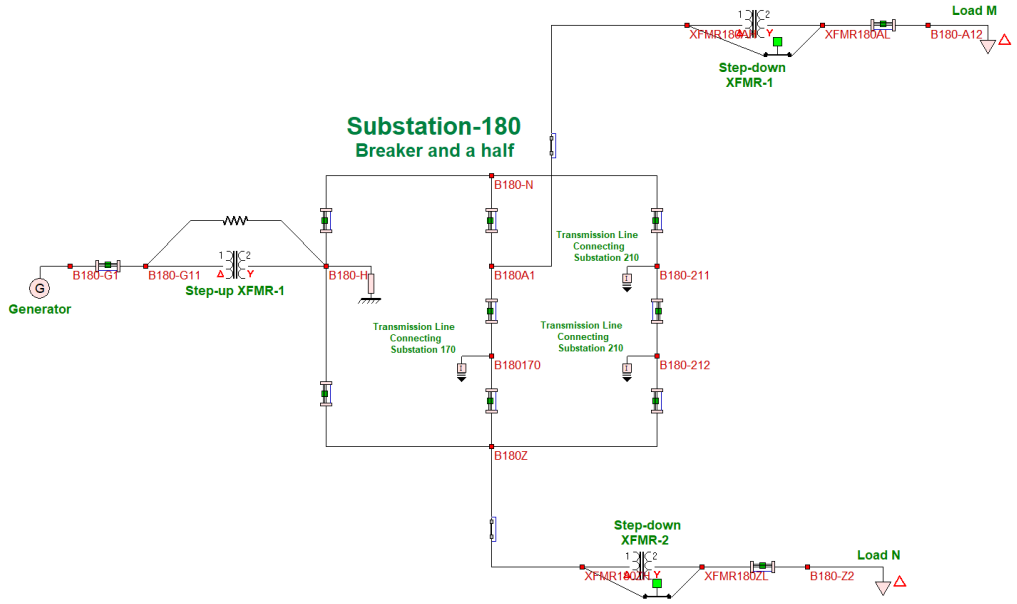


Figure A22.2 Substation-180: Breaker and a Half Configuration, Single Line Diagram

Protection and Control of Substation 180
Description of Substation 180

The substation-180 has a breaker and a half configuration. Figure 22.4 shows the co-model of Substation-180 (power system + protection and control). The protection zones defined in Substation-180 can be seen in the figure 22.5. Substation 180 has seven protection zones: (a) one generator-XFMR unit protection zone, (b) one Bus protection zone, (c) three transmission line protection zones and (d) two transformer protection zones. There are twenty-four MUs in Substation-180. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

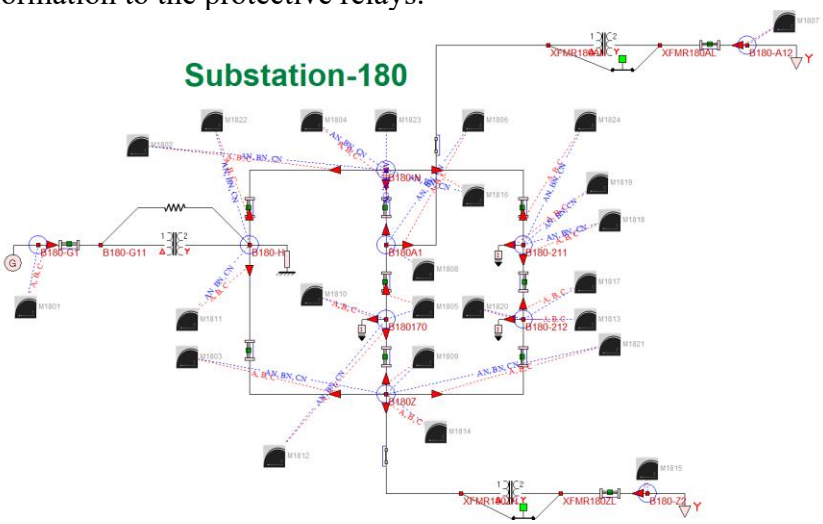


Figure A22.3 Substation-180: Merging Units Location

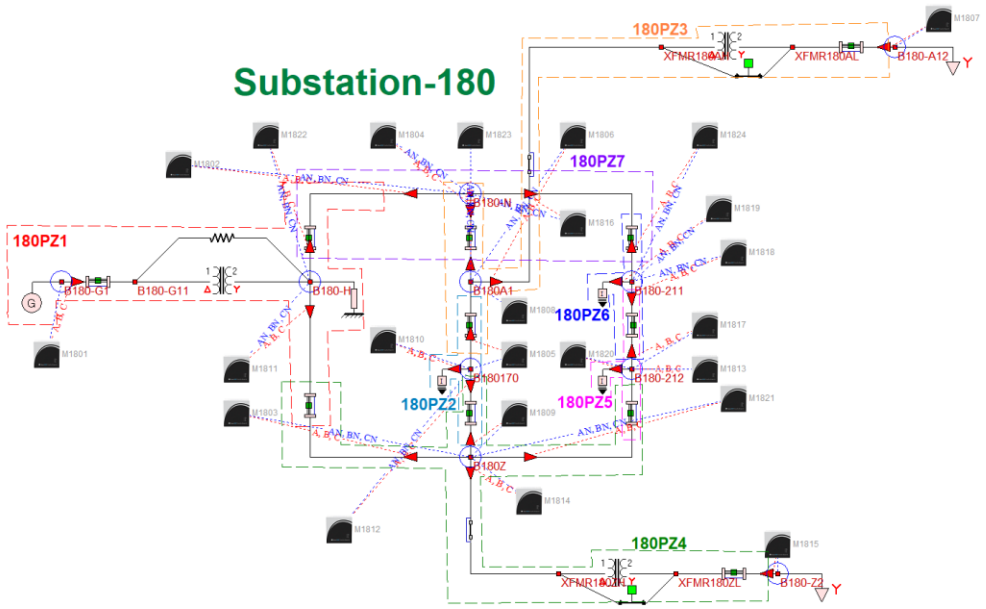


Figure A22.4 Co-model of Substation-180: Merging Units and Relays (Protection zones).

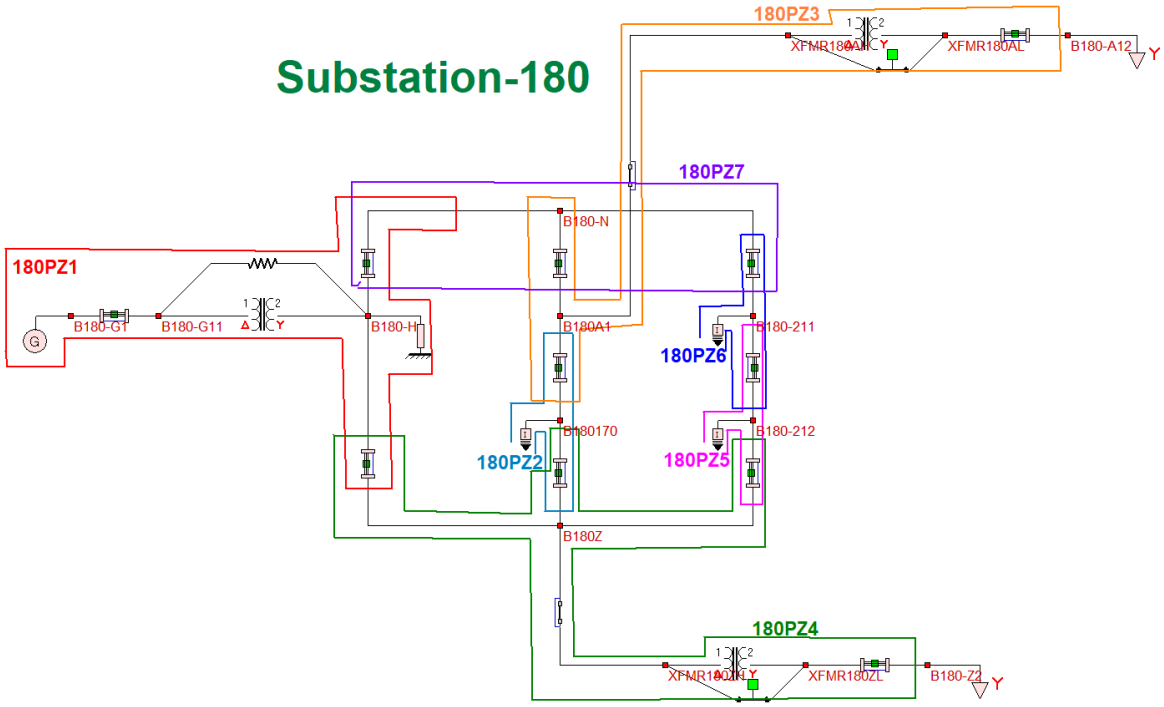


Figure A22.5 Substation-180 Defined Protection Zones

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The seven protection zones are briefly described below.

1. 180PZ1 protects the generator-XFMR at B180-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 180PZ2 protects the transmission line B180170 to B170180, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 180PZ3 protects the transformer XFMR180AL, it has one step-down XFMR, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 180PZ4 protects the transformer XFMR180ZL, it has one step-down XFMR, four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) each and eight merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 180PZ5 protects the transmission line B180-212 to B210-182, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 180PZ6 protects the transmission line B180-211 to B210-180, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 180PZ7 protects the North side Bus B180-N, it has one bus, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 180PZ1

This protection zone consists of:

1. A three phase generator that has a 115kV, 45 MVA rating. A step-up XFMR with a setting of 115:230kV, 45 MVA. The 230kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B180-G1 to B180-G11) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B180-N to B180-H; B180-H to B180Z) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The

CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B180-N to B180-H), two units collecting the voltage and current measurements from the CTs and PTs, present on both the nodes of the circuit breaker B180-H to B180Z connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B180-G1 to B180-G11).

Note: As an example, B180-G1 is a node.

For EBP:
An EBP relay monitors the unit protection zone.

For Legacy Protection:
A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using five merging units namely MU1801, MU1802, MU1803, MU1811 and MU1822 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2– 180PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B180170 to B170180, the transmission line is a 230 kV line that is 10 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.

2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 180 and 170 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B180A1 to B180170 and B180170 to B180Z respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B180A1 to B180170 and B180170 to B180Z). One unit collects the voltage and current measurements from the CTs and PTs, at the node B180170.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units namely MU1805, MU1808, MU1809, MU1810 and MU1812 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3 – 180PZ3
This protection zone consists of:

1. A three phase load-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are three circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR180AL to B180-A12) and has a rating of 50kV and a 10kA interrupt capability. There are two circuit breakers connected to the delta terminal of the XFMR (B180-N to B180A1; B180170 to B180A1) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are six Merging Units collecting measurements within the protection zone, six units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B180-N to B180A1; B180170 to B180A1).One unit collects the voltage and current measurements at node B180-A1 and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present at B180-A12.

Note: As an example, B180-A12 is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 3 are collected using six merging units namely MU1804, MU1805, MU1806, MU1807, MU1808 and MU1823 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 4 – 180PZ4
This protection zone consists of:

1. A three phase load-XFMR that has a 100 MVA rating. It is a step-down XFMR with a setting of 230:50 kV. The 50kV is Wye connected and the 230kV is delta connected.

Additionally, there are three phase CTs, and PTs connected across both the sides of the XFMR measuring the voltages and currents at the ends of the XFMR, these values are fed to the Merging Units.

2. There are four circuit breakers in total. One circuit breaker is connected to the wye terminal of the transformer (XFMR180ZL to B180-Z2) and has a rating of 50kV and a 10kA interrupt capability. There are three circuit breakers connected to the delta terminal of the XFMR (B180-H to B180Z; B180170 to B180Z; B180-212 to B180Z) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are eight Merging Units collecting measurements within the protection zone, six units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the delta terminal of the transformer (B180-H to B180Z; B180170 to B180Z; B180-212 to B180Z).One unit collects the voltage and current measurements at node B180Z and one unit collects the voltage and current measurements from the CTs and PTs, at the nodes present at B180-Z2

Note: As an example, B180-Z2 is a node.

For EBP:
An EBP relay monitors the transformer protection zone.

For Legacy Protection:
A numerical relay (SEL-787L) monitors this protection zone, the functions that are set in this relay is:

1. 87L: Line Differential Element.
2. 87HBL: Second Harmonic Blocking.
3. 50 P: Max Phase overcurrent.
4. 67 P: Max Phase overcurrent with directional control.
5. 50 Q: Negative Sequence Overcurrent.

Measurements for protection zone 4 are collected using eight merging units namely MU1803, MU1809, MU1811, MU1812, MU1813, MU1814, MU1815 and MU1821 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 5– 180PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B180-212 to B210-182, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 180 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B180-211 to B180-212 and B180-212 to B180Z respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B180-211 to B180-212 and B180-212 to B180Z). One unit collects the voltage and current measurements from the CTs and PTs, at the node B180-212.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU1813, MU1817, MU1818, MU1820 and MU1821 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6– 180PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B180-211 to B210-181, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 180 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B180-211 to B180-212 and B180-211 to B180-N respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B180-211 to B180-212 and B180-211 to B180-N). One unit collects the voltage and current measurements from the CTs and PTs, at the node B180-211.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU1816, MU1817, MU1818, MU1819 and MU1824 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the

current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 180PZ7

This protection zone consists of:

1. Three Circuit Breakers forms the substation north bus B180-N, namely B180-N to B180-H, B180-A1 to B180-N, B180-211 to B180-N. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Six Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B180-N to B180-H, B180-A1 to B180-N, B180-211 to B180-N.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using six merging units namely MU1802, MU1804, MU1816, MU1822, MU1823 and MU1824 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-23. Substation-210 System Description

This section of the document describes the Substation-210 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 23.1 shows the single line diagram of the system network model of Substation-210. There are five 230 kV transmission lines. These devices connect

Substation-210 with other substations including Substation 180 (transmission line B210-181 to B180-211 and B210-182 to B180-212), Substation 150 (transmission line B210-151 to B150-211 and transmission line B210-152 to B150-212) and Substation 220 (transmission line B210-220 to B220-210) respectively as can be seen in the figure.

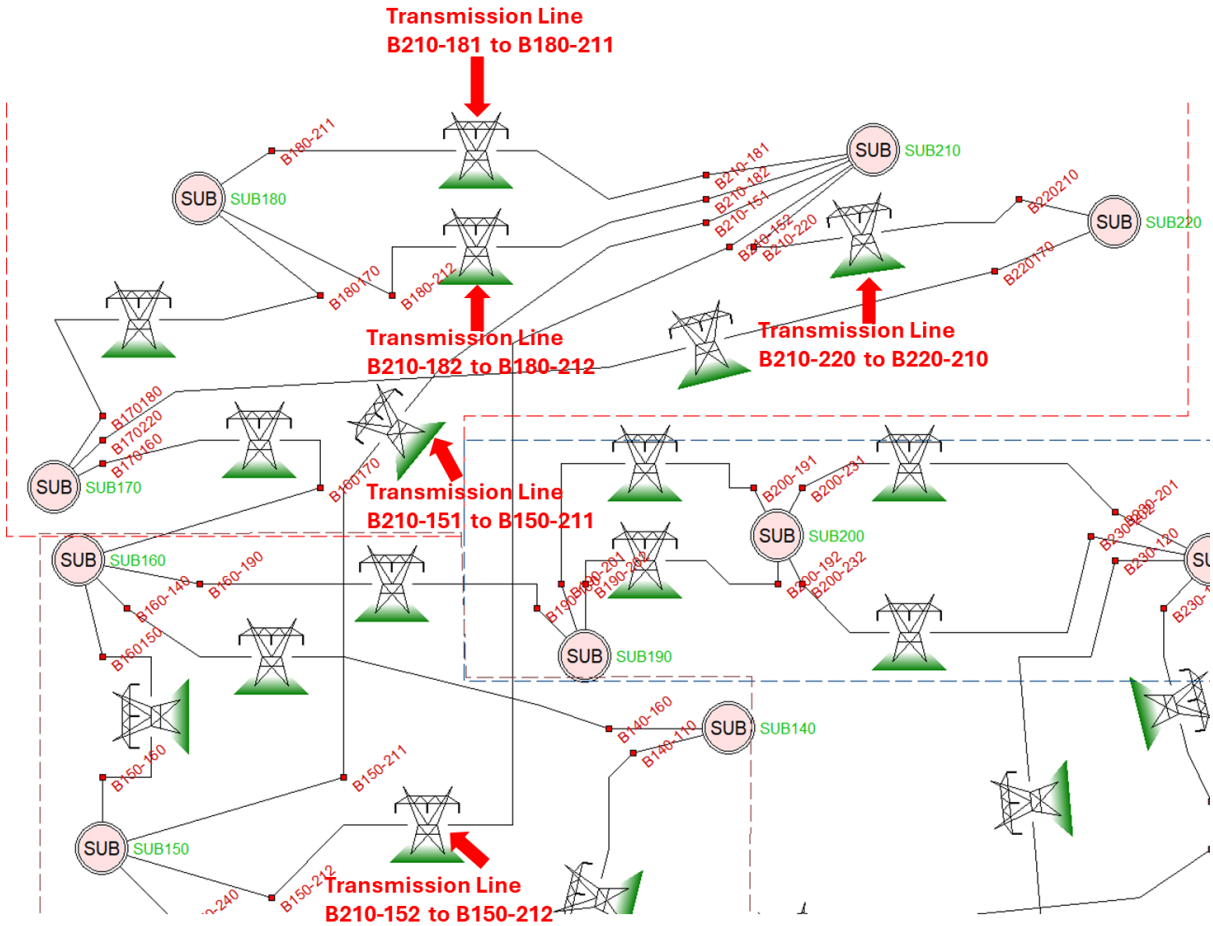


Figure A23.0.18 Single line diagram of system network connected to Substation-210.

The single line diagram of Substation-210 is shown in Figure 23.2. Substation-210 is a 230 kV substation. It has a breaker and a half arrangement. This substation consists of five 230 kV lines connecting Substation 210 to Substations 180,150 and 220, one generator–step-up transformer unit and two substation buses. The substation model is represented with ten (10) three-phase nodes, ten (10) circuit breakers, and twenty-four (24) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-210 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

Note: The isolation switches are present on either side of every breaker. Due to space constraints for this substation, isolation switches on either of the substation circuit breakers have not been shown in the model.

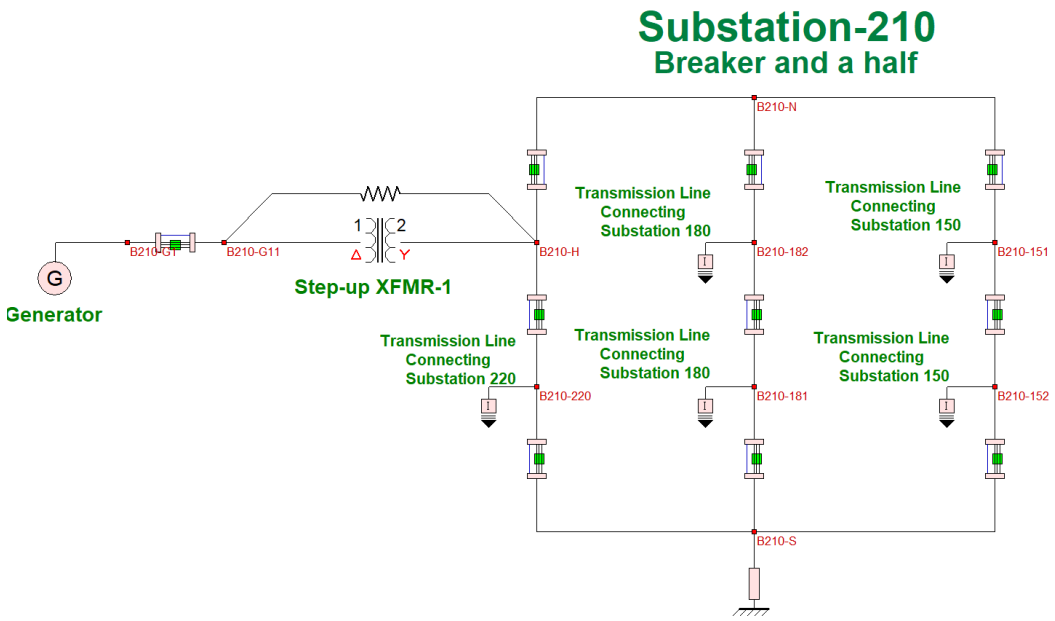


Figure A23.2 Substation-210: Breaker and a Half Configuration, Single Line Diagram

Protection and Control of Substation 210
Description of Substation 210

The substation-210 has a breaker and a half configuration. Figure 23.4 shows the co-model of Substation-210 (power system + protection and control). The protection zones defined in Substation-210 can be seen in the figure 23.5. Substation 210 has eight protection zones: (a) one generator-XFMR unit protection zone, (b) two Bus protection zone, and (c) five transmission line protection zones. There are twenty-four MUs in Substation-210. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

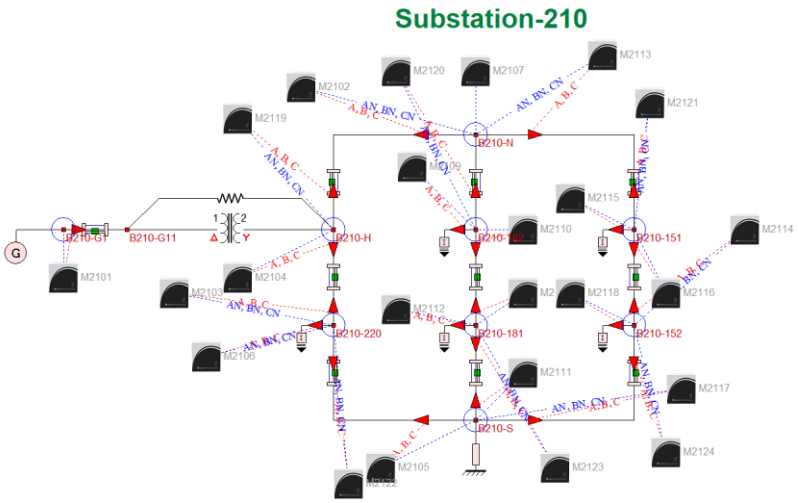


Figure A23.3 Substation-210: Merging Units Location

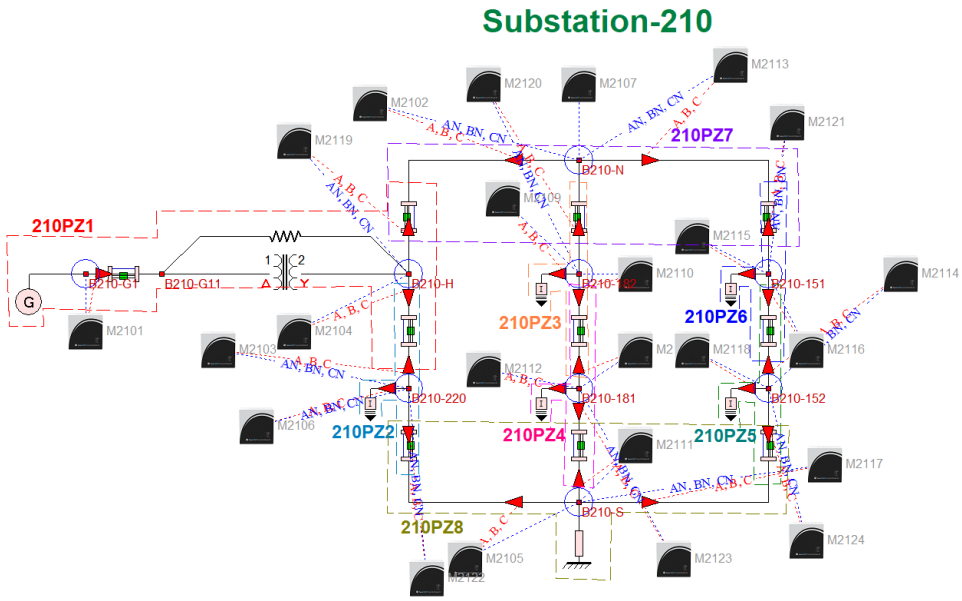


Figure A23.4 Co-model of Substation-210: Merging Units and Relays (Protection zones).

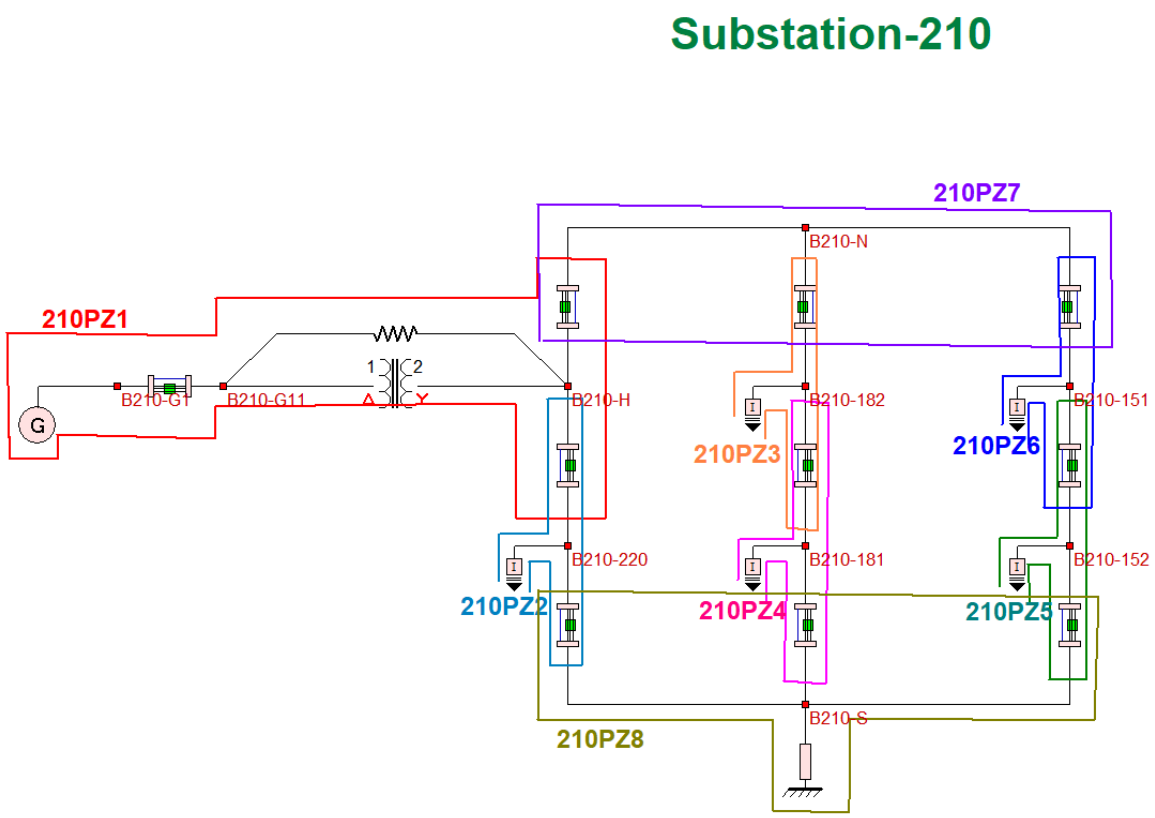


Figure A23.5 Substation-210 Defined Protection Zones

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The eight protection zones are briefly described below.

1. 210PZ1 protects the generator-XFMR at B210-G1, it has one generator, one step-up transformer, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 210PZ2 protects the transmission line B210-220 to B220-210, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 210PZ3 protects the transmission line B210-182 to B180-212, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

4. 210PZ4 protects the transmission line B210-181 to B180-211, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 210PZ5 protects the transmission line B210-152 to B150-212, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
6. 210PZ6 protects the transmission line B210-151 to B150-211, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
7. 180PZ7 protects the North side Bus B210-N, it has one bus, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
8. 180PZ8 protects the South side Bus B210-S, it has one bus, three circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and six merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 210PZ1

This protection zone consists of:

1. A three phase generator that has a 115kV, 100 MVA rating. A step-up XFMR with a setting of 115:230kV, 100 MVA. The 230kV is Wye connected and the 115kV is Delta connected. There is a 30-degree phase shift from the delta to the wye side.

2. There are three circuit breakers in total. One circuit breaker is connected to the delta terminal of the transformer (B210-G1 to B210-G11) and has a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B210-N to B210-H; B210-H to B210-220) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are Five Merging Units collecting measurements within the protection zone, two units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breaker connected to the Wye terminal of the transformer (B210-N to B210-H), two units collecting the voltage and current measurements from the CTs and PTs, present on both the nodes of the circuit breaker B210-H to B210-220 connected to the Wye terminal of the transformer. One unit collects the voltage and current measurements from the CTs and PTs, at

the nodes present on either side of the circuit breaker which is connected to the delta terminal of the transformer (B210-G1 to B210-G11).

Note: As an example, B210-G1 is a node.

For EBP: An EBP relay monitors the unit protection zone.
For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using five merging units namely MU2101, MU2102, MU2103, MU2104 and MU2119 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2– 210PZ2
This protection zone consists of:

1. The transmission line that is connected between buses B210-220 to B220-210, the transmission line is a 230 kV line that is 47.1 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The soil resistivity is 100 ohms-meter.
3. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 210 and 220 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B210-H to B210-220 and B210-220 to B210-S respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B210-H to B210-220 and B210-220 to B210-S). One unit collects the voltage and current measurements from the CTs and PTs, at the node B210-220.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 2 are collected using five merging units MU2103, MU2104, MU2105, MU2106 and MU2122 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 3– 210PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B210-182 to B180-212, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 180 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from B210-N to B210-182 and B210-182 to B210-181 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each

circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B210-N to B210-182 and B210-182 to B210-181). One unit collects the voltage and current measurements from the CTs and PTs, at the node B210-182.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU2107, MU2108, MU2109, MU2110 and MU2120 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4– 210PZ4
This protection zone consists of:

1. The transmission line that is connected between buses B210-181 to B180-211, the transmission line is a 230 kV line that is 18 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 180 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B210-S to B210-181 and B210-182 to B210-181 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B210-S to B210-181 and B210-182 to B210-181). One unit collects the voltage and current measurements from the CTs and PTs, at the node B210-181.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU2108, MU2110, MU2111, MU2112 and MU2123 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 5– 210PZ5
This protection zone consists of:

1. The transmission line that is connected between buses B210-152 to B150-212, the transmission line is a 230 kV line that is 34 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.
4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B210-S to B210-152 and B210-152 to B210-151 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B210-S to B210-152 and B210-152 to B210-151). One unit collects the voltage and current measurements from the CTs and PTs, at the node B210-152.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 5 are collected using five merging units namely MU2114, MU2116, MU2117, MU2118 and MU2124 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 6– 210PZ6
This protection zone consists of:

1. The transmission line that is connected between buses B210-151 to B150-211, the transmission line is a 230 kV line that is 34 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size CARDINAL/SSAC with an Ampacity of 1059.8 A.
2. The shields are of HS type and are of the size 5/16HS.
3. The ground impedance is given as: R =25 ohms and X_c or X_L = 0 ohms.

4. The soil resistivity is 100 ohms-meter.
5. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 150 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B210-N to B210-151 and B210-152 to B210-151 respectively. These circuit breakers have a rated voltage of 230 kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B210-N to B210-151 and B210-152 to B210-151). One unit collects the voltage and current measurements from the CTs and PTs, at the node B210-151.

For EBP:
An EBP relay monitors the transmission line protection zone.

For Legacy Protection:
A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 6 are collected using five merging units namely MU2113, MU2114, MU2115, MU2116 and MU2121 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 7 – 210PZ7

This protection zone consists of:

1. Three Circuit Breakers forms the substation north bus B210-N, namely B210-N to B210-H, B210-N to B210-182, B210-N to B210-151. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two

isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Six Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B210-N to B210-H, B210-N to B210-182, B210-N to B210-151.

For EBP:

An EBP relay monitors the bus protection zone.

For Legacy protection and control:

A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 7 are collected using six merging units namely MU2102, MU2107, MU2113, MU2119, MU2120 and MU2121 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 8 – 210PZ8

This protection zone consists of:

1. Three Circuit Breakers forms the substation South bus B210-S, namely B210-S to B210-220, B210-S to B210-181, B210-S to B210-152. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, it has one set of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages (total 2 sets of 3 phase CTs and PTs), these values are then fed to the Merging Units.

2. Six Merging Units, collecting the voltage and current measurements from the CTs and PTs, at the nodes present on both the sides of the circuit breakers: B210-S to B210-220, B210-S to B210-181, B210-S to B210-152.

For EBP: An EBP relay monitors the bus protection zone.
For Legacy protection and control: A numerical relay (SEL-487B) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 P: Phase Instantaneous overcurrent.
3. 51: Time overcurrent.
4. 27: Under Voltage.
5. 59: Overvoltage.
6. 50BF: Breaker Failure Overcurrent.

Measurements for protection zone 8 are collected using six merging units namely MU2105, MU2111, MU2117, MU2122, MU2123 and MU2124 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

A-24. Substation-220 System Description

This section of the document describes the Substation-220 system, which serves to demonstrate the functionality of a high-fidelity substation co-model. This model is a subset of the larger IEEE 24 substation RTS co-model. Figure 24.1 shows the single line diagram of the system network model of Substation-220. There are two 230 kV transmission lines. These devices connect Substation-220 with other substations including Substation 170 (transmission line B220170 to B170220) and Substation 210 (transmission line B220-210 to B210-220) as can be seen in the figure.

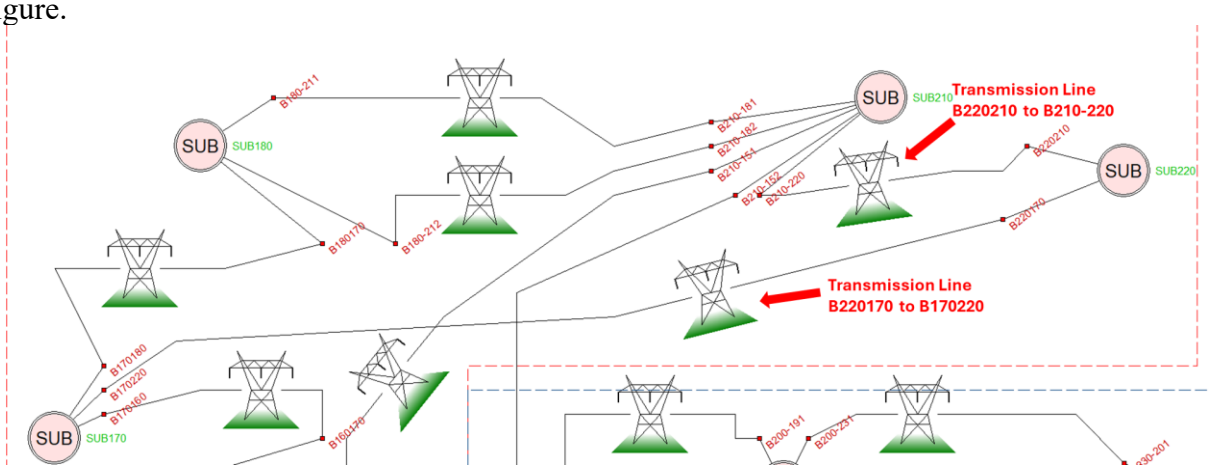


Figure A24.0.19 Single line diagram of system network connected to Substation-220.

The single line diagram of Substation-220 is shown in Figure 24.2. Substation-220 is a 230 kV substation. It has a ring bus arrangement. This substation consists of two 230 kV lines connecting Substation 220 to Substations 170 and 210, three generator/inverter-step-up three winding transformer units and multiple substation buses. The substation model is represented with thirty-one (31) three-phase nodes, eleven (11) circuit breakers, and fifteen (15) isolation switches that can be used to isolate or control a zone within the substation.

Note: Substation-220 is represented by a circular icon. Double-clicking on this icon will open the substation single-line diagram view in WinIGS-T.

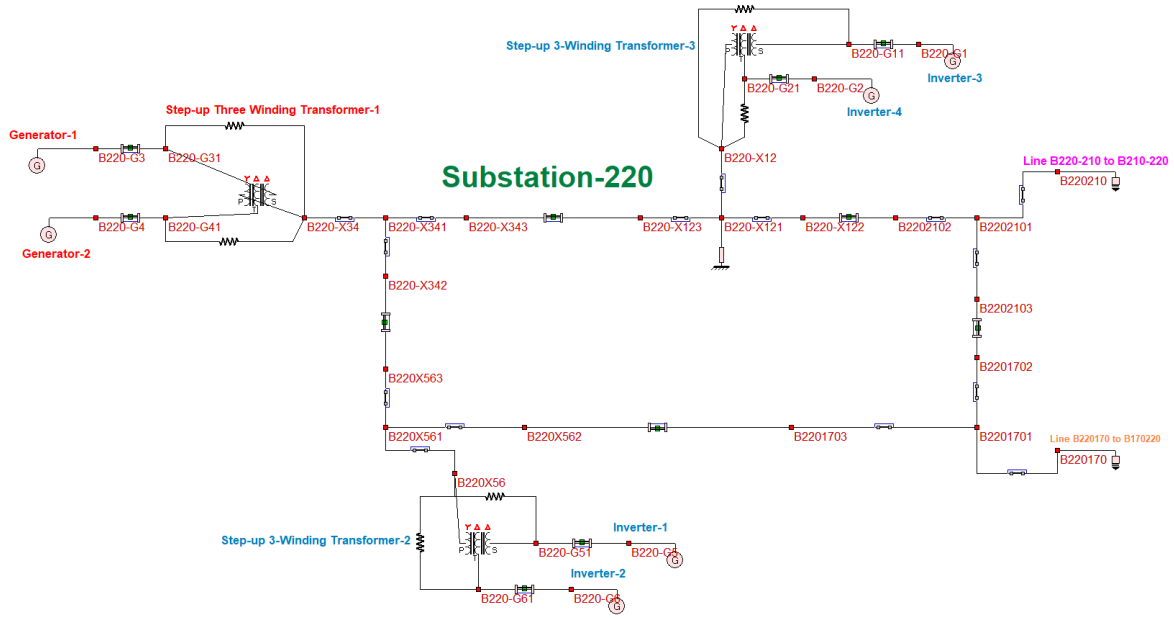


Figure A24.2 Substation-220: Ring Bus Configuration, Single Line Diagram

Protection and Control of Substation 220
Description of Substation 220

The substation-220 has a ring bus configuration. Figure 24.3 shows the co-model of Substation-220 (power system + protection and control). The protection zones defined in Substation-220 can be seen in the figure. Substation 220 has five protection zones: (a) two transmission line protection zones and (c) three generator/inverter-transformer unit protection zones. There are twenty-one MUs in Substation-220. The locations of the current and voltage measurements for each MU are labelled with red (current measurements) and blue dashed lines (voltage measurements), respectively. The MUs present within the protection zones send the measurements to the Centralized SVDC which then sends the information to the protective relays.

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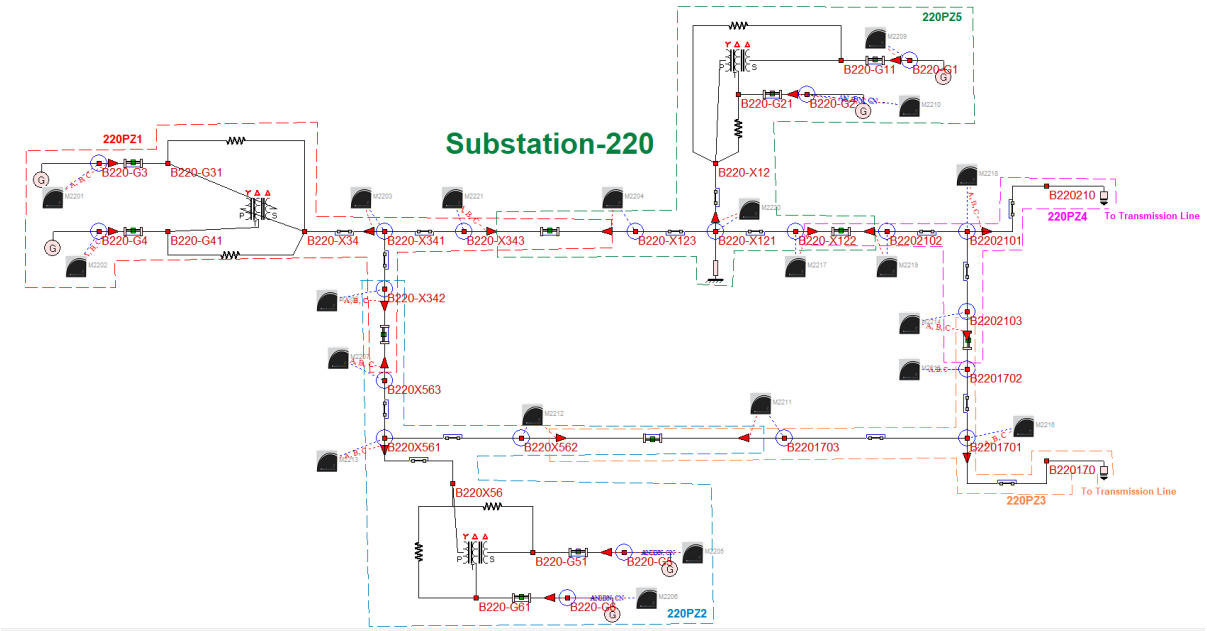


Figure A24.3 Co-model of Substation-220: Merging Units and Relays (Protection zones).

Note: Line protection zones are indicated with open borders (continuing to transmission line/ cable) since this substation does not contain the entire protection zone, the other half of the line protection zone is present in the other substation connected to this substation.

The five protection zones are briefly described below.

1. 220PZ1 protects the generators-XFMR at B220-G3 and B220-G4, it has two generators, one step-up three winding transformer, four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and seven merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
2. 220PZ2 protects the inverters-XFMR at B220-G5 and B220-G5, it has two inverters, one step-up three winding transformer, four circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and seven merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
3. 220PZ3 protects the transmission line B220170 to B170220, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
4. 220PZ4 protects the transmission line B220210 to B210-220, it has one transmission line, two circuit breakers, each with two sets of three phase current and voltage transformers (CTs/PTs) and five merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.
5. 220PZ5 protects the inverters-XFMR at B220-G1 and B220-G2, it has two inverters, one step-up three winding transformer, four circuit breakers, each with two sets of three phase

current and voltage transformers (CTs/PTs) and seven merging units measuring the voltages and currents. A protective relay is used to protect the protection zone.

Protection Zone 1 – 220PZ1

This protection zone consists of:

1. Two three phase generators that have a 115kV, 100 MVA rating each. A step-up three winding XFMR with a setting of 115:115:230kV, 300 MVA. The 230 kV is the primary terminal and is Wye connected and both the 115kV is Delta connected and is Secondary and Tertiary terminals respectively. There is a 30-degree phase shift from the delta to the wye side.

2. There are four circuit breakers in total. One circuit breaker is connected to the secondary terminal of the transformer (B130-G3 to B130-G31), the other is connected to tertiary terminal of the transformer (B130-G4 to B130-G41), both have a rating of 115kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B220-X343 to B220-X123; B220-X342 to B220X563) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are seven Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B220-X343 to B220-X123; B220-X342 to B220X563).One unit collects the voltage and current measurements from the CTs and PTs at node B220-X341. One unit collects the voltage and current measurements from the CTs and PTs, at node B220-G3 and another unit collects the measurements at node B220-G4.

For EBP: An EBP relay monitors the unit protection zone.
For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 1 are collected using seven merging units namely MU2201, MU2202, MU2203, MU2204, MU2207, MU2208 and MU2221 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents.

The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 2 – 220PZ2

This protection zone consists of:

1. Two three phase inverters that have a 34.5kV, 50 MVA rating each. A step-up three winding XFMR with a setting of 34.5:34.5:230kV, 200 MVA. The 230 kV is the primary terminal and is Wye connected and both the 34.5kV is Delta connected and is Secondary and Tertiary terminals respectively. There is a 30-degree phase shift from the delta to the wye side.

2. There are four circuit breakers in total. One circuit breaker is connected to the secondary terminal of the transformer (B130-G5 to B130-G51), the other is connected to tertiary terminal of the transformer (B130-G6 to B130-G61), both have a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B220X562 to B2201703; B220-X342 to B220X563) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are seven Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B220X562 to B2201703; B220-X342 to B220X563).One unit collects the voltage and current measurements from the CTs and PTs at node B220X561. One unit collects the voltage and current measurements from the CTs and PTs, at node B220-G5 and another unit collects the measurements at node B220-G6.

For EBP: An EBP relay monitors the unit protection zone.
For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 2 are collected using seven merging units namely MU2205, MU2206, MU2207, MU2208, MU2211, MU2212 and MU2213 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents.

The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Protection Zone 3 – 220PZ3
This protection zone consists of:

1. The transmission line that is connected between buses B220170 to B170220, the transmission line is a 230 kV line that is 73 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2FLYCATCHER/SSAC with an Ampacity of 1076.6 A.
2. The soil resistivity is 100 ohms-meter.
3. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 220 and 170 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B220X562 to B2201703; and B2202103 to B2201702; respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B220X562 to B2201703; and B2202103 to B2201702). One unit collects the voltage and current measurements from the CTs and PTs, at the node B2201701.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 3 are collected using five merging units namely MU2211, MU2212, MU2214, MU2215, and MU2216 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 4 – 220PZ4
This protection zone consists of:

1. The transmission line that is connected between buses B220210 to B210-220, the transmission line is a 230 kV line that is 47.1 miles long. The transmission line is modelled as follows:

1. The phase conductors of the line are of the type ACSR and size T2HAWK/SSAC with an Ampacity of 1076 A.
2. The soil resistivity is 100 ohms-meter.
3. The span length is 0.1m.

Additionally, there are three phase CTs, and PTs connected across both the sides of the overhead line (present in Substations 220 and 210 respectively) measuring the voltages and currents at the ends of the line, these values are fed to the Merging Units.

2. Two circuit breakers are present, namely the ones connected from nodes B220-X122 to B2202102; and B2202103 to B2201702; respectively. These circuit breakers have a rated voltage of 230kV and interrupt capability of 40kA. The neutrals of these breakers are closed. Each circuit breaker has two isolating switches on either side of the breaker for isolation protection. Additionally, each circuit breaker has two sets of three phase Current Transformers (CTs) and Voltage Transformers (PTs) connected on either side of the breaker to monitor the currents and voltages, these values are then fed to the Merging Units.

3. There are Five Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers (B220-X122 to B2202102; and B2202103 to B2201702). One unit collects the voltage and current measurements from the CTs and PTs, at the node B2202101.

For EBP: An EBP relay monitors the transmission line protection zone.
For Legacy Protection: A numerical relay (SEL-421) monitors this protection zone, the functions that are set in this relay is:

1. 21MG/21MP: Mho ground/phase Distance protection.
2. 21XG/21XP: Quadrilateral ground/phase Distance protection.
3. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
4. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
5. 67 N/G/P/Q: Ground/Phase/Negative Sequence Directional.

Measurements for protection zone 4 are collected using five merging units namely MU2214, MU2215, MU2217, MU2218, and MU2219 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurement) and blue dashed lines (voltage measurement), respectively.

Protection Zone 5 – 220PZ5

This protection zone consists of:

1. Two three phase inverters that have a 34.5kV, 50 MVA rating each. A step-up three winding XFMR with a setting of 34.5:34.5:230kV, 200 MVA. The 230 kV is the primary terminal and is Wye connected and both the 34.5kV is Delta connected and is Secondary and Tertiary terminals respectively. There is a 30-degree phase shift from the delta to the wye side.

2. There are four circuit breakers in total. One circuit breaker is connected to the secondary terminal of the transformer (B130-G1 to B130-G11), the other is connected to tertiary terminal of the transformer (B130-G2 to B130-G21), both have a rating of 34.5kV and a 40kA interrupt capability. There are two circuit breakers connected to the wye terminal of the XFMR (B220-X122 to B2202102; B220-X343 to B220-X123) and have a rating of 230kV and 40kA interrupt capability. Each circuit breaker contains two sets of three phase CTs and PTs connected on either side of the circuit breaker. The CTs and PTs monitor the voltages and currents at designated nodes. These measurements are taken by the Merging Units. In addition, each circuit breaker contains two isolation switches on either side of the breaker.

3. There are seven Merging Units collecting measurements within the protection zone, four units collecting the voltage and current measurements from the CTs and PTs, at the nodes present on either side of the circuit breakers connected to the Wye terminal of the transformer (B220-X122 to B2202102; B220-X343 to B220-X123).One unit collects the voltage and current measurements from the CTs and PTs at node B220-X121. One unit collects the voltage and current measurements from the CTs and PTs, at node B220-G1 and another unit collects the measurements at node B220-G2.

For EBP: An EBP relay monitors the unit protection zone.
For Legacy Protection: A numerical relay (SEL-787) monitors this protection zone, the functions that are set in this relay is:

1. 87: Voltage/Current Differential.
2. 50 N/G/P/Q: Ground/Phase/Negative Sequence Instantaneous overcurrent.
3. 51 N/G/P/Q: Ground/Phase/Negative Sequence Time overcurrent.
4. 27: Under Voltage.
5. 59/Q: Overvoltage/ Negative Sequence Overvoltage.
6. 24: V/f Relay.

The primary function that we are going to focus on is the differential protection.

Measurements for protection zone 5 are collected using seven merging units namely MU2204, MU2209, MU2210, MU2217, MU2219, MU2220 and MU2221 respectively. Measurements are collected from six sets of instrumentation channels: three sets of voltages and three sets of currents. The locations of the current and voltage measurements for each MU are labeled with red (current measurements) and blue dashed lines (voltage measurements), respectively.

Appendix B: Co-Simulation Results

This Appendix presents detailed information about the events performed on the IEEE 24 Substation RTS co-model and the response of the protection and control to these events.

The summary of the co-simulation results is presented in Chapter 3. In this appendix, we present the detailed results of the co-simulation.

B-1. Events:

We conducted a set of selected events to evaluate the performance of the protection and control system in the IEEE 24-Substation RTS. This section describes some of such events carried out across different substations, along with the corresponding responses of some of the protection and control schemes of these substations. Each event was carefully chosen and designed to test system performance under varying conditions. It is important to note that these events are unique and are modeled to emulate real-world scenarios.

B-1.1. Event-1 (Substation-170):

This section describes Event-1 of Substation-170. The event lasts until about 10.25s. It includes several disturbances during the simulation period. The data recording starts at 0.25 seconds of the simulation; this time is referenced as time 0s in the timeline. Data is stored in COMTRADE format (Note: In the COMTRADE file the data recording is from 0 to 10 seconds with 0 being 0.25s in the actual simulation. i.e. the recording is from 0.25 to 10.25s).

The timeline of Event-1 is shown in Figure B-1.1E1., where the negative events such as electric faults and addition of loads, etc. are labeled in red and blue, and the positive events including recovery of electric faults and loads that have been turned off are labeled in green. In Event-1, the data recording starts at 0.25s from the start of the simulation. There are more disturbances that occur over the base case. An A-G fault occurs on bus FA170180 for 9 cycles at 5 miles from substation-170 (50% of the transmission line B170180 to B180170). Another AB-G fault occurs on the bus FB170180 for 9 cycles at 7.5 miles from substation-170 (75% of the transmission line B170180 to B180170). The single-line-to-ground electric fault at FA170180 starts at 2.05s and clears at 2.2s. The double-line-to-ground electric fault at FB170180 starts at 8.05s from the start of the simulation and clears at 8.2s. In addition to electrical faults, there are three load changes that occur at different times where the performance of the system is disturbed.

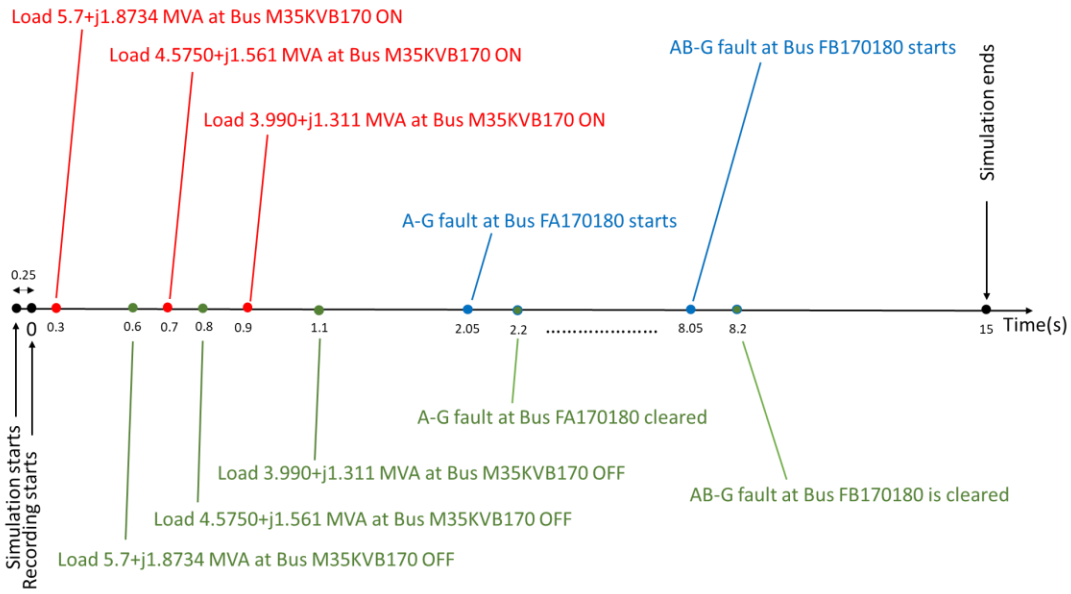


Figure B-1.1E1. Timeline of Substation-170: Event-1.

Figures B-1.1E2, B-1.1E3 and B-1.1E4 show the COMTRADE data for Event-1 for protection zones 170PZ1, 170PZ2 and 170PZ3. As indicated, there are 5 subevents occurring in the system during the event. We can observe the electric faults occurring in the system in the COMTRADE file at around 1.8s and 7.8s respectively. The load changes occur roughly in the interval from 0.3s to 1.1 s and are independent events.

There are multiple subevents in Event-1. The subevents are listed below:

Table B-1.1: List of subevents for Event-1.

Subevent No	Subevent Name	Subevent Duration
1.	Load addition (6 MVA)	0.3s to 0.6s
2.	Load addition (5MVA)	0.7s to 0.8s
3.	Load addition (4.2 MVA)	0.9s to 1.1s
4.	A-G Fault on line B170180 to B180170 at 5 miles from Substation-170 (50% of the line length).	2.05s to 2.2s
5.	AB-G Fault on line B170180 to B180170 at 7.5 miles from Substation-170 (75% of the line length).	8.05s to 8.2s

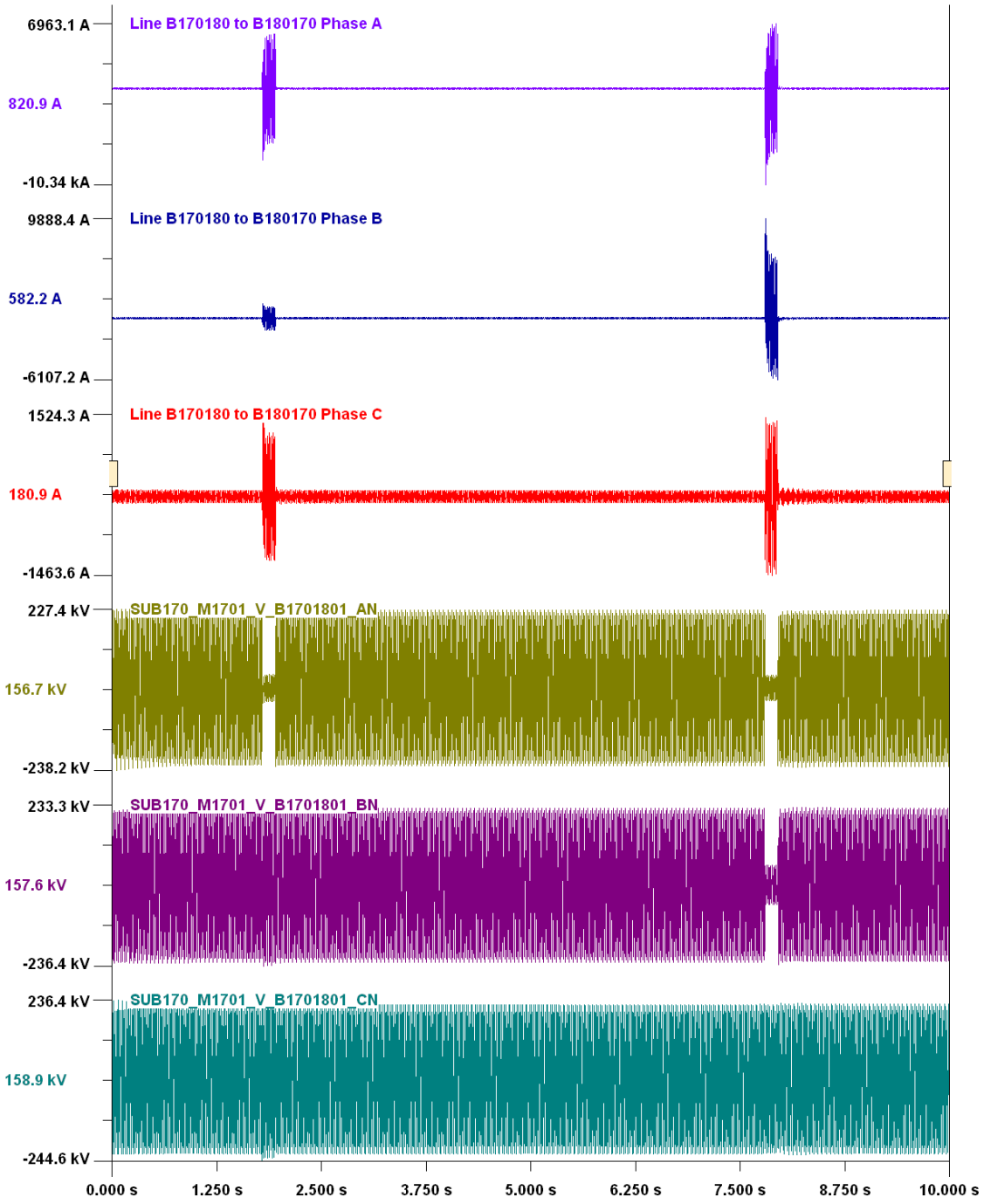


Figure B-1.1E2 COMTRADE data for Event-1 (170PZ1). Merging Unit 1701.

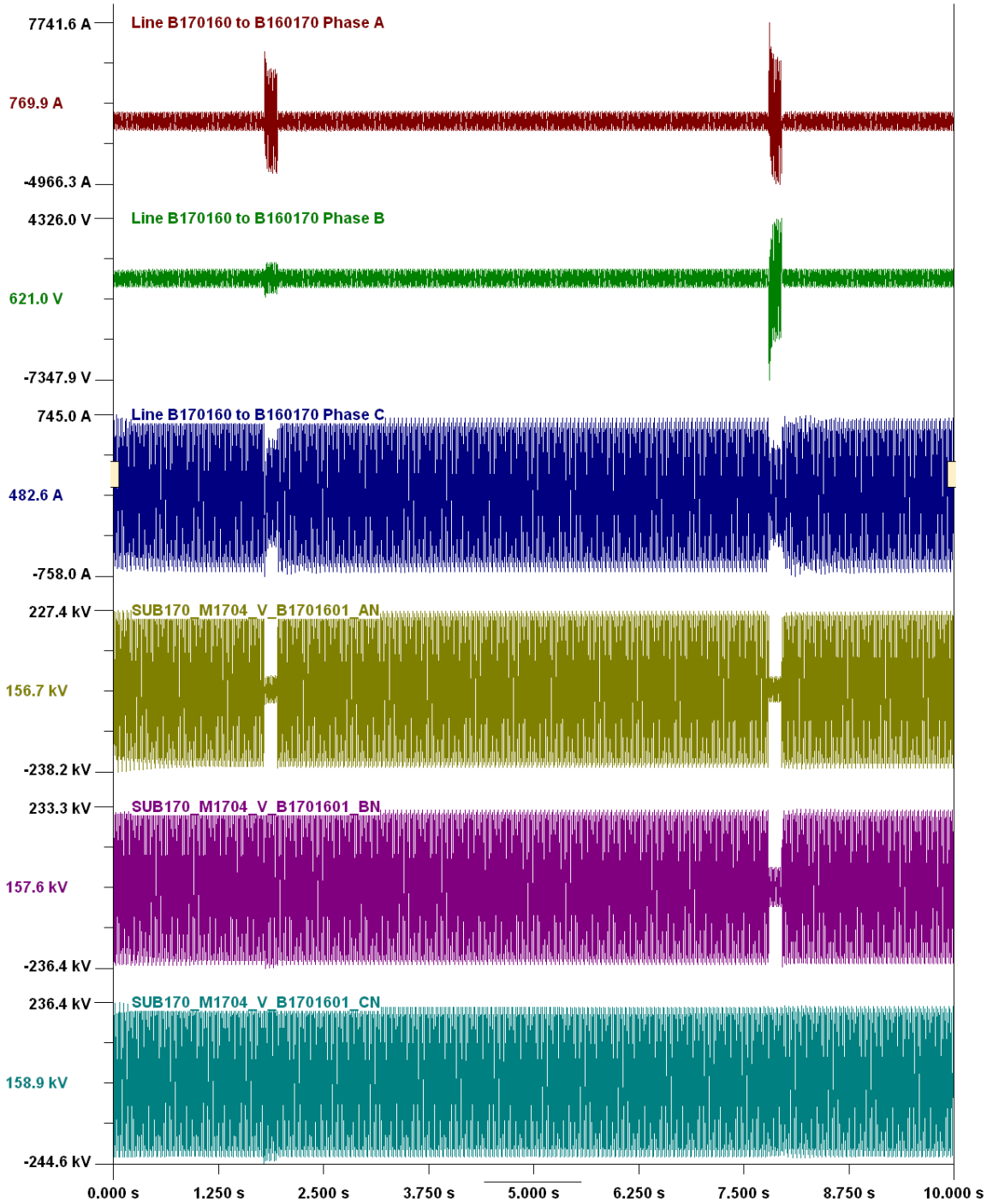


Figure B-1.1E3 COMTRADE data for Event-1 (170PZ2). Merging Unit 1704.

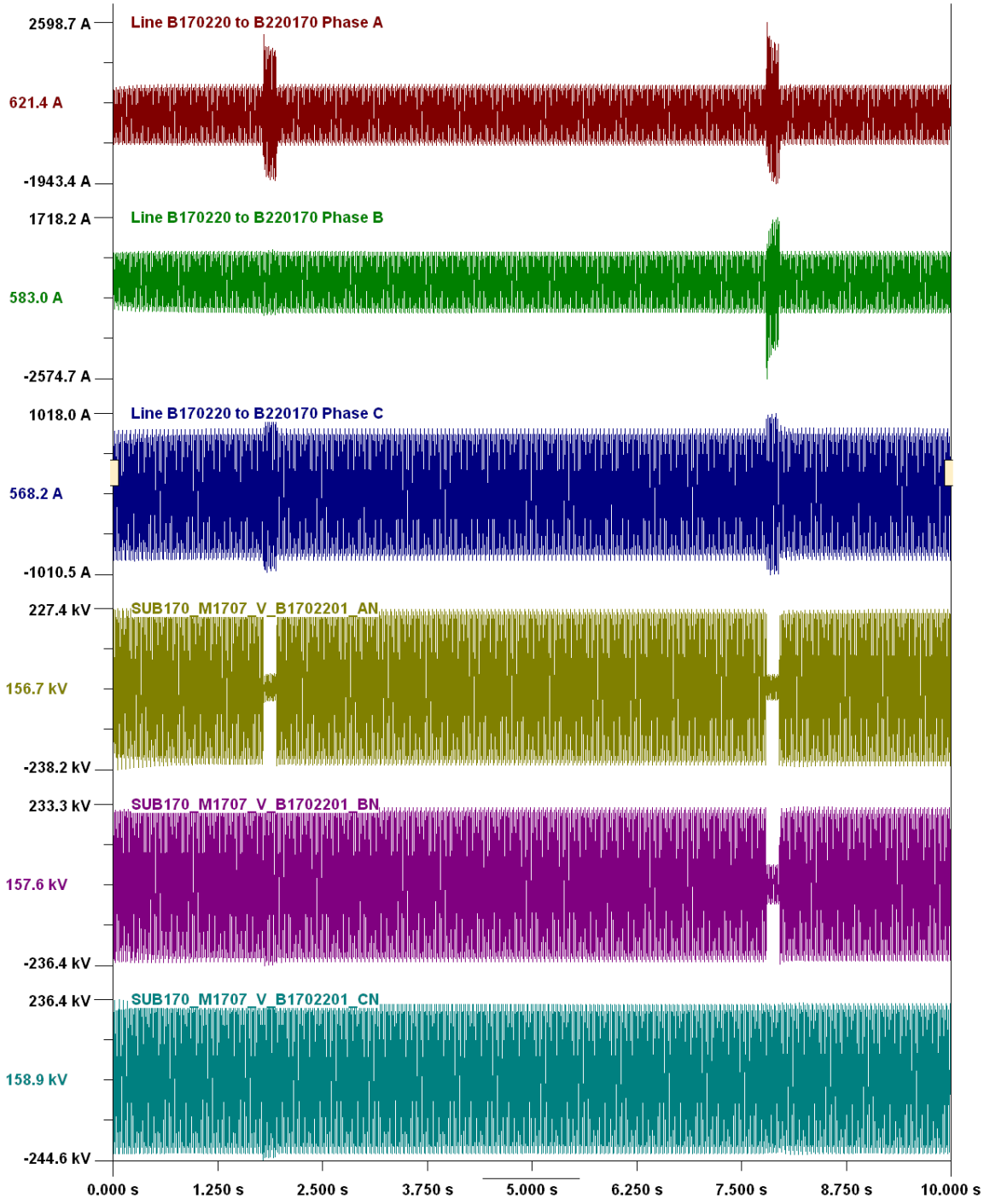


Figure B-1.1E4 COMTRADE data for Event-1 (170PZ3). Merging Unit 1707.

B-1.2. Event-2 (Substation-240):

This section describes Event-2 of Substation 240. The event duration is 2 seconds. It includes several disturbances during the simulation period. Data is stored in COMTRADE format.

The timeline of Event-2 is shown in Figure B-1.2E1, where the negative events such as electric faults are labeled in red and blue, and the positive events including recovery of electric faults are labeled in green. An A-G fault occurs at 75% of the line length of the transmission line B240150 to B150240. Another B-G fault occurs at 75% of the line length of the transmission line B24030 to B30240. The A-G electric fault starts at 1.3s and clears at 1.45s. The B-G electric fault starts at 1.6s from the start of the simulation and clears at 1.75s.

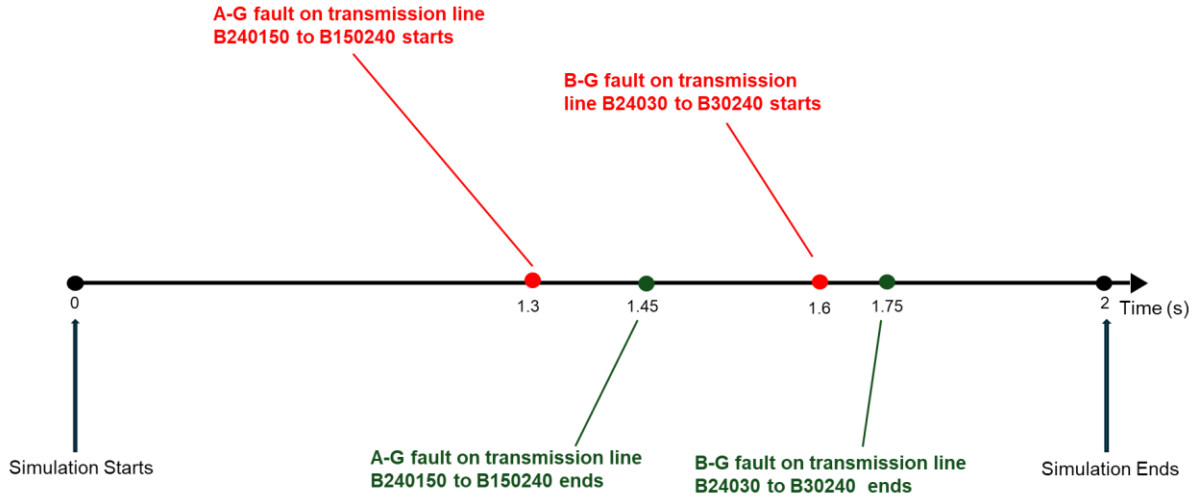


Figure B-1.2E1 Timeline of Event-2.

Figures B-1.2E2 and B-1.2E3 show the COMTRADE data for Event-2 for protection zones 240PZ1, 240PZ3. As indicated, there are 2 subevents occurring in the system during the event. We can observe the electric faults occurring in the system in the COMTRADE file at around 1.3s and 1.6s respectively.

There are two subevents in Event-2. The subevents are listed below:

Table B-1.2: List of subevents for Event-2.

Subevent No	Subevent Name	Subevent Duration
1.	A-G Fault on line B240150 to B150240 at 27 miles from Substation-240 (75% of the line length).	1.3s to 1.45s
2.	B-G Fault on line B24030 to B30240 at 13.2883 miles from Substation-240 (75% of the line length).	1.6s to 1.75s

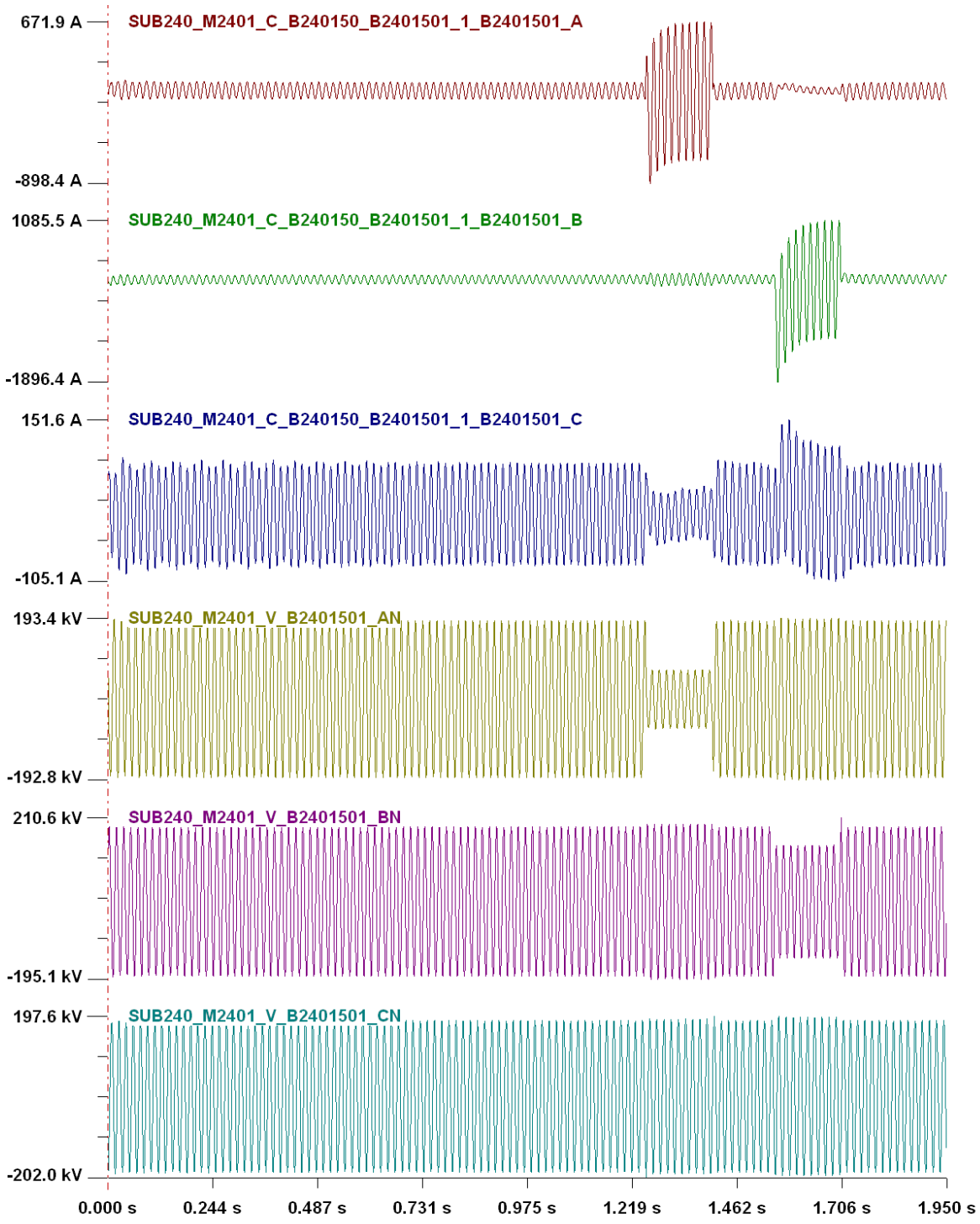


Figure B-1.2E2 COMTRADE data for Event-2 (240PZ1). Merging Units 2401.

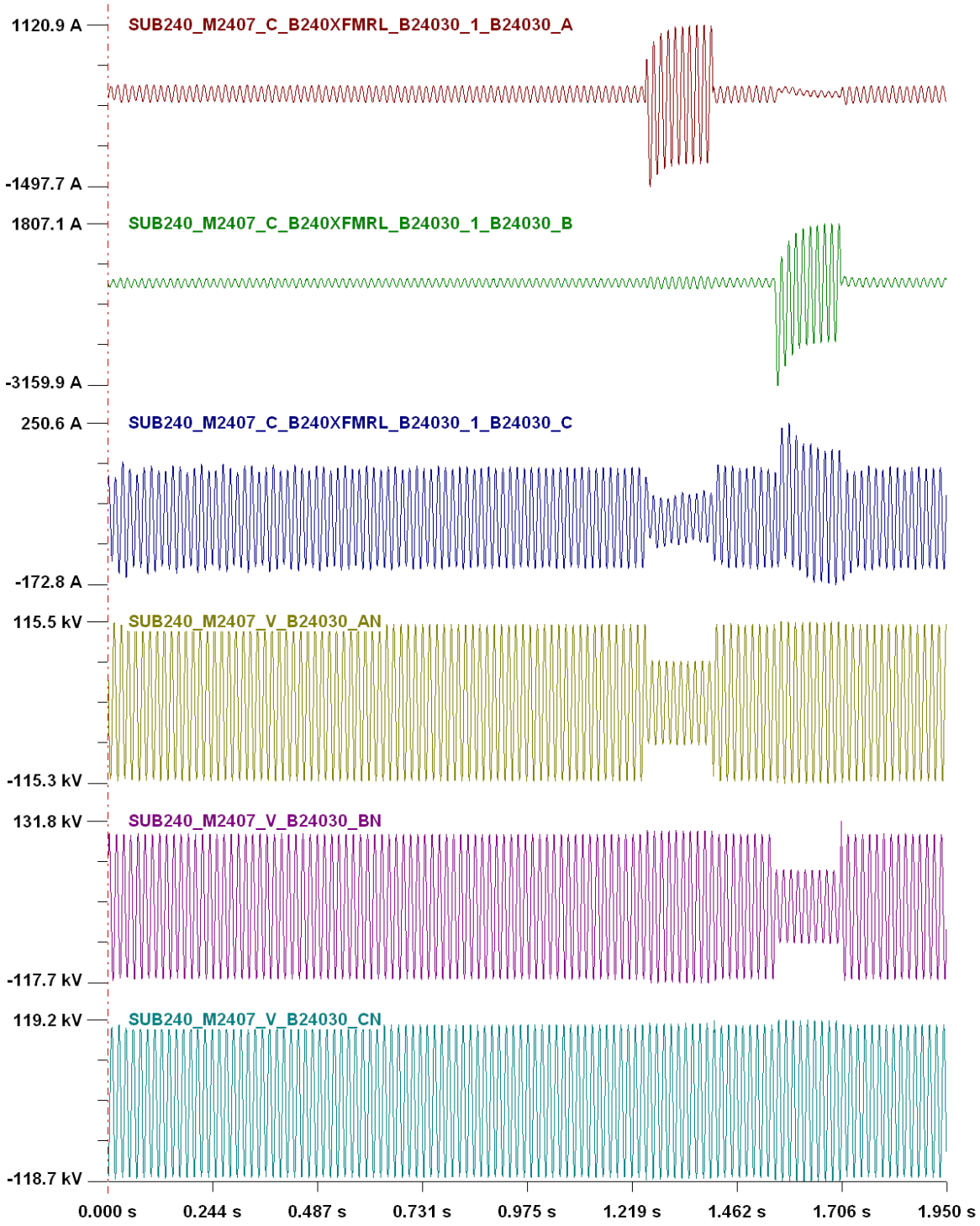


Figure B-1.2E3 COMTRADE data for Event-2 (240PZ3). Merging Unit 2407.

B-1.3. Event-3 (Substation-50):

This section describes Event-3 of Substation 50. The event duration is 3 seconds. It includes several disturbances during the simulation period. Data is stored in COMTRADE format.

The timeline of Event-3 is shown in Figure B-1.3E1, where the negative events such as electric faults are labeled in red and blue, and the positive events including recovery of electric faults are labeled in green. An A-G fault occurs at 75% of the line length of the transmission line B5010 to B1050. Another B-G fault occurs at 75% of the line length of the transmission line B50100 to B10050. The A-G electric fault starts at 1.3s and clears at 1.45s. The B-G electric fault starts at 2.3s from the start of the simulation and clears at 2.45s.

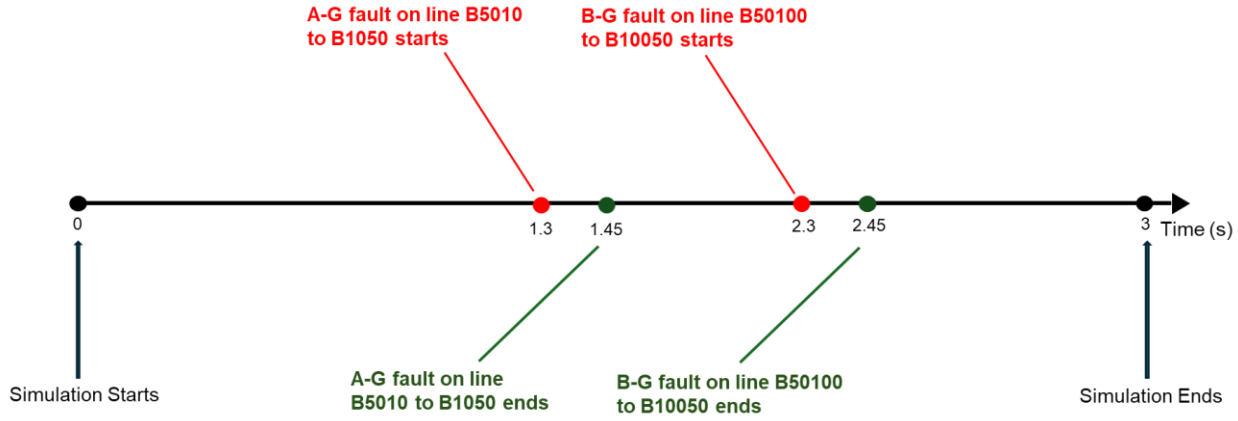


Figure B-1.3E1 Timeline of Event-3.

Figures B-1.3E2 and B-1.3E3 show the COMTRADE data for Event-3 for protection zones 50PZ1, 50PZ2. As indicated, there are 2 subevents occurring in the system during the event. We can observe the electric faults occurring in the system in the COMTRADE file at around 1.3s and 2.3s respectively.

There are two subevents in Event-3. The subevents are listed below:

Table B-1.3: List of subevents for Event-3.

Subevent No	Subevent Name	Subevent Duration
1.	A-G Fault on line B5010 to B1050 at 16.5 miles from Substation-50 (75% of the line length).	1.3s to 1.45s
2.	B-G Fault on line B50100 to B10050 at 17.7175 miles from Substation-50 (75% of the line length).	2.3s to 2.45s

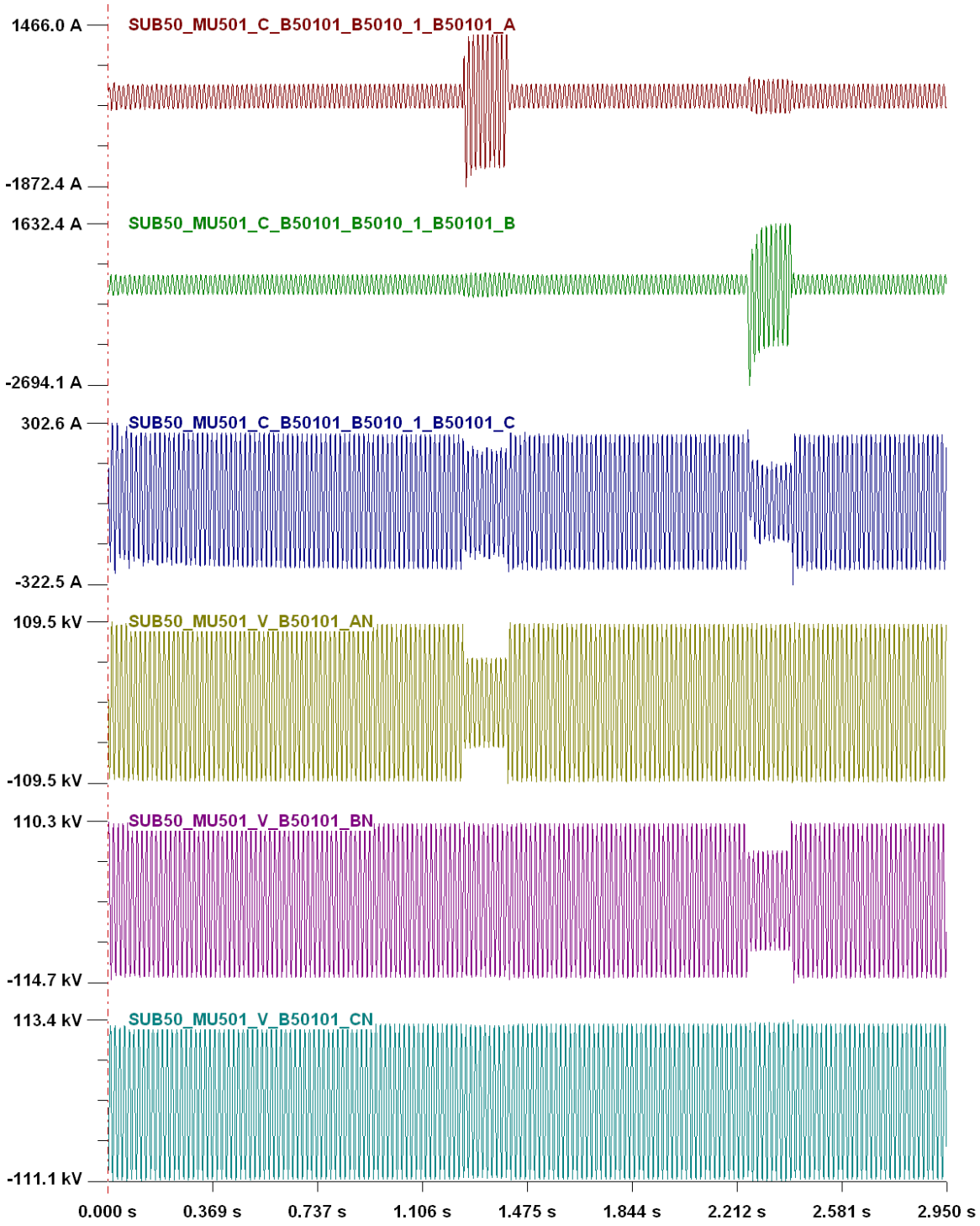


Figure B-1.3E2 COMTRADE data for Event-3 (50PZ1). Merging Units 501.

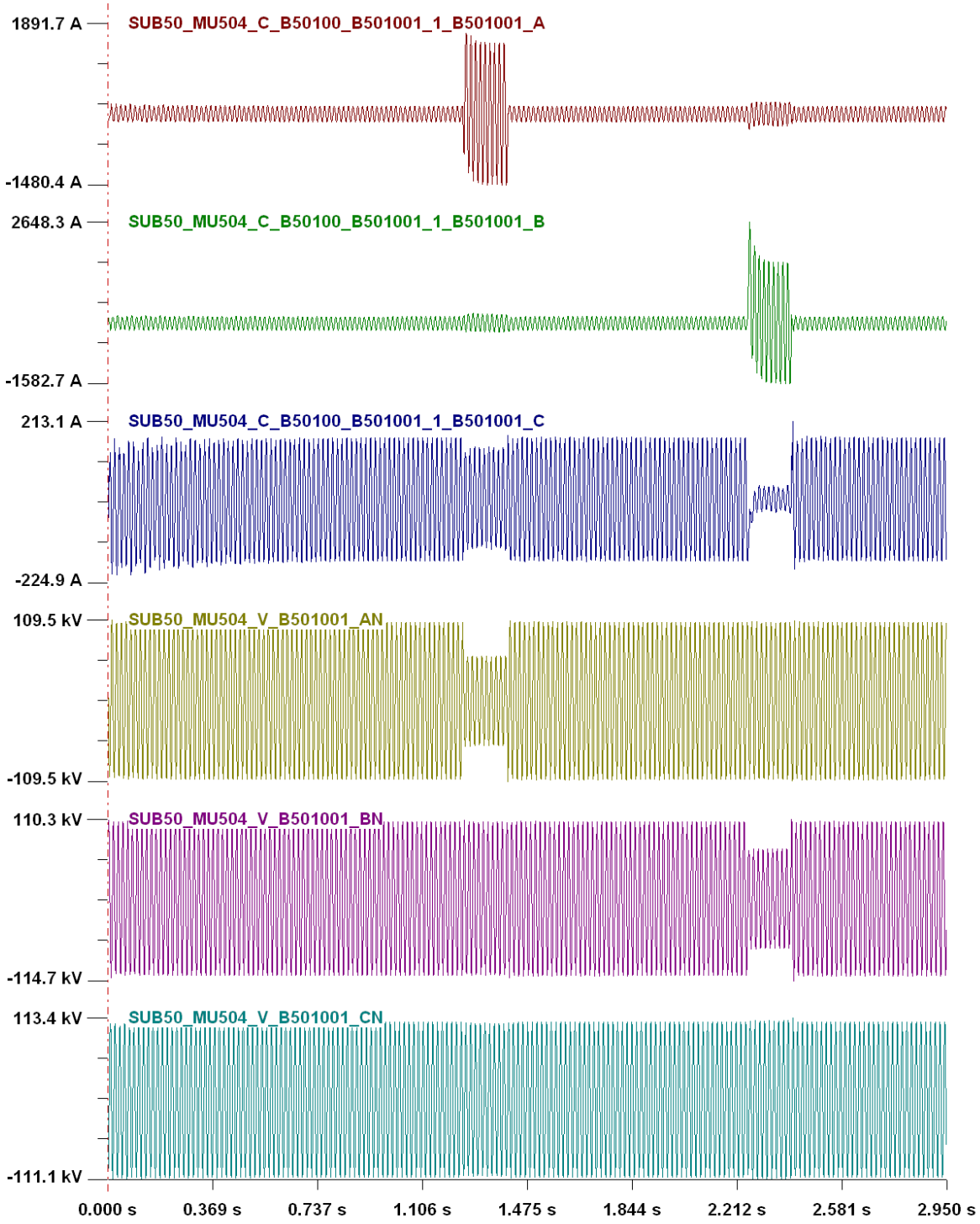


Figure B-1.3E3 COMTRADE data for Event-3 (50PZ2). Merging Unit 504.

B-1.4. Event-4 (Substation-40):

This section describes Event-4 of Substation 40. The event duration is 3 seconds. It includes several disturbances during the simulation period. Data is stored in COMTRADE format.

The timeline of Event-4 is shown in Figure B-1.4E1, where the negative events such as electric faults are labeled in red and blue, and the positive events including recovery of electric faults are labeled in green. An A-G fault occurs at 75% of the line length of the transmission line B4020 to B2040. Another B-G fault occurs at 75% of the line length of the transmission line B4090 to B9040. The A-G electric fault starts at 1.3s and clears at 1.45s. The B-G electric fault starts at 2.3s from the start of the simulation and clears at 2.45s.

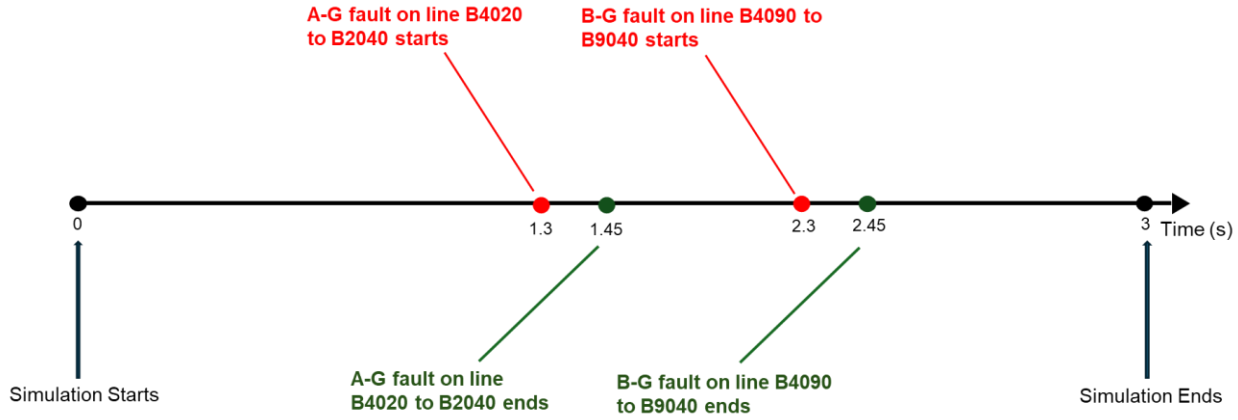


Figure B-1.4E1 Timeline of Event-4.

Figures B-1.4E2 and B-1.4E3 show the COMTRADE data for Event-4 for protection zones 40PZ1, 40PZ2. As indicated, there are 2 subevents occurring in the system during the event. We can observe the electric faults occurring in the system in the COMTRADE file at around 1.3s and 2.3s respectively.

There are two subevents in Event-4. The subevents are listed below:

Table B-1.4: List of subevents for Event-4.

Subevent No	Subevent Name	Subevent Duration
1.	A-G Fault on line B4020 to B2040 at 24.75 miles from Substation-40 (75% of the line length).	1.3s to 1.45s
2.	B-G Fault on line B4090 to B9040 at 19.875 miles from Substation-40 (75% of the line length).	2.3s to 2.45s

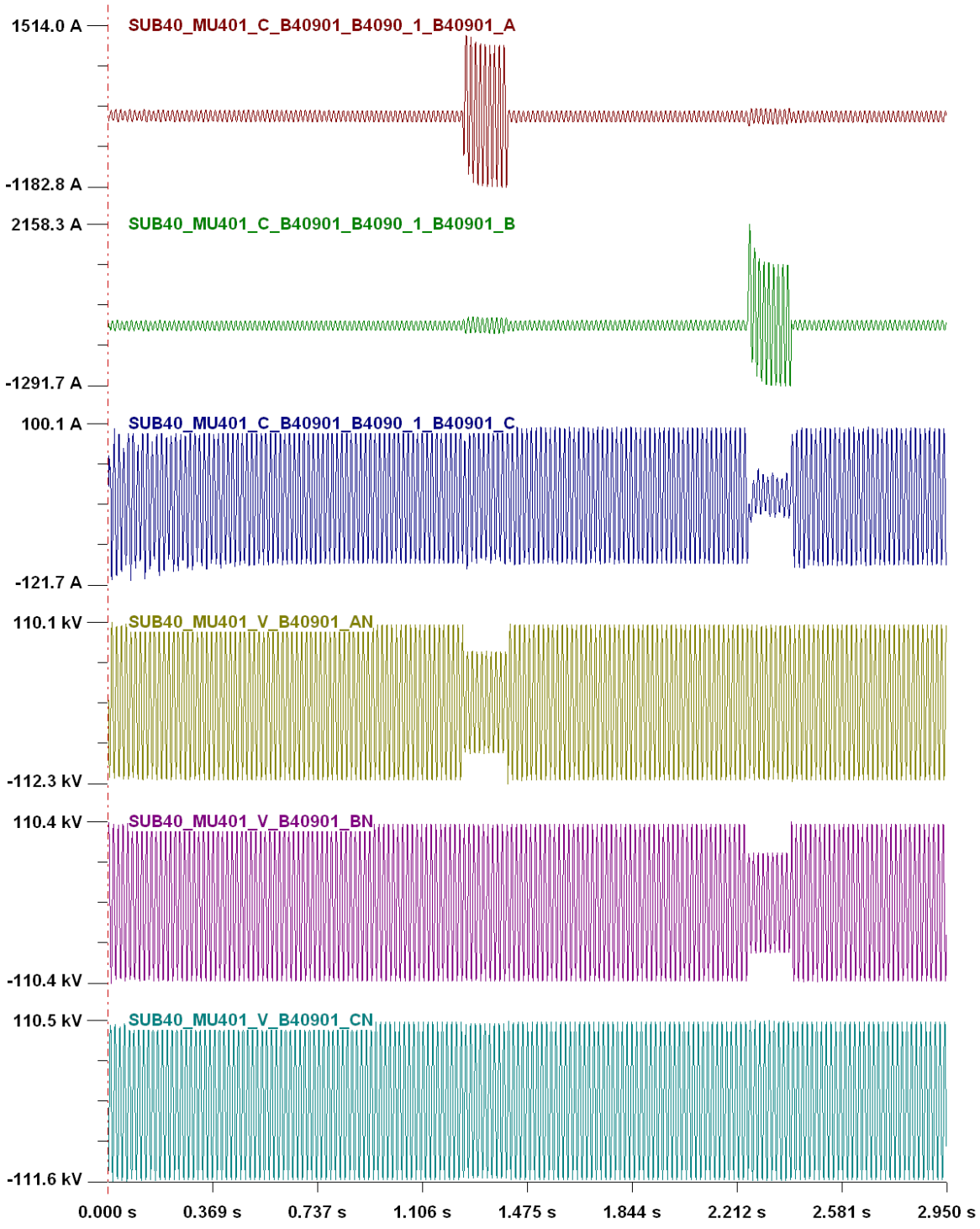


Figure B-1.4E2 COMTRADE data for Event-4 (40PZ1). Merging Units 401.

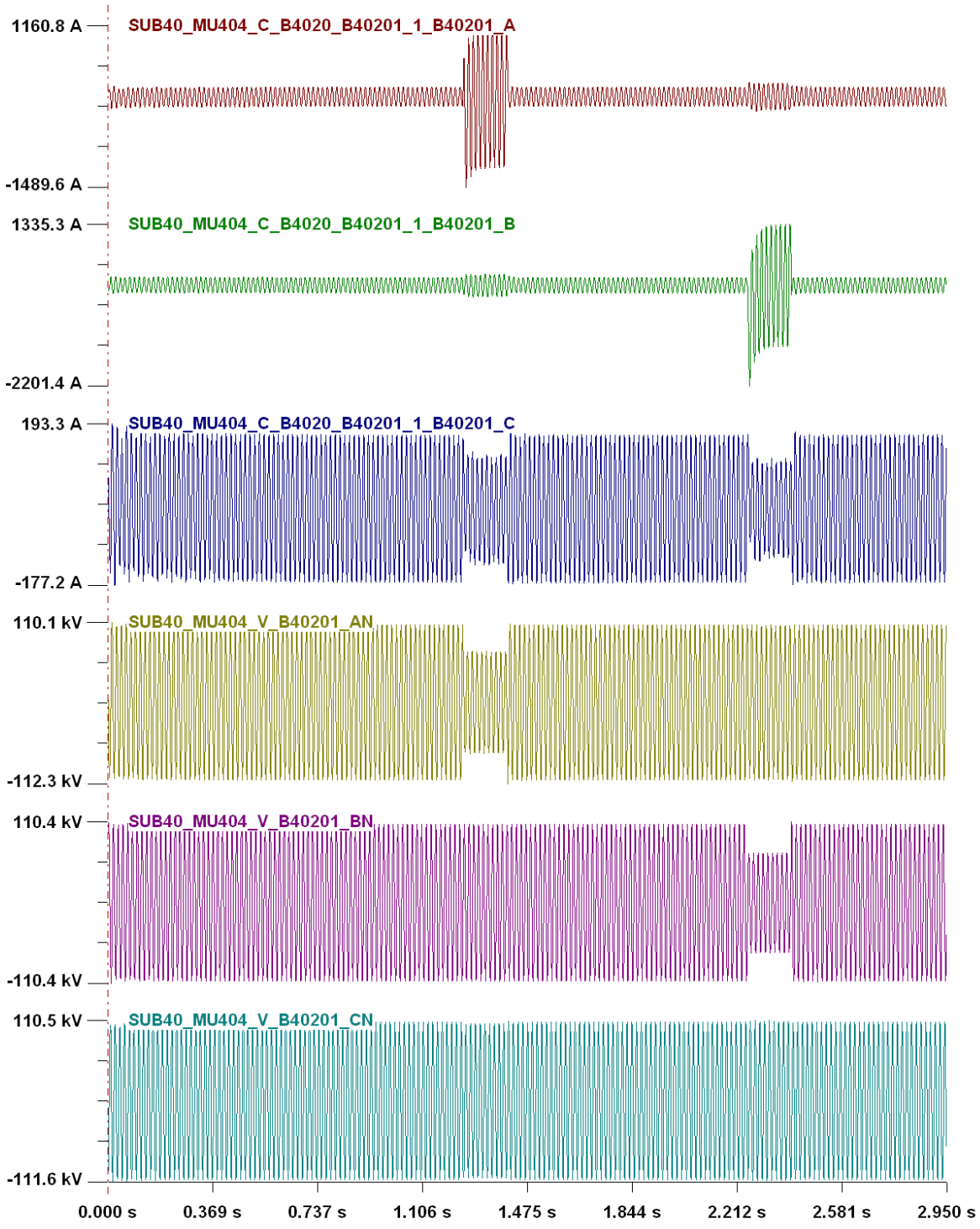


Figure B-1.4E3 COMTRADE data for Event-4 (40PZ2). Merging Unit 404.

B-1.5. Event-5 (Substation-70):

This section describes Event-5 of Substation 70. The event duration is 3 seconds. It includes several disturbances during the simulation period. Data is stored in COMTRADE format.

The timeline of Event-5 is shown in Figure B-1.5E1, where the negative events such as electric faults are labeled in red and blue, and the positive events including recovery of electric faults are labeled in green. An A-G fault occurs at 75% of the line length of the transmission line B7080 to B8070. Another B-G fault occurs on the high side of the transformer XFMR70ZL to XFMR70ZH. The A-G electric fault starts at 1.3s and clears at 1.45s. The B-G electric fault starts at 2.3s from the start of the simulation and clears at 2.45s.

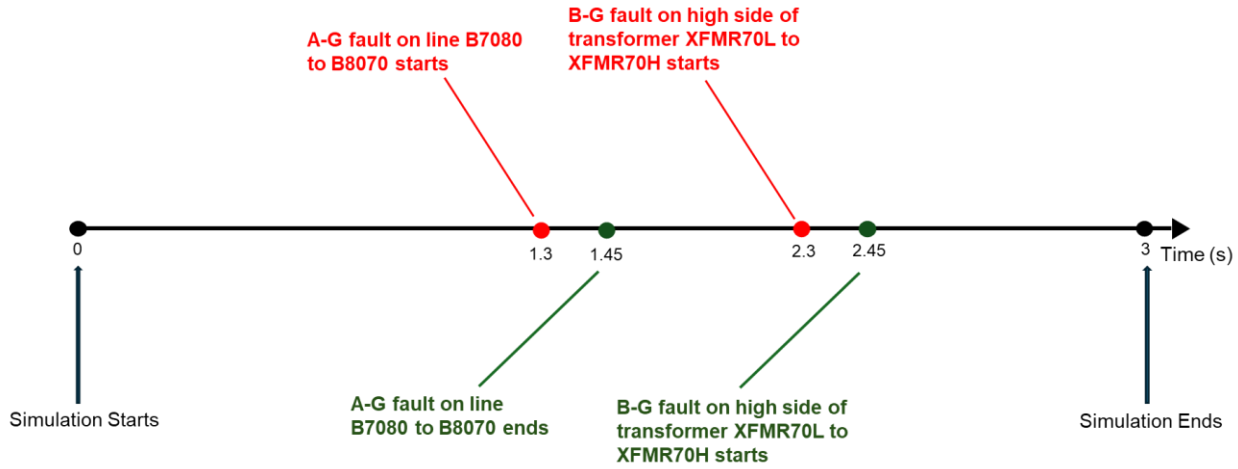


Figure B-1.5E1 Timeline of Event-5.

Figures B-1.5E2 and B-1.5E3 show the COMTRADE data for Event-5 for protection zones 70PZ1, 70PZ2. As indicated, there are 2 subevents occurring in the system during the event. We can observe the electric faults occurring in the system in the COMTRADE file at around 1.3s and 2.3s respectively.

There are two subevents in Event-5. The subevents are listed below:

Table B-1.5: List of subevents for Event-5.

Subevent No	Subevent Name	Subevent Duration
1.	A-G Fault on line B7080 to B8070 at 12 miles from Substation-70 (75% of the line length).	1.3s to 1.45s
2.	B-G Fault on high side of transformer XFMR70ZL to XFMR70ZH	2.3s to 2.45s

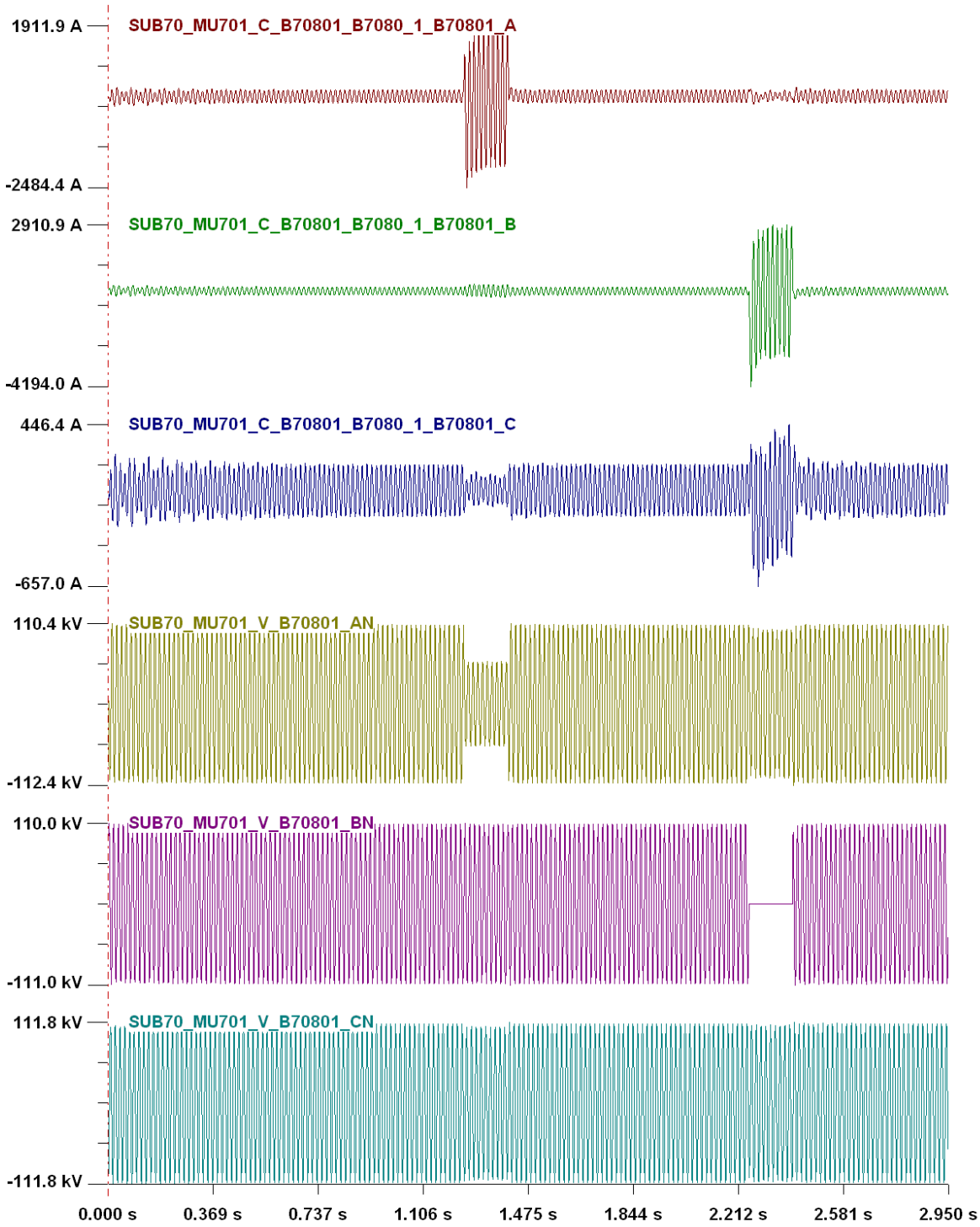


Figure B-1.5E2 COMTRADE data for Event-5 (70PZ1). Merging Units 701.

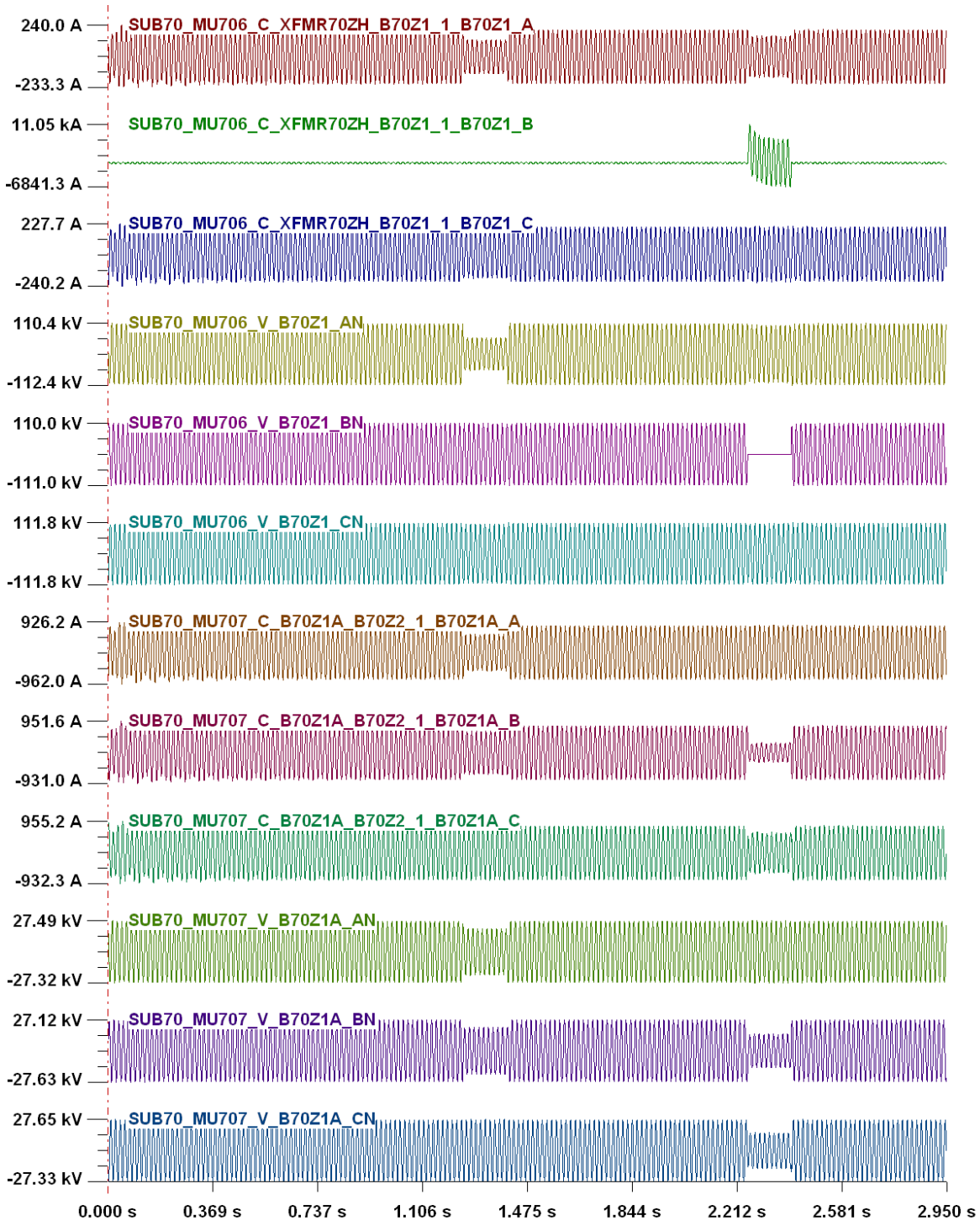


Figure B-1.5E3 COMTRADE data for Event-5 (70PZ2). Merging Units 706 and 707.

B-2. Response of Protection and Control to the Events:

The response of the protection and control system in each substation of the IEEE 24 Substation RTS was recorded for several events designed to test the performance of the protection and control systems. In this section, we present the responses of the protection systems (legacy and estimation-based protection) to the events described in Section B-1. The motivation for this analysis arises from the challenges that high penetrations of inverter-based resources (IBRs) pose to protection and control systems. Specifically, we aim to determine whether increasing IBR penetration leads to significant issues and, if so, which protection functions are most affected. Ultimately, the objective is to assess whether protective relays continue to operate correctly under high IBR conditions or if they are prone to mis-operation.

We specifically chose to study Estimation-Based Protection alongside legacy protection to provide a direct comparison between traditional relays and modern approaches. As discussed in Section 3.4, inverter-based resources (IBRs) suppress the negative- and zero-sequence components of fault currents, which can prevent traditional setting-based relays from reliably detecting faults when IBRs are present in large numbers. This limitation highlights the need for alternative methods, and Estimation-Based Protection offers a promising solution since it is inherently "setting-less."

B-2.1. Response of Legacy Protection and Control Systems

We analyze the response of the legacy protection system within selected protection zones, focusing on the protective relays installed at the substations. Each protection zone is equipped with a corresponding relay, and the performance of selected relays is documented to assess whether they operate as expected or result in a mis-operation. In cases of mis-operation, the root cause is identified and examined.

Event-1:

As described in section B-1.1 Event-1 is an event performed on Substation-170. The performance of the legacy protection and control of some of the protection zones is given below:

Performance of 170PZ1 Protection and Control

For Event 1, there are multiple subevents as listed in Table B-1.1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180

to B180170. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line for subevents 4 and 5**.

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-1 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

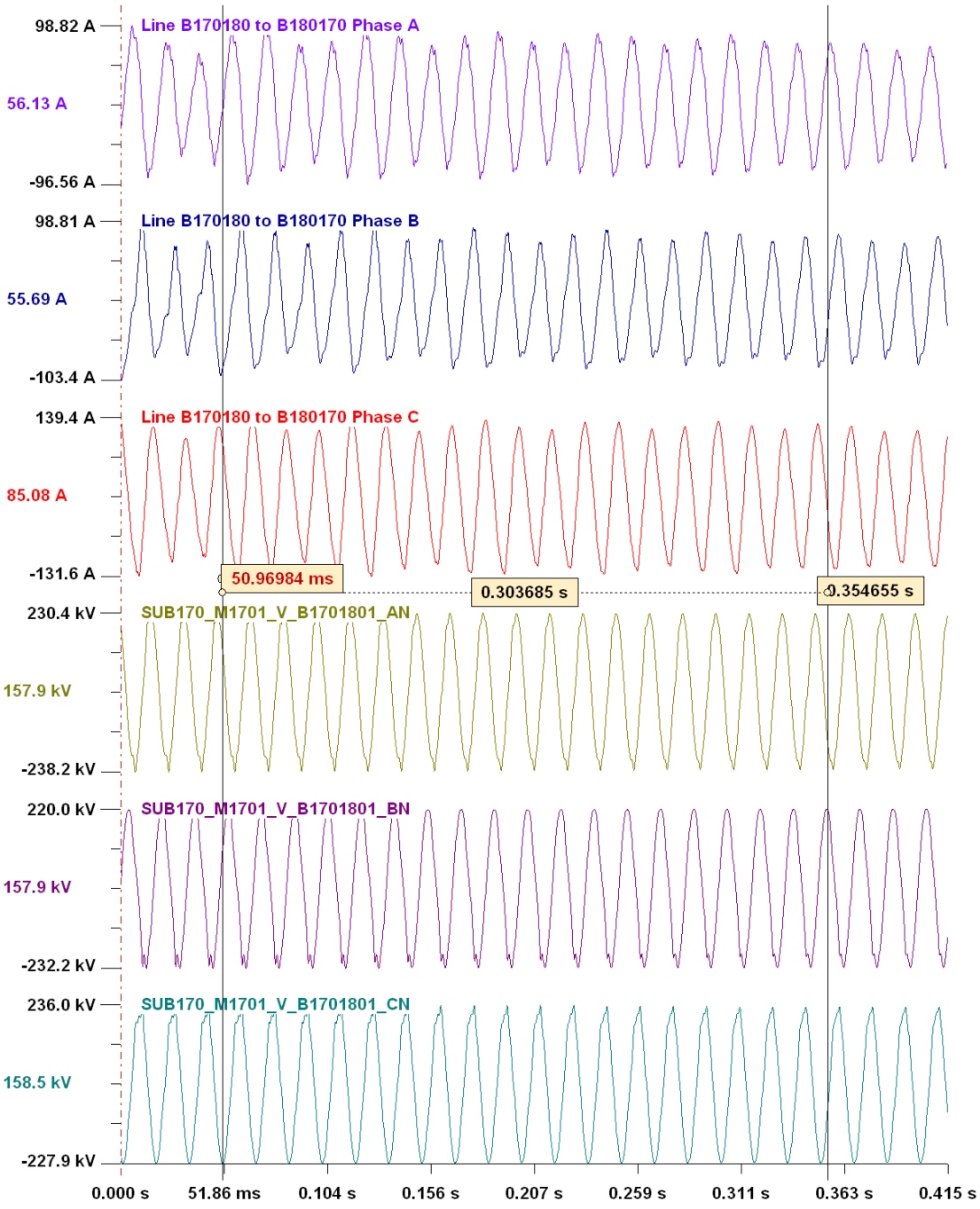


Figure B-2.1E1.1 Currents and Voltage observed in 170PZ1 for subevent 1. Merging Unit 1701.

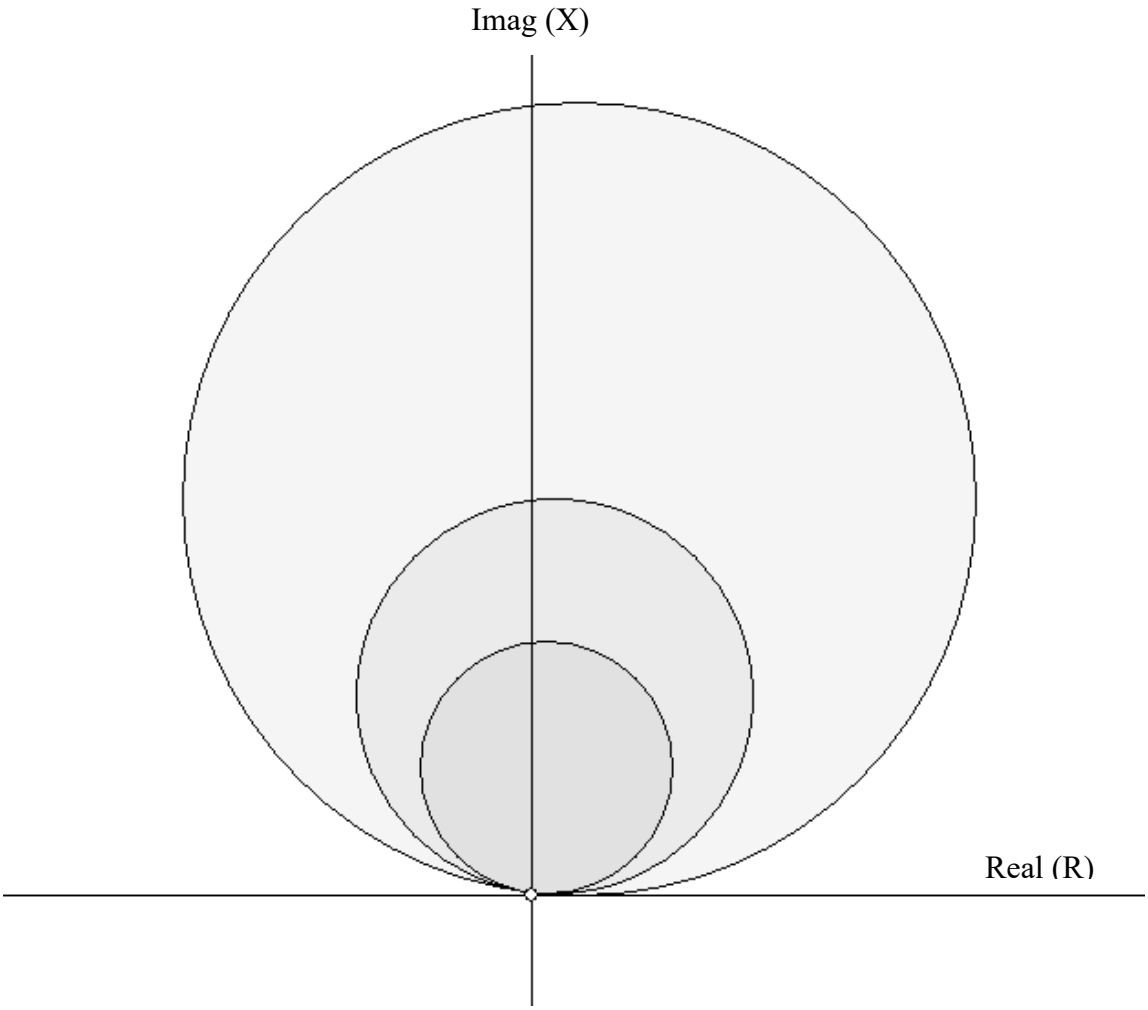


Figure B-2.1E1.2 Distance relay response of 170PZ1 for subevent 1.

Figure B-2.1E1.1 shows the currents and voltages of 170PZ1 for subevent 1, and Figure B-2.1E1.2 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

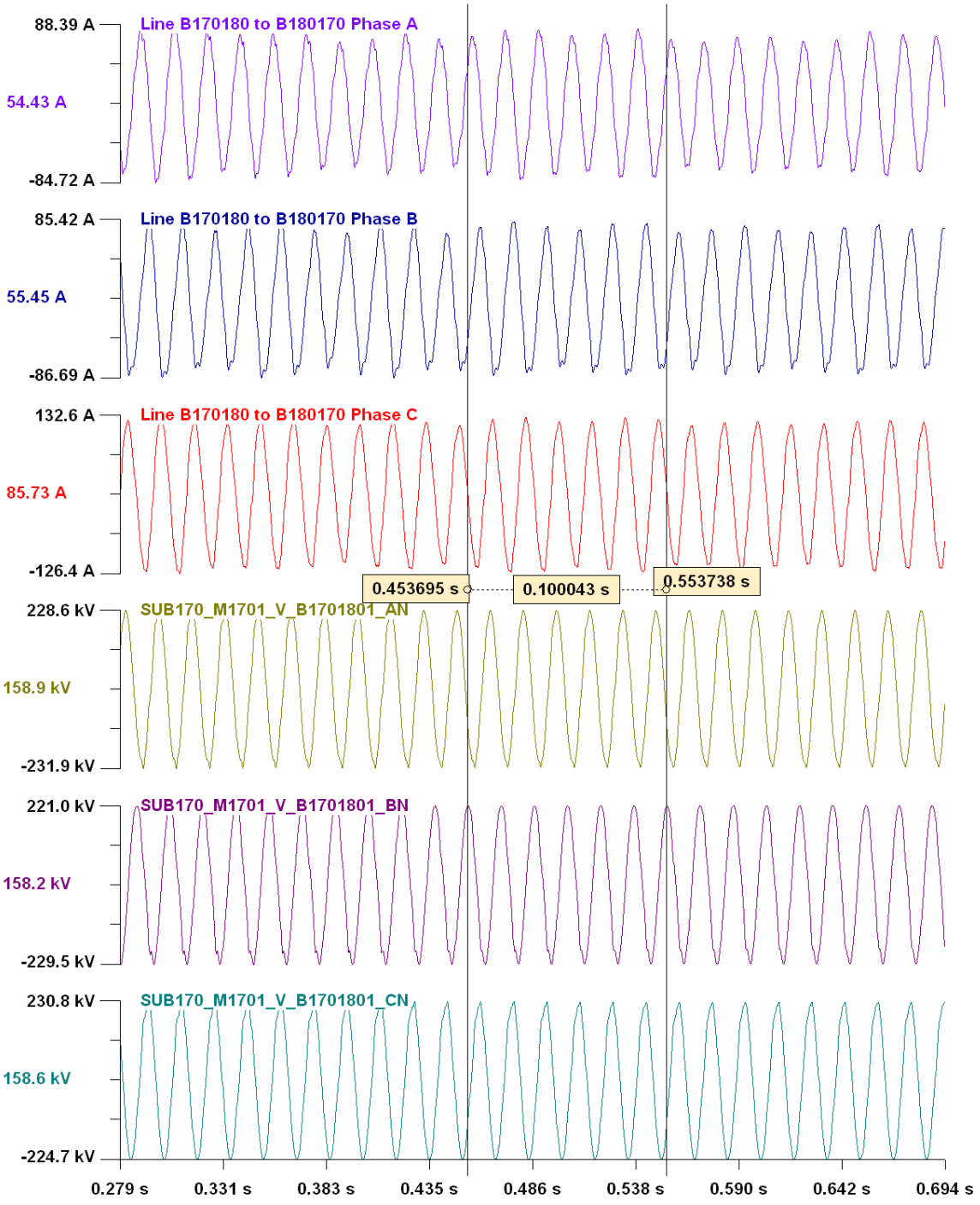


Figure B-2.1E1.3Currents and Voltage observed in 170PZ1 for subevent 2. Merging Unit 1701.

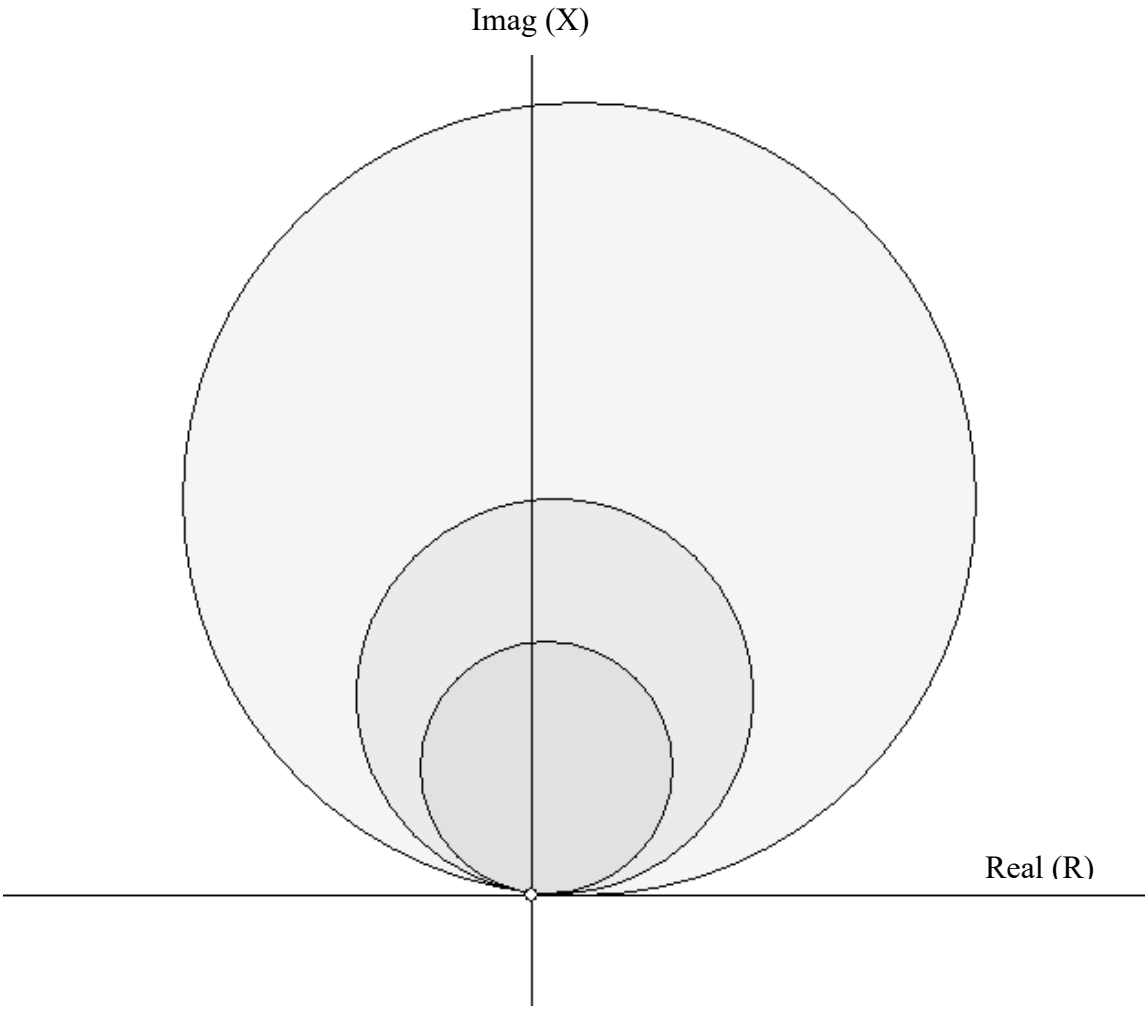


Figure B-2.1E1.4 Distance relay response of 170PZ1 for subevent 2.

Figure B-2.1E1.3 shows the currents and voltages of 170PZ1 for subevent 2, and Figure B-2.1E1.4 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-3:

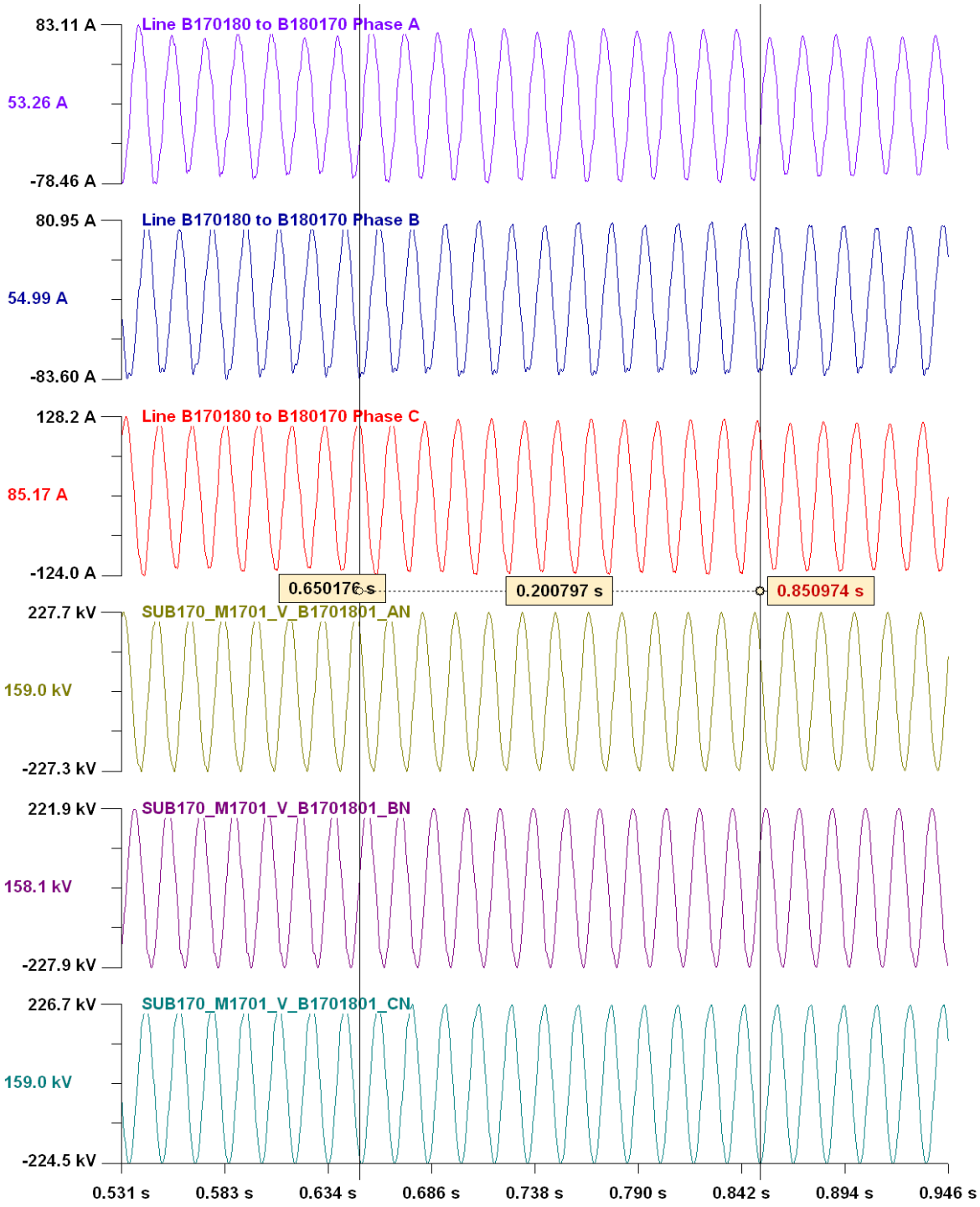


Figure B-2.1E1.5 Currents and Voltage observed in 170PZ1 for subevent 3. Merging Unit 1701.

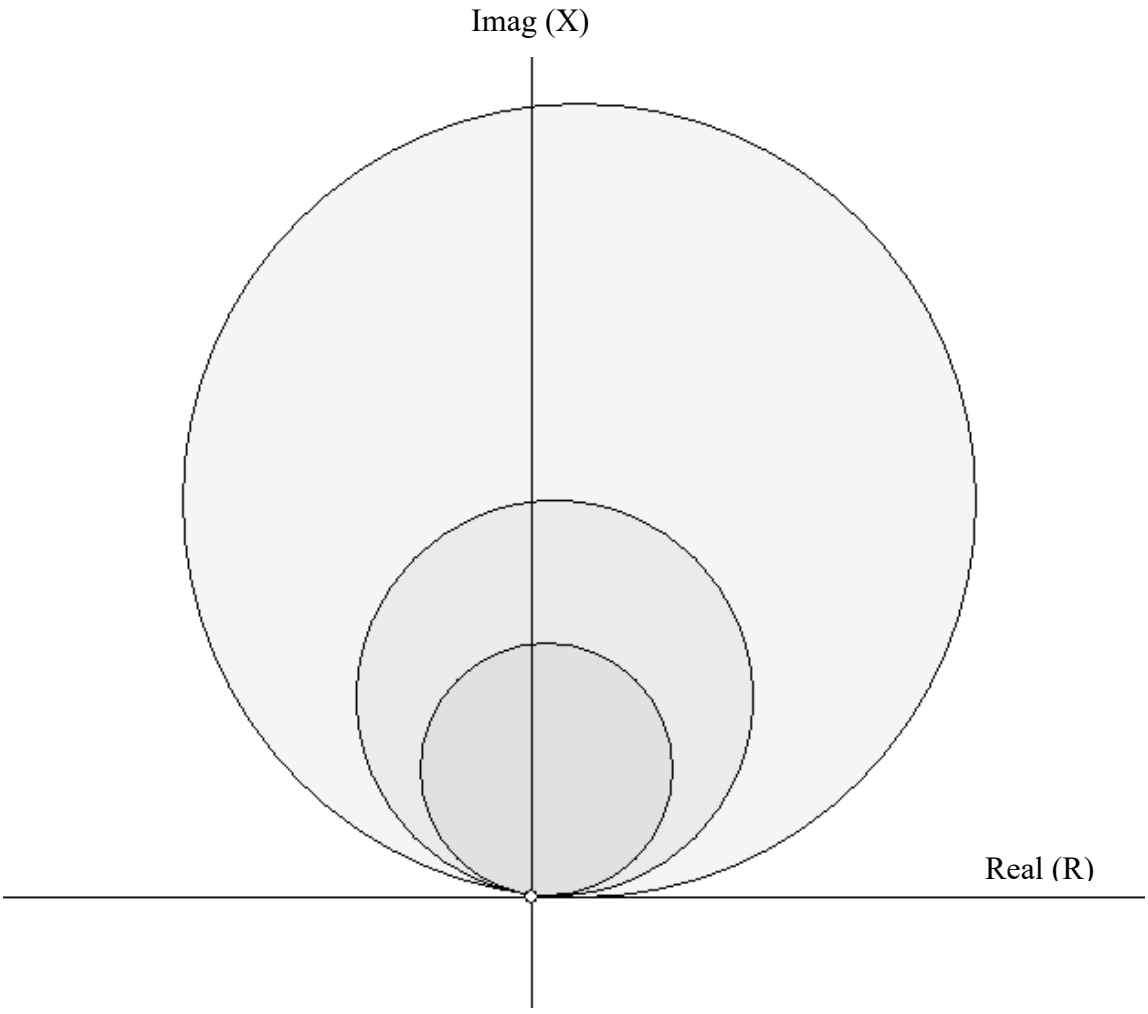


Figure B-2.1E1.6 Distance relay response of 170PZ1 for subevent 3.

Figure B-2.1E1.5 shows the currents and voltages of 170PZ1 for subevent 3, and Figure B-2.1E1.6 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-4:

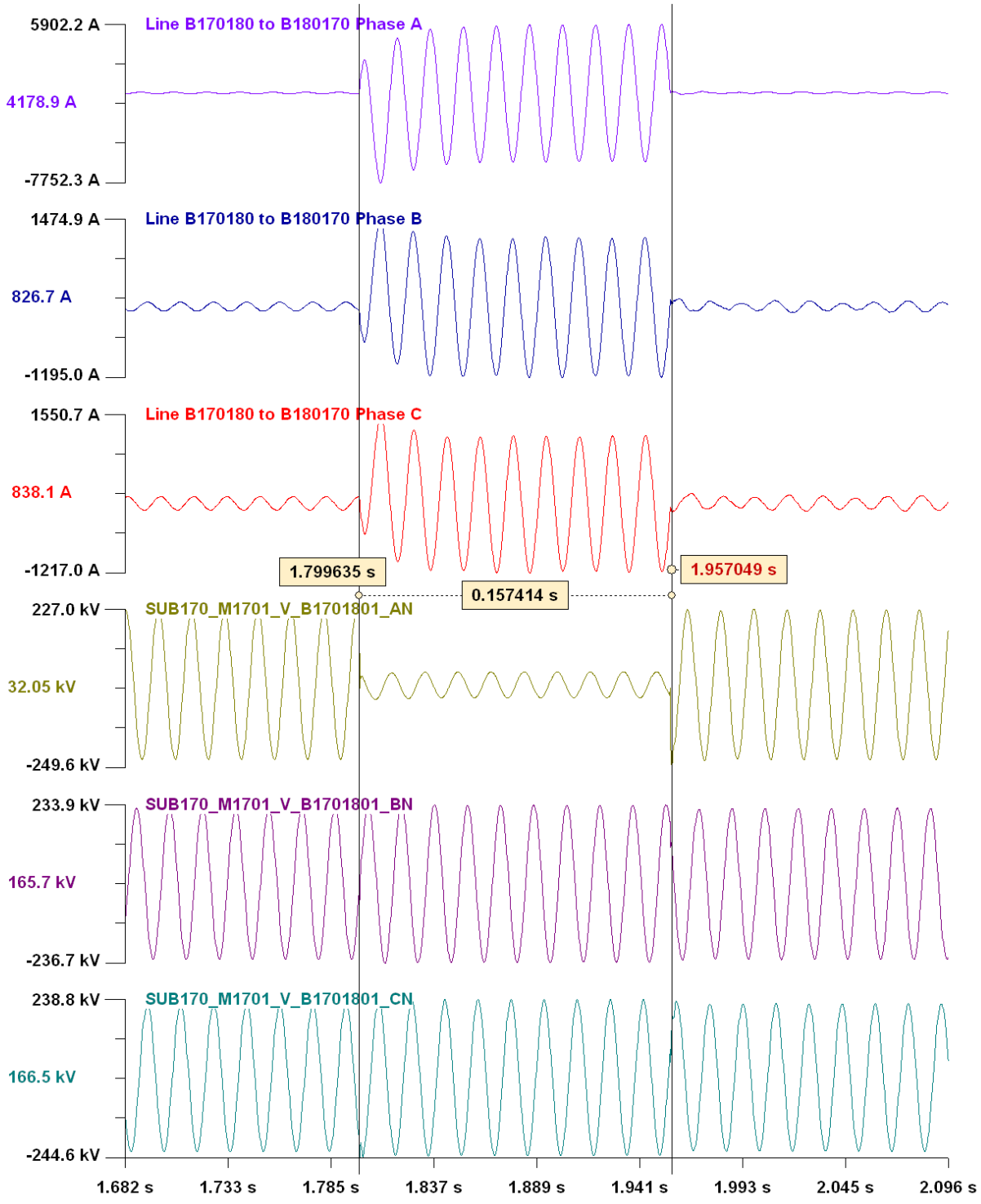


Figure B-2.1E1.7 Currents and Voltage observed in 170PZ1 for subevent 4. Merging Unit 1701.

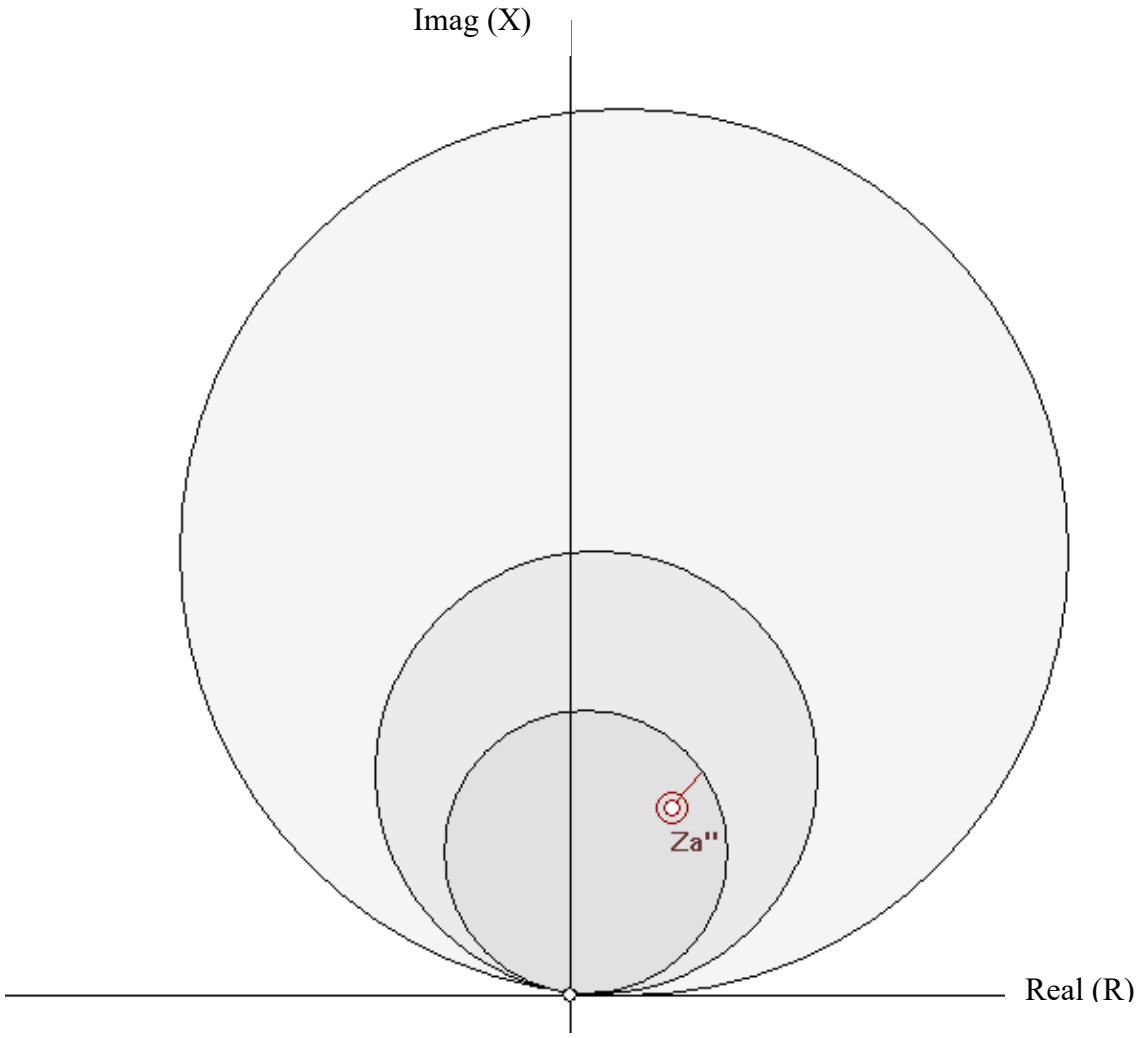


Figure B-2.1E1.8 Distance relay response of 170PZ1 for subevent 4.

Figure B-2.1E1.7 shows the currents and voltages of 170PZ1 for subevent 4, and Figure B-2.1E1.8 shows the performance of this relay in WinXFM. Note that this relay will respond instantaneously to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

It can also be noted that while the distance relay responded instantaneously to disconnect the line the impedance measured by the distance relay is not accurate and is close to 75% of the line length

as seen in Fig B-2.1E1.7, this will result in the misoperation of the distance relay if the fault distance is more than 80% of the line length.

Subevent-5:

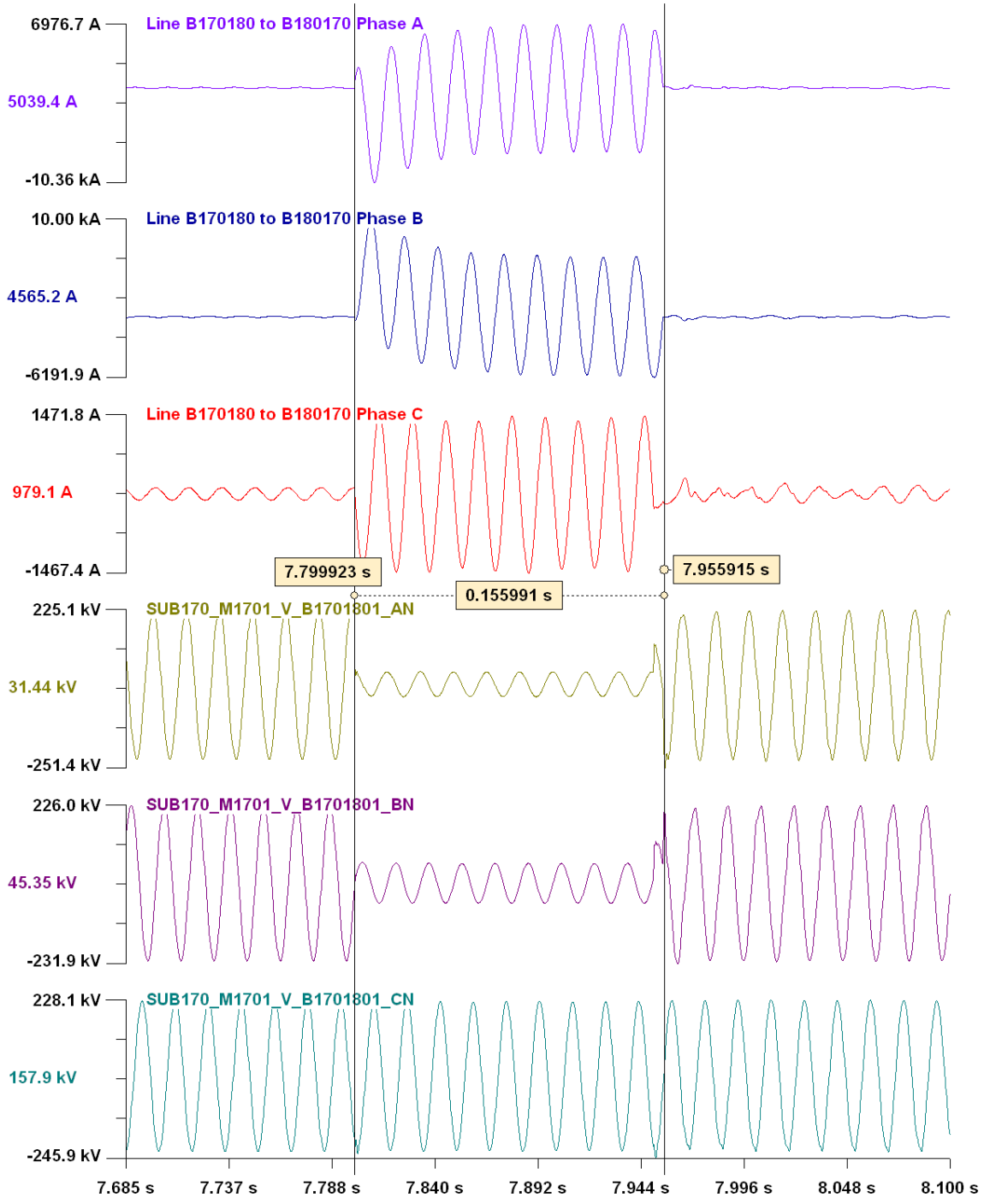


Figure B-2.1E1.9 Currents and Voltage observed in 170PZ1 for subevent 5. Merging Unit 1701.

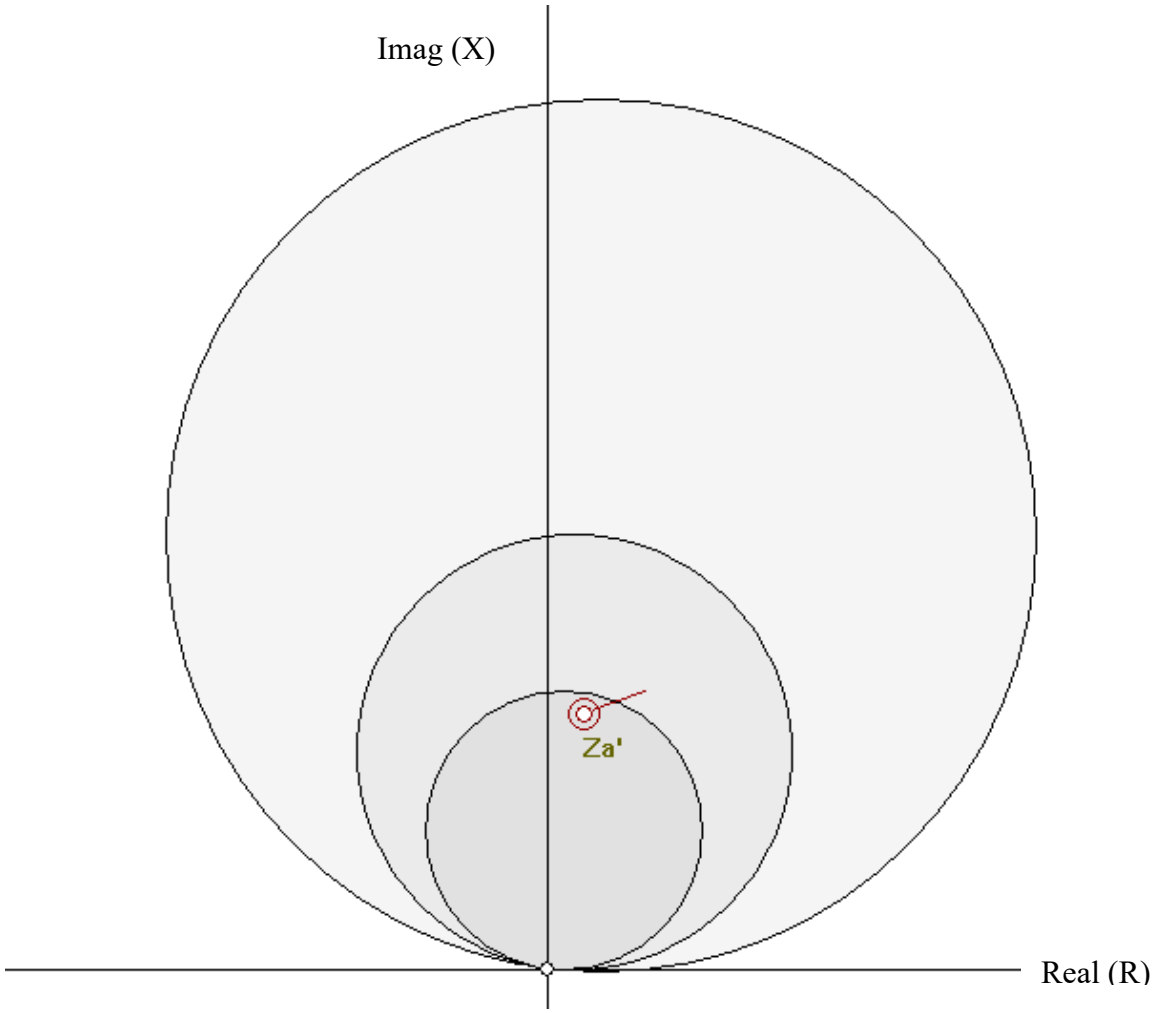


Figure B-2.1E1.10 Distance relay response of 170PZ1 for subevent 5.

Figure B-2.1E1.9 shows the currents and voltages of 170PZ1 for subevent 5, and Figure B-2.1E1.10 shows the performance of this relay in WinXFM (Note: We have shown only the minimum value for the line-to-line equation and not the line to ground equation). Note that this relay will respond instantaneously to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

It can also be noted that while the distance relay responded instantaneously to disconnect the line the impedance measured by the distance relay is not accurate and is close to 80% of the line length as seen in Fig B-2.1E1.9, this will result in the misoperation of the distance relay if the fault distance is more than 80% of the line length.

Performance of 170PZ2 Protection and Control

For Event 1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180 to B180170. In this case the correct action of the protection and control system is that **the protective relay for Sub-170 PZ2 (distance relay monitoring the line B170160 to B160170) should not operate to isolate the line B170160 to B160170 for any of the events.**

The voltages and currents measured by the MUs in protection zone-2 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

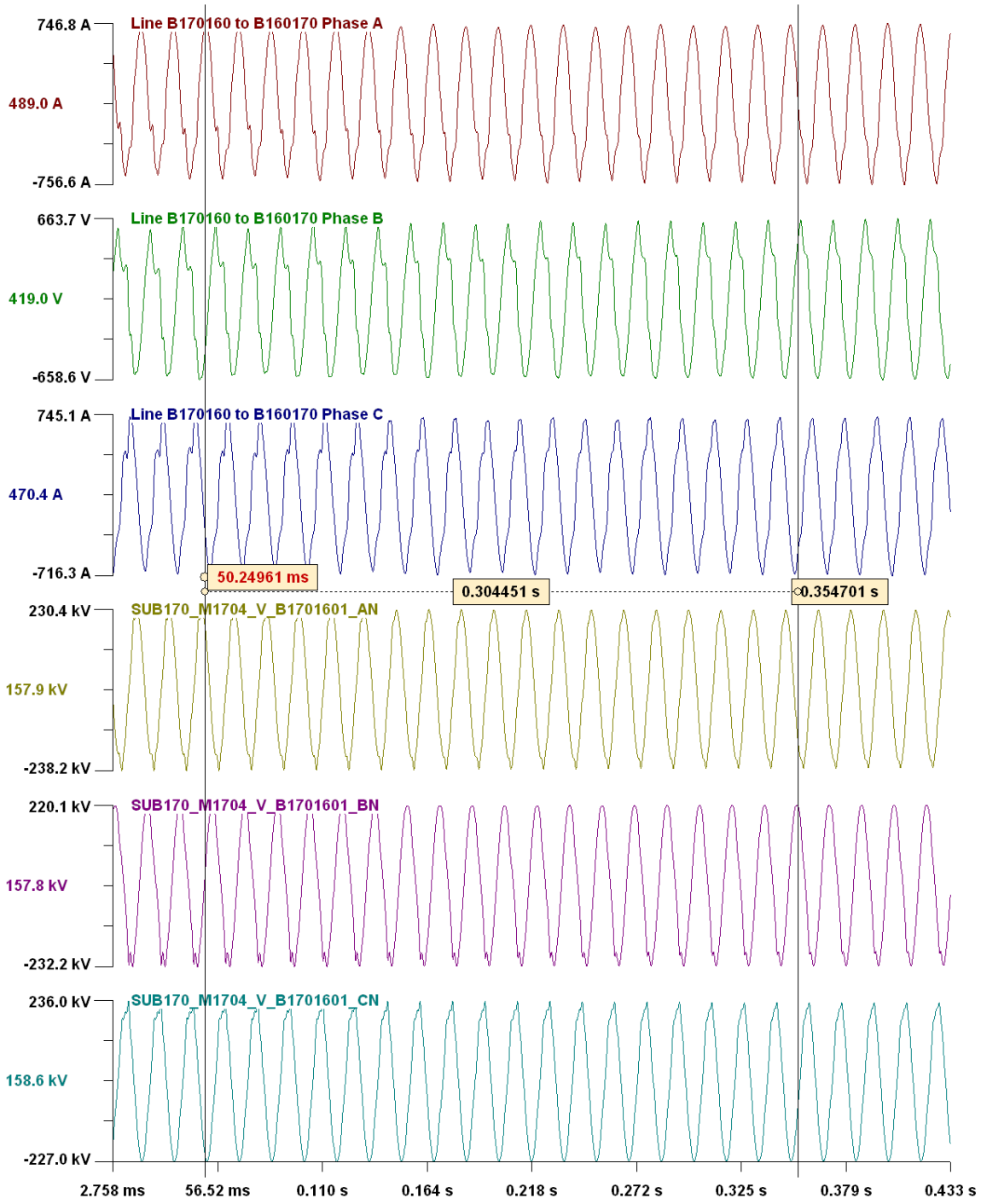


Figure B-2.1E1.11 Currents and Voltage observed in 170PZ2 for subevent 1. Merging Unit 1704.

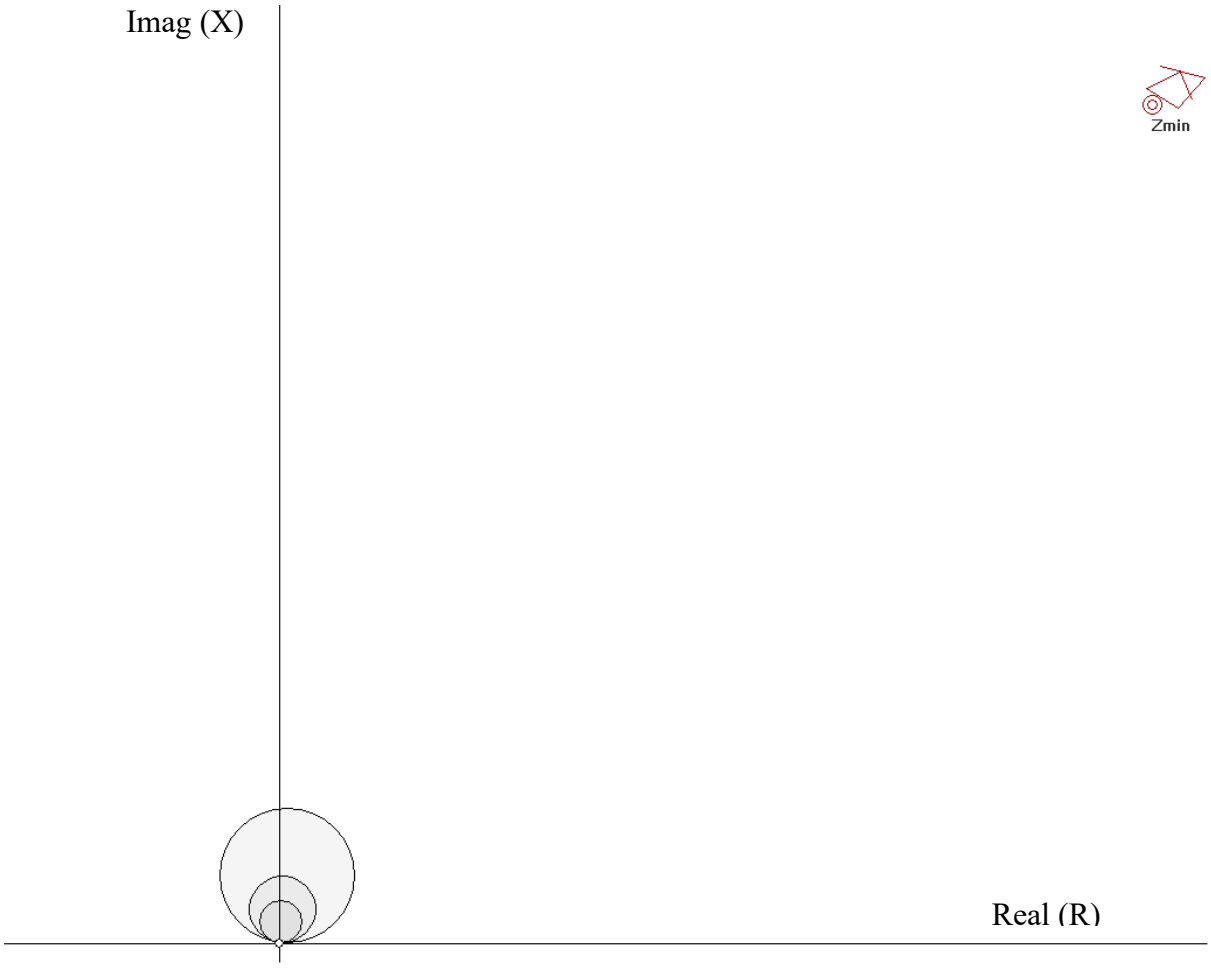


Figure B-2.1E1.12 Distance relay response of 170PZ2 for subevent 1.

Figure B-2.1E1.11 shows the currents and voltages of 170PZ2 for subevent 1, and Figure B-2.1E1.12 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

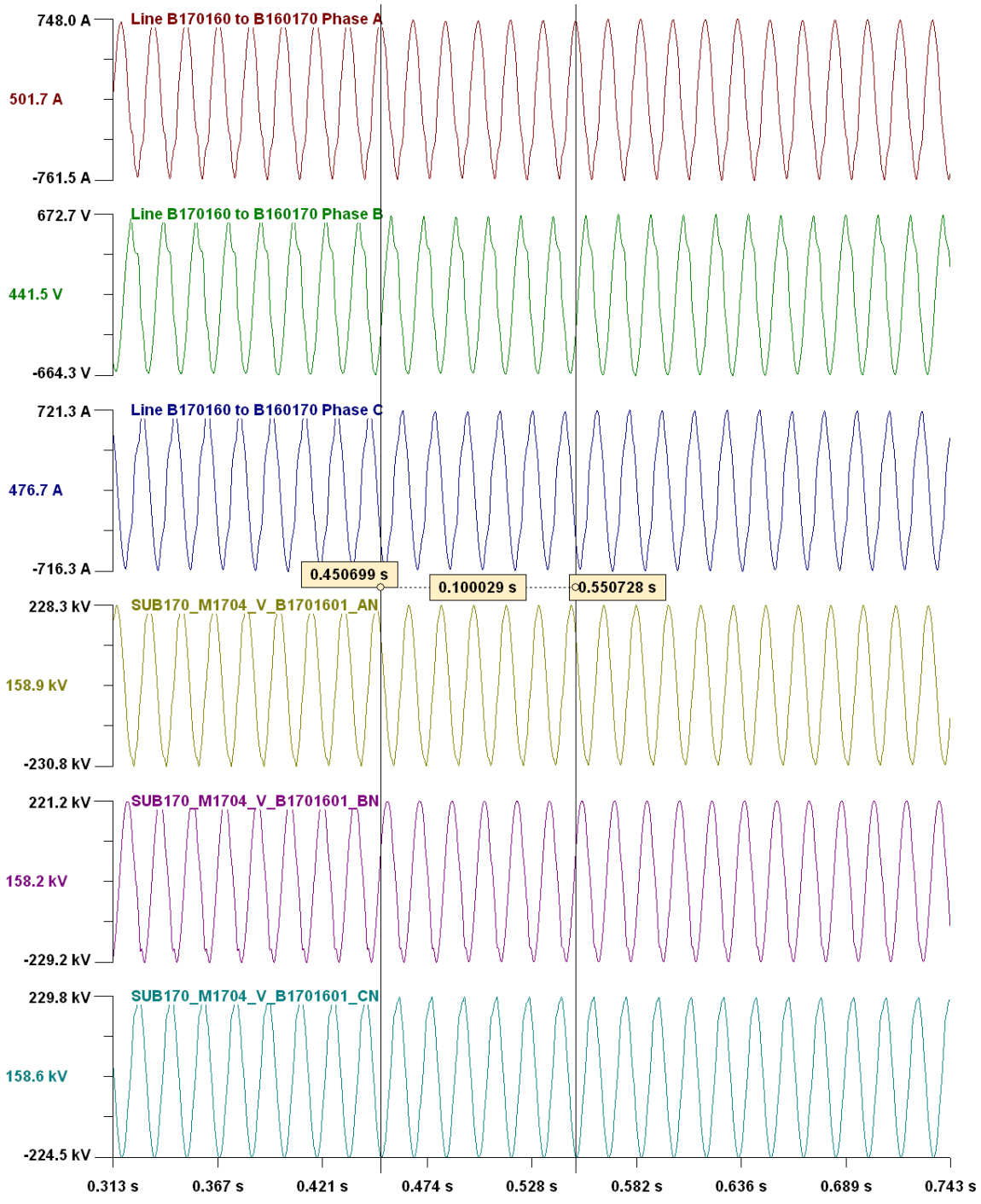


Figure B-2.1E1.13 Currents and Voltage observed in 170PZ2 for subevent 2. Merging Unit 1704.

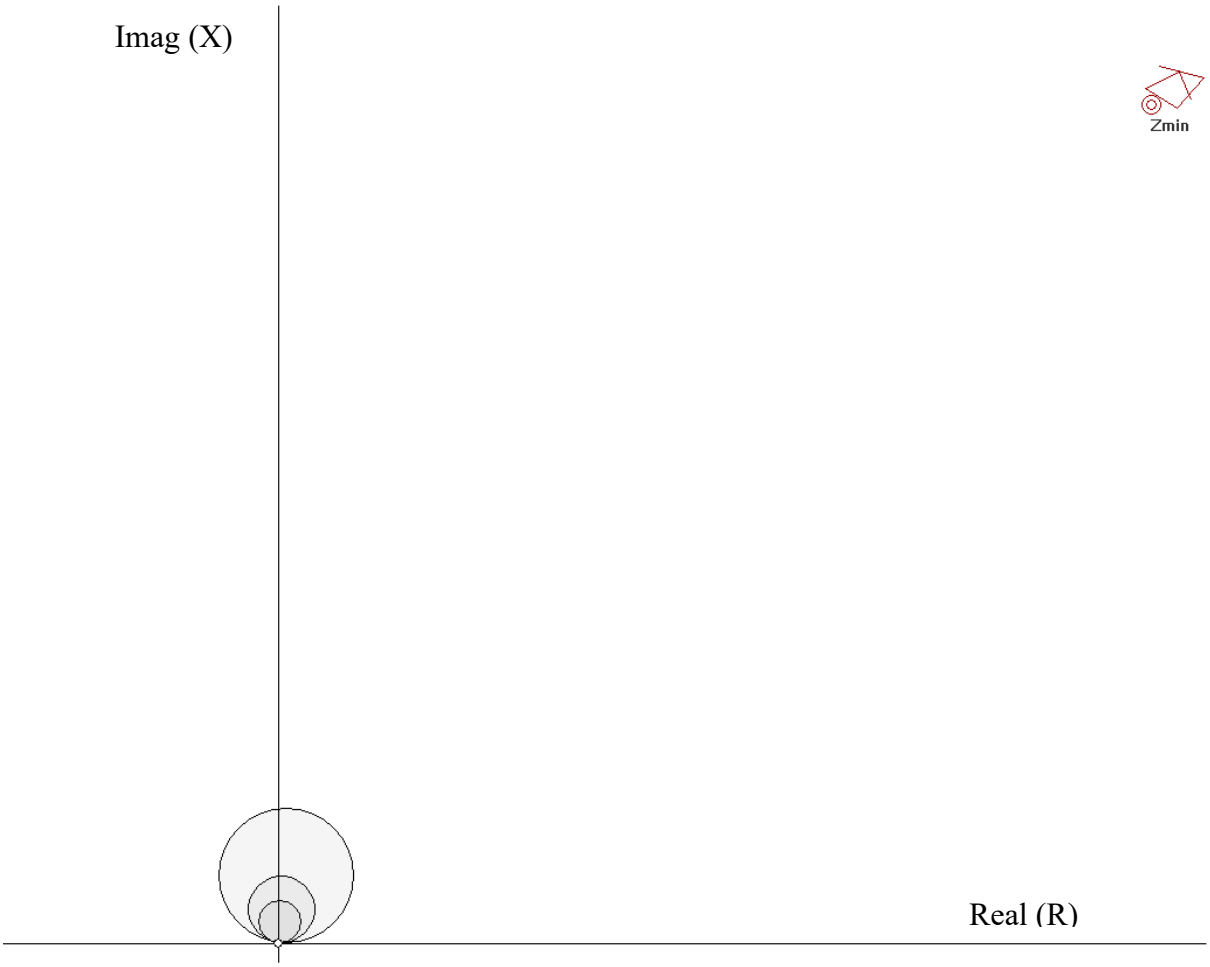


Figure B-2.1E1.14 Distance relay response of 170PZ2 for subevent 2.

Figure B-2.1E1.13 shows the currents and voltages of 170PZ2 for subevent 2, and Figure B-2.1E1.14 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-3:

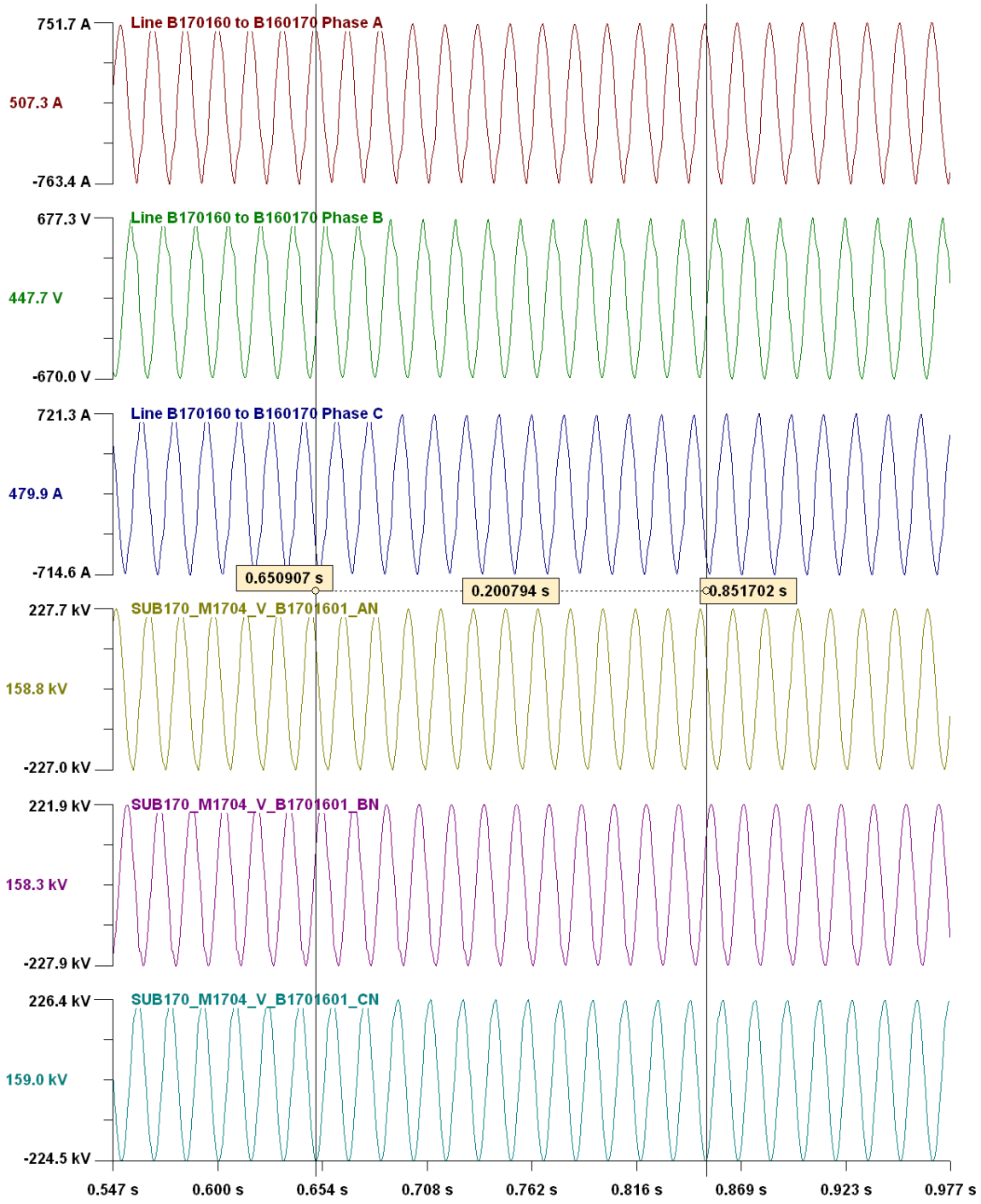


Figure B-2.1E1.15 Currents and Voltage observed in 170PZ2 for subevent 3. Merging Unit 1704.

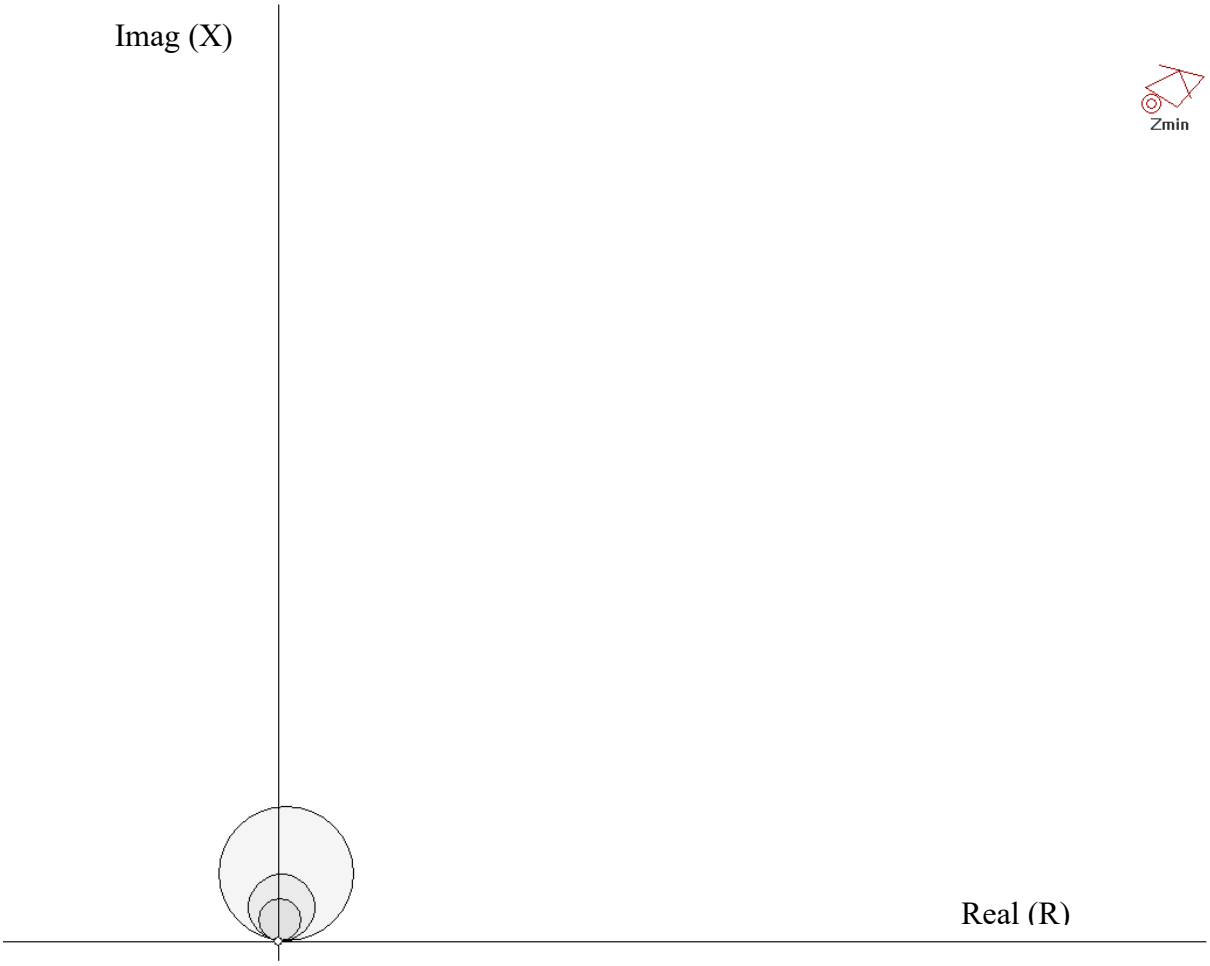


Figure B-2.1E1.16 Distance relay response of 170PZ2 for subevent 3.

Figure B-2.1E1.15 shows the currents and voltages of 170PZ2 for subevent 3, and Figure B-2.1E1.16 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-4:

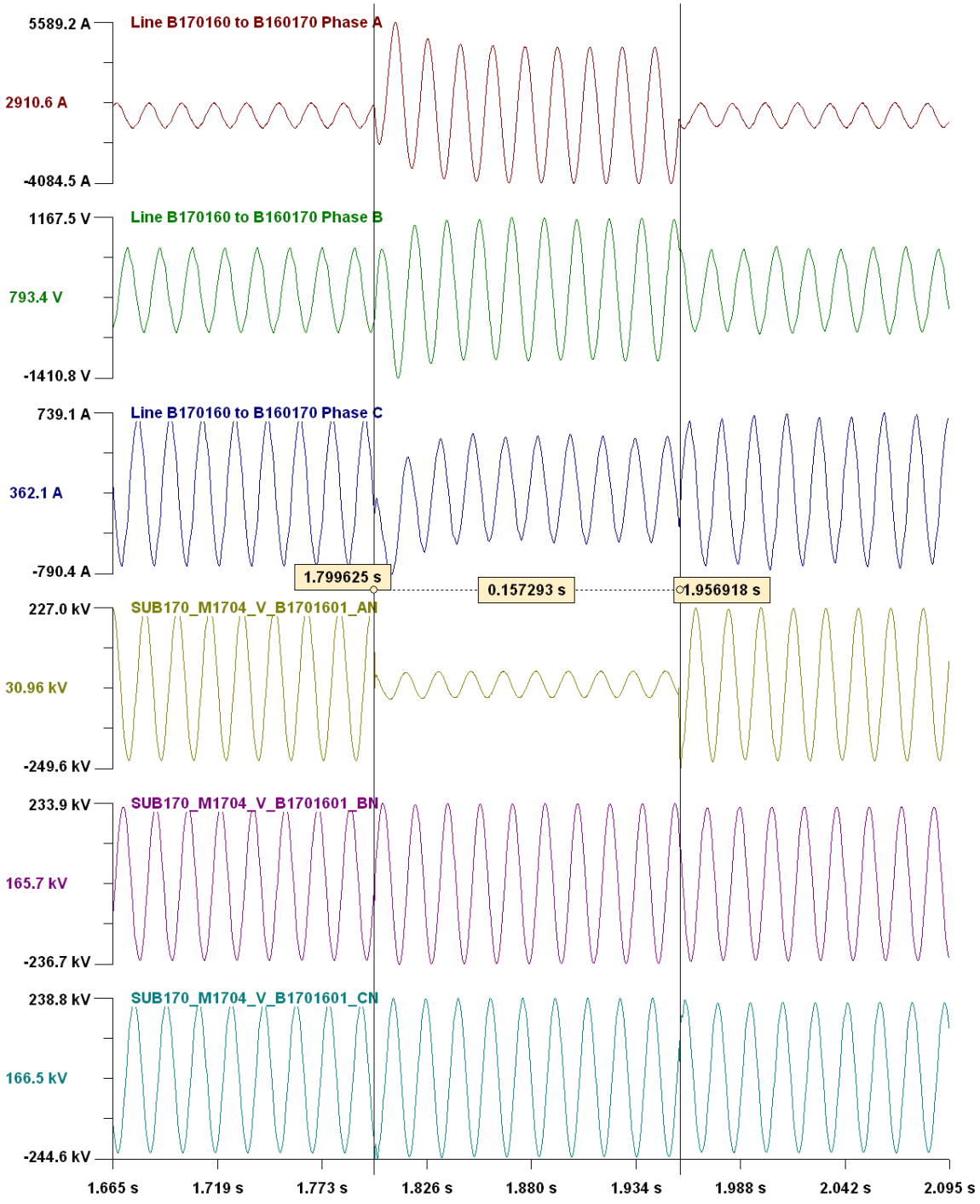


Figure B-2.1E1.17 Currents and Voltage observed in 170PZ2 for subevent 4. Merging Unit 1704.

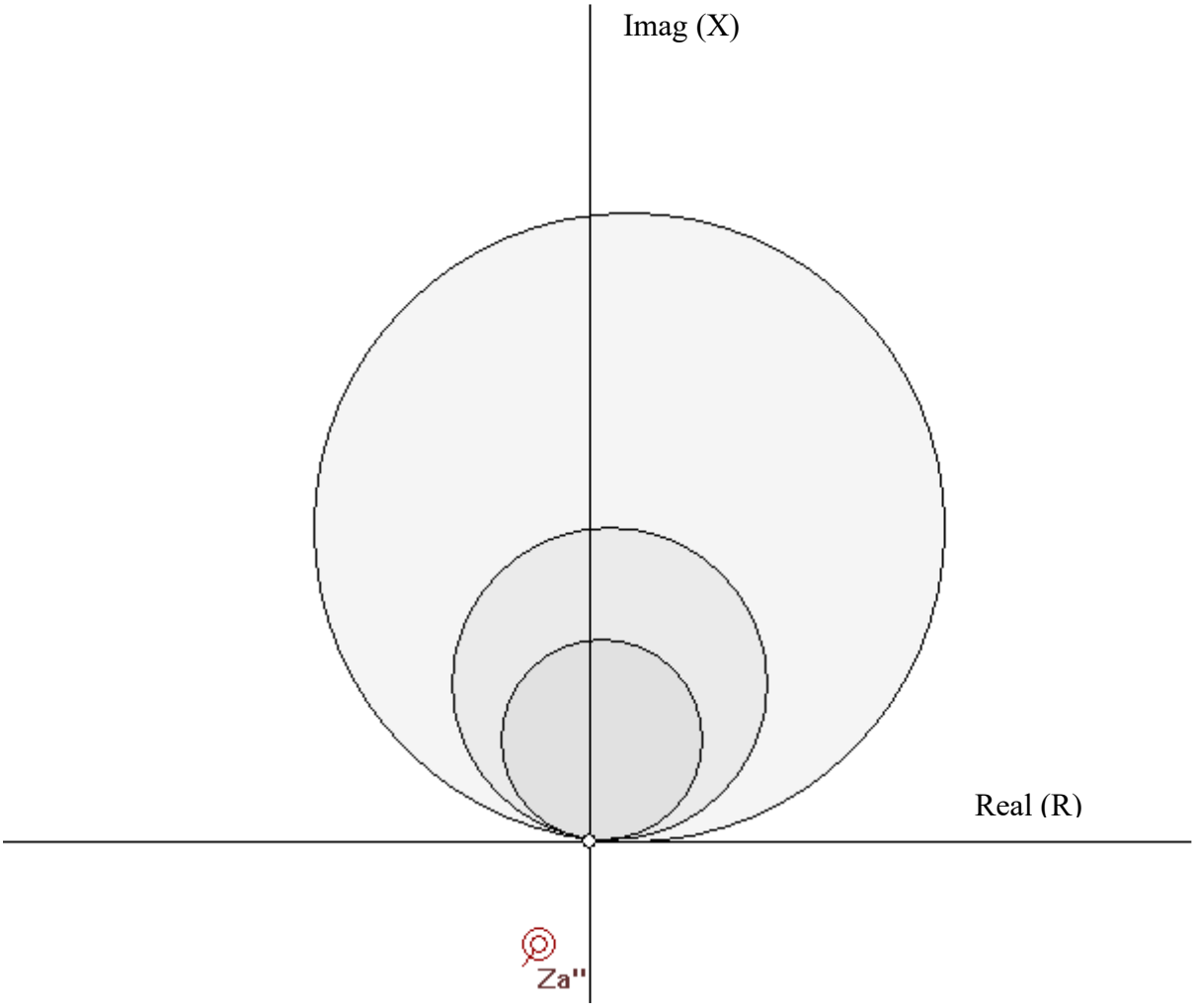


Figure B-2.1E1.18 Distance relay response of 170PZ2 for subevent 4.

Figure B-2.1E1.17 shows the currents and voltages of 170PZ2 for subevent 4, and Figure B-2.1E1.18 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-5:

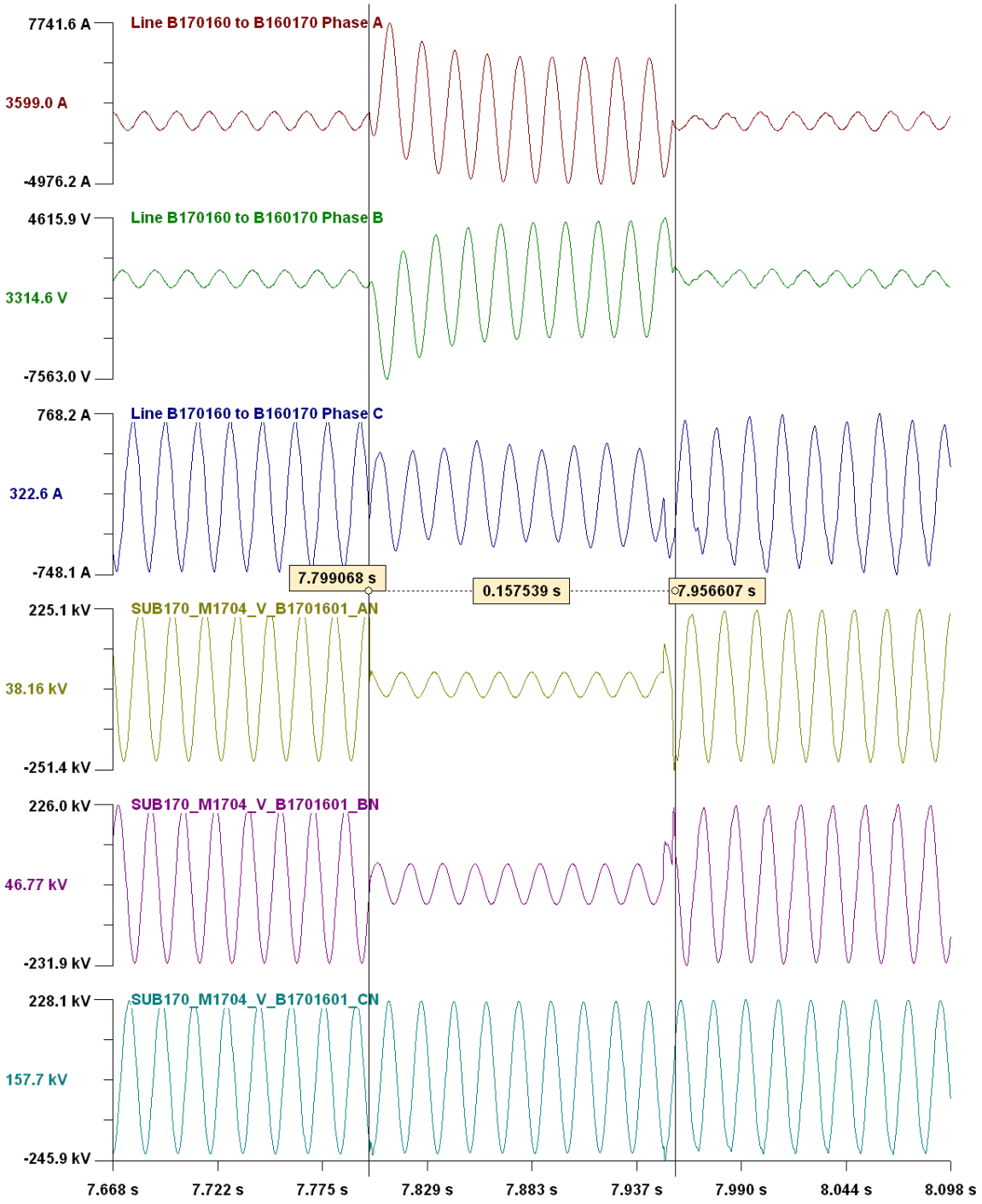


Figure B-2.1E1.19 Currents and Voltage observed in 170PZ2 for subevent 5. Merging Unit 1704.

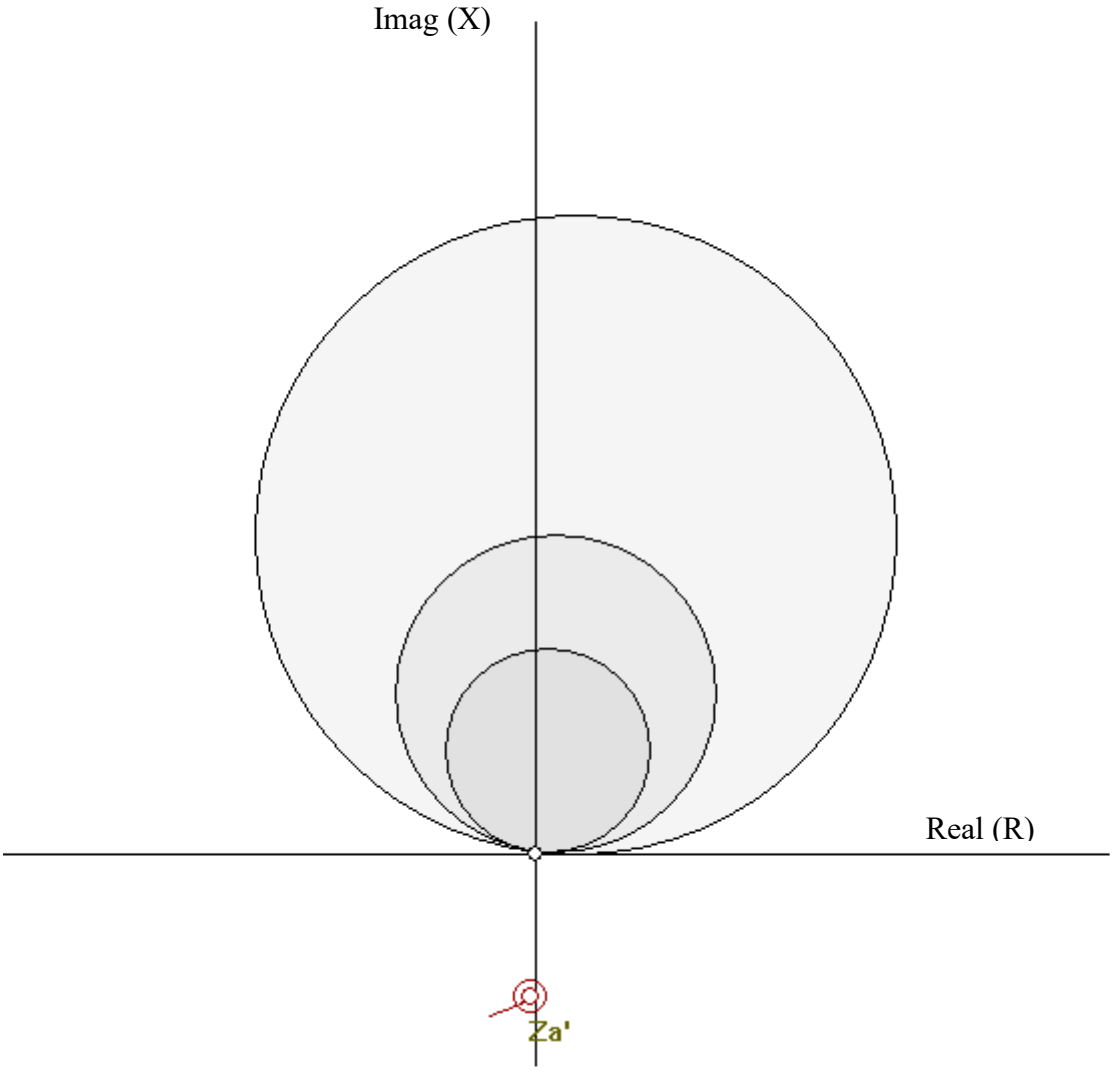


Figure B-2.1E1.20 Distance relay response of 170PZ2 for subevent 5.

Figure B-2.1E1.19 shows the currents and voltages of 170PZ2 for subevent 5, and Figure B-2.1E1.20 shows the performance of this relay in WinXFM (Note: We have shown only the minimum value for the line-to-line equation and not the line to ground equation). Note that this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Performance of 170PZ3 Protection and Control

For Event 1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180 to B180170. In this case the correct action of the protection and control system is that **the protective relay for Sub-170 PZ3 (distance relay monitoring the line B170220 to B220170) should not operate to isolate the line B170220 to B220170 for any of the events.**

The voltages and currents measured by the MUs in protection zone-3 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

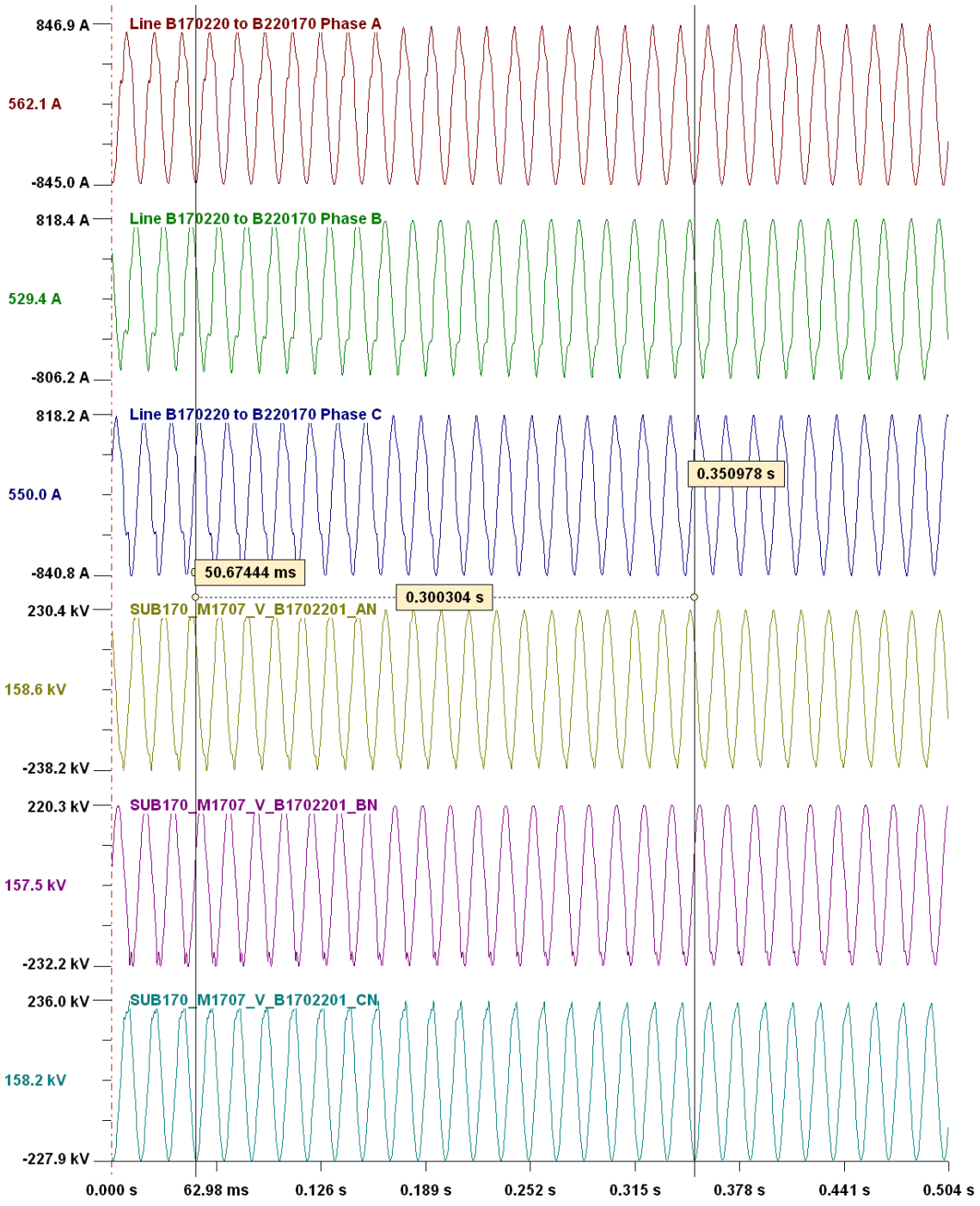


Figure B-2.1E1.21 Currents and Voltage observed in 170PZ3 for subevent 1. Merging Unit 1707.

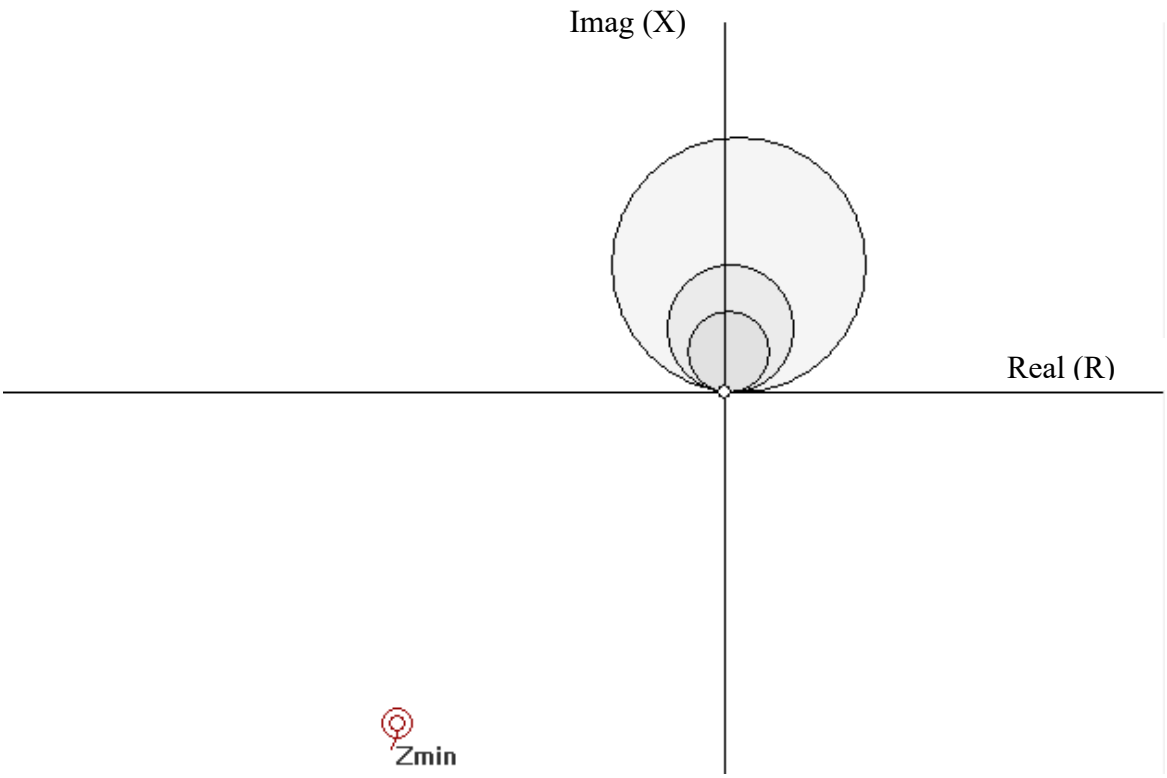


Figure B-2.1E1.22 Distance relay response of 170PZ3 for subevent 1.

Figure B-2.1E1.21 shows the currents and voltages of 170PZ3 for subevent 1, and Figure B-2.1E1.22 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

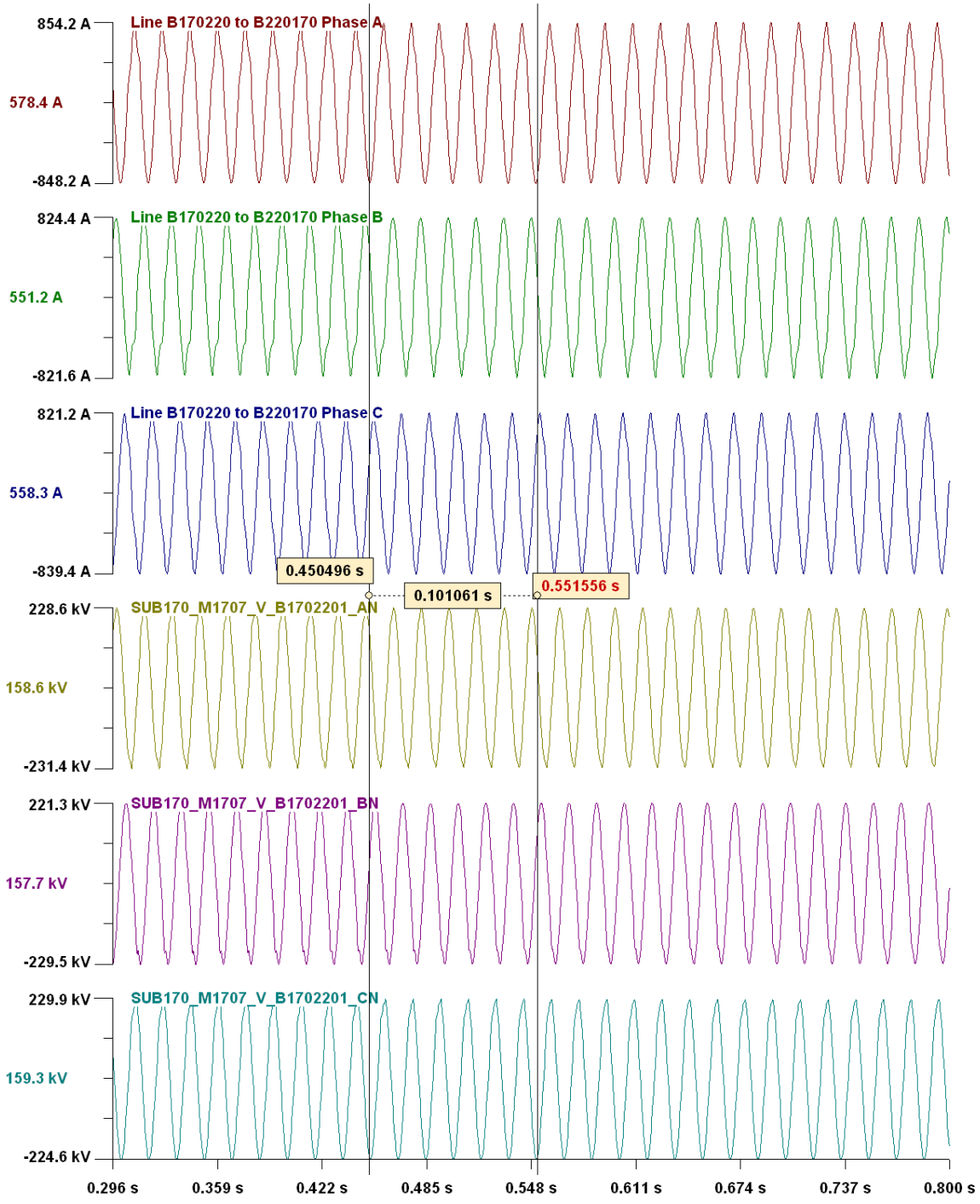


Figure B-2.1E1.23 Currents and Voltage observed in 170PZ3 for subevent 2. Merging Unit 1707.

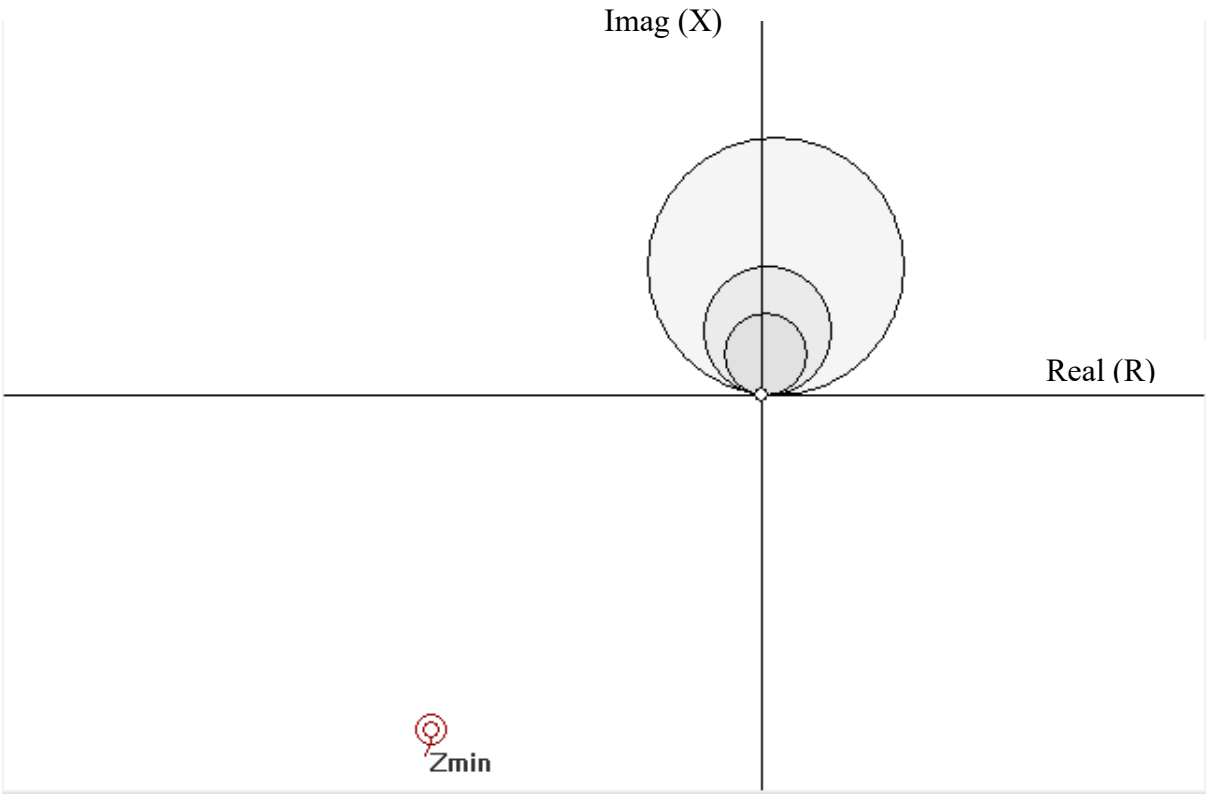


Figure B-2.1E1.24 Distance relay response of 170PZ3 for subevent 2.

Figure B-2.1E1.23 shows the currents and voltages of 170PZ3 for subevent 2, and Figure B-2.1E1.24 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-3:

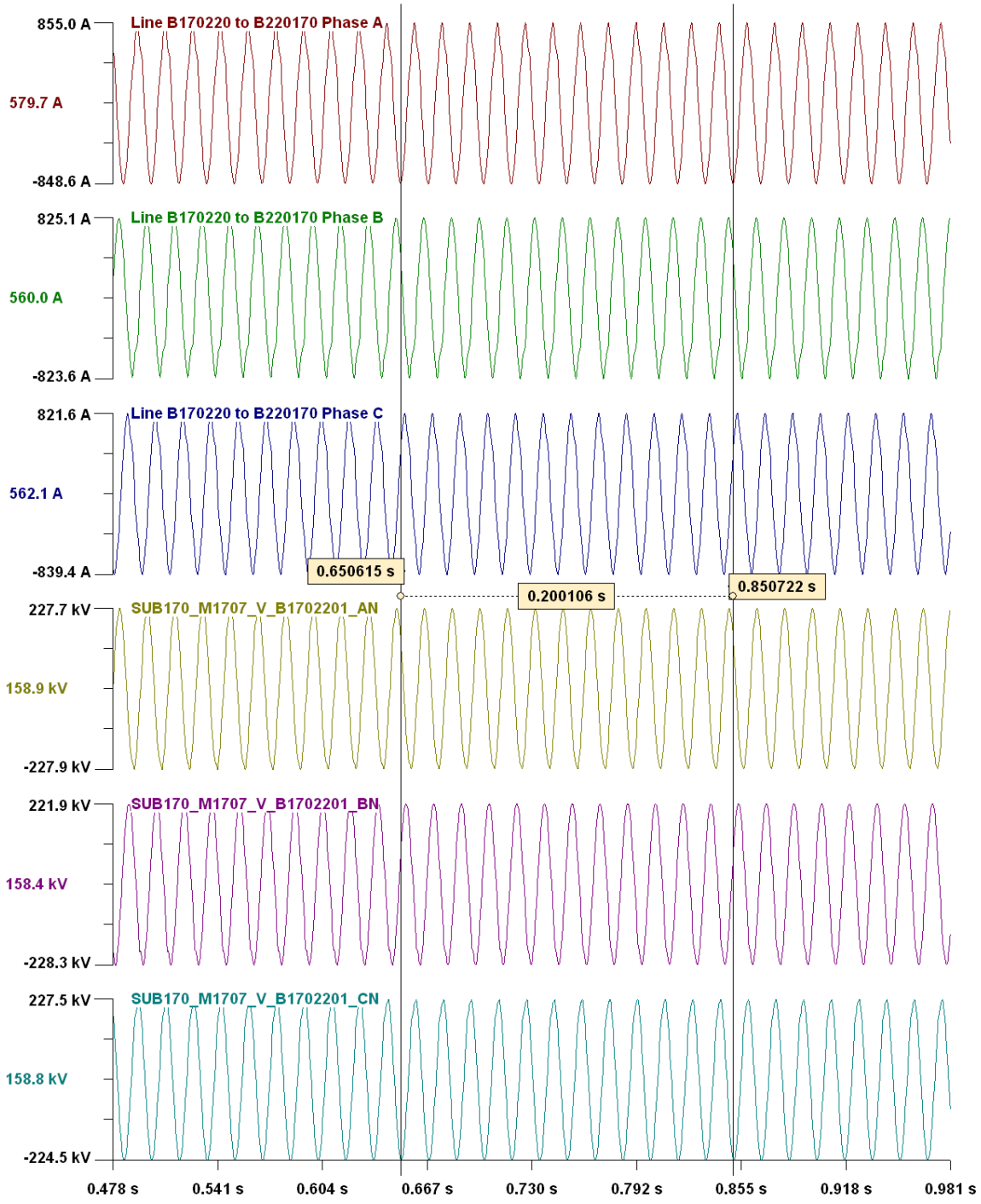


Figure B-2.1E1.25 Currents and Voltage observed in 170PZ3 for subevent 3. Merging Unit 1707.

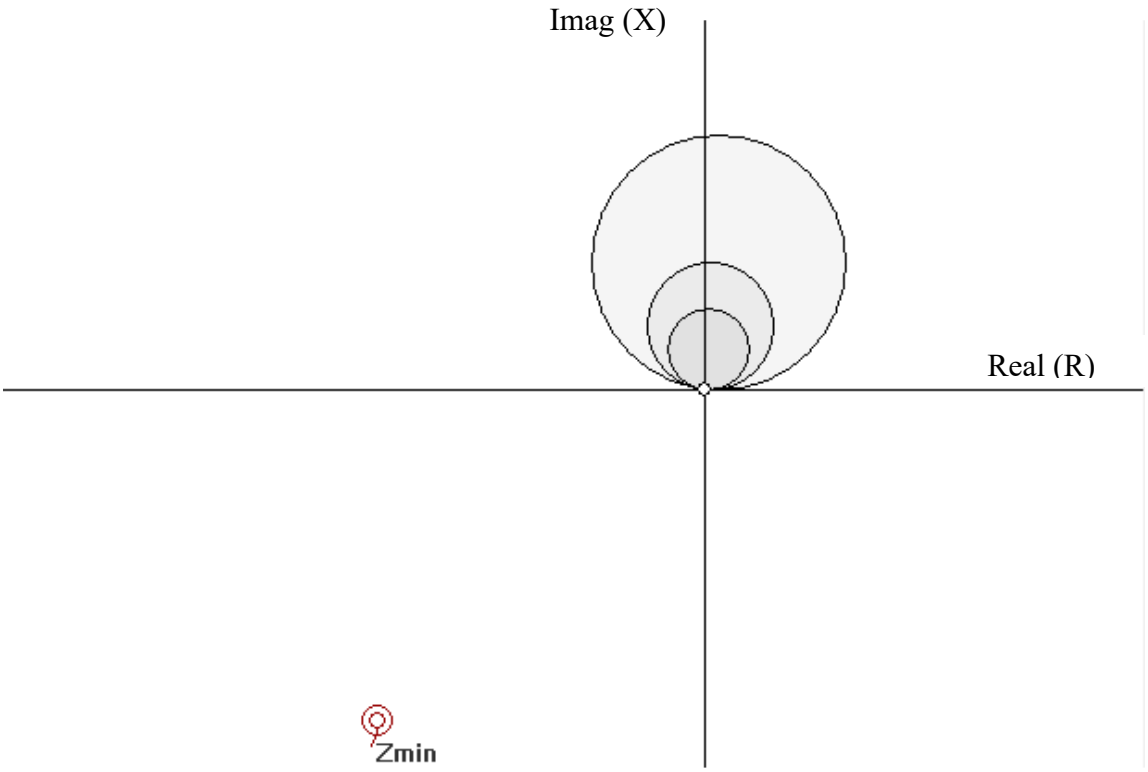


Figure B-2.1E1.26 Distance relay response of 170PZ3 for subevent 3.

Figure B-2.1E1.25 shows the currents and voltages of 170PZ3 for subevent 3, and Figure B-2.1E1.26 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-4:

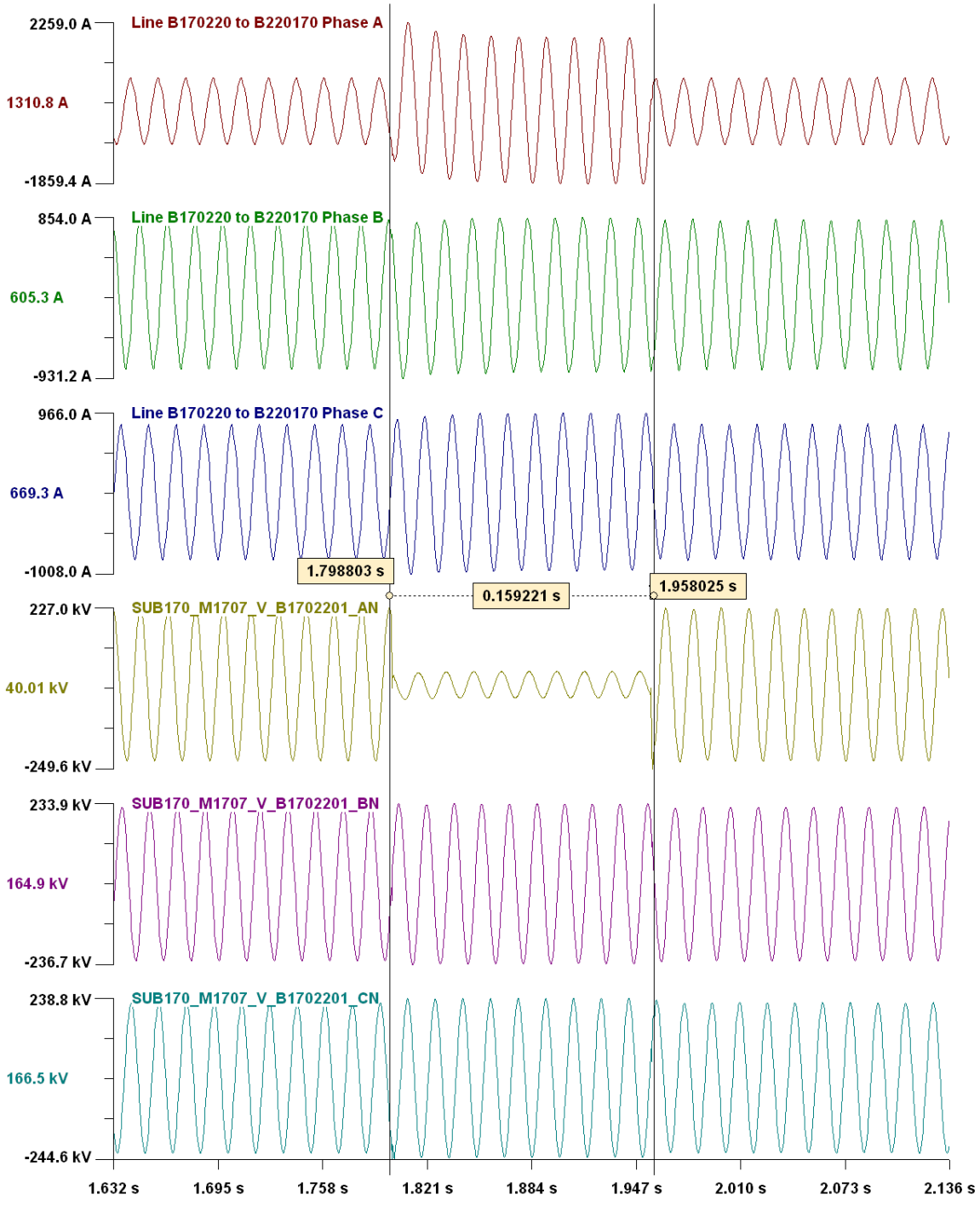


Figure B-2.1E1.27 Currents and Voltage observed in 170PZ3 for subevent 4. Merging Unit 1707.

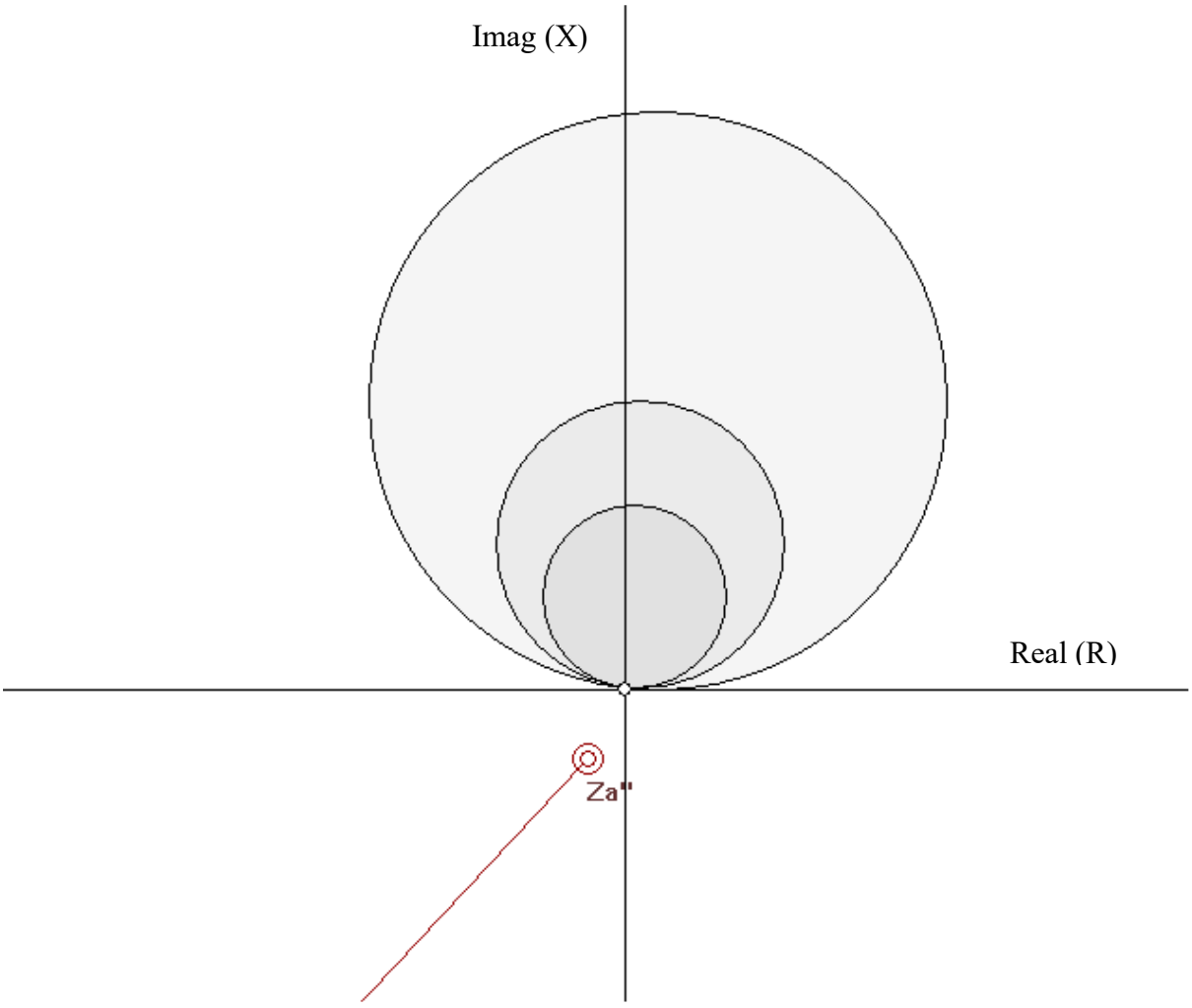


Figure B-2.1E1.28 Distance relay response of 170PZ3 for subevent 4.

Figure B-2.1E1.27 shows the currents and voltages of 170PZ3 for subevent 4, and Figure B-2.1E1.28 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-5:

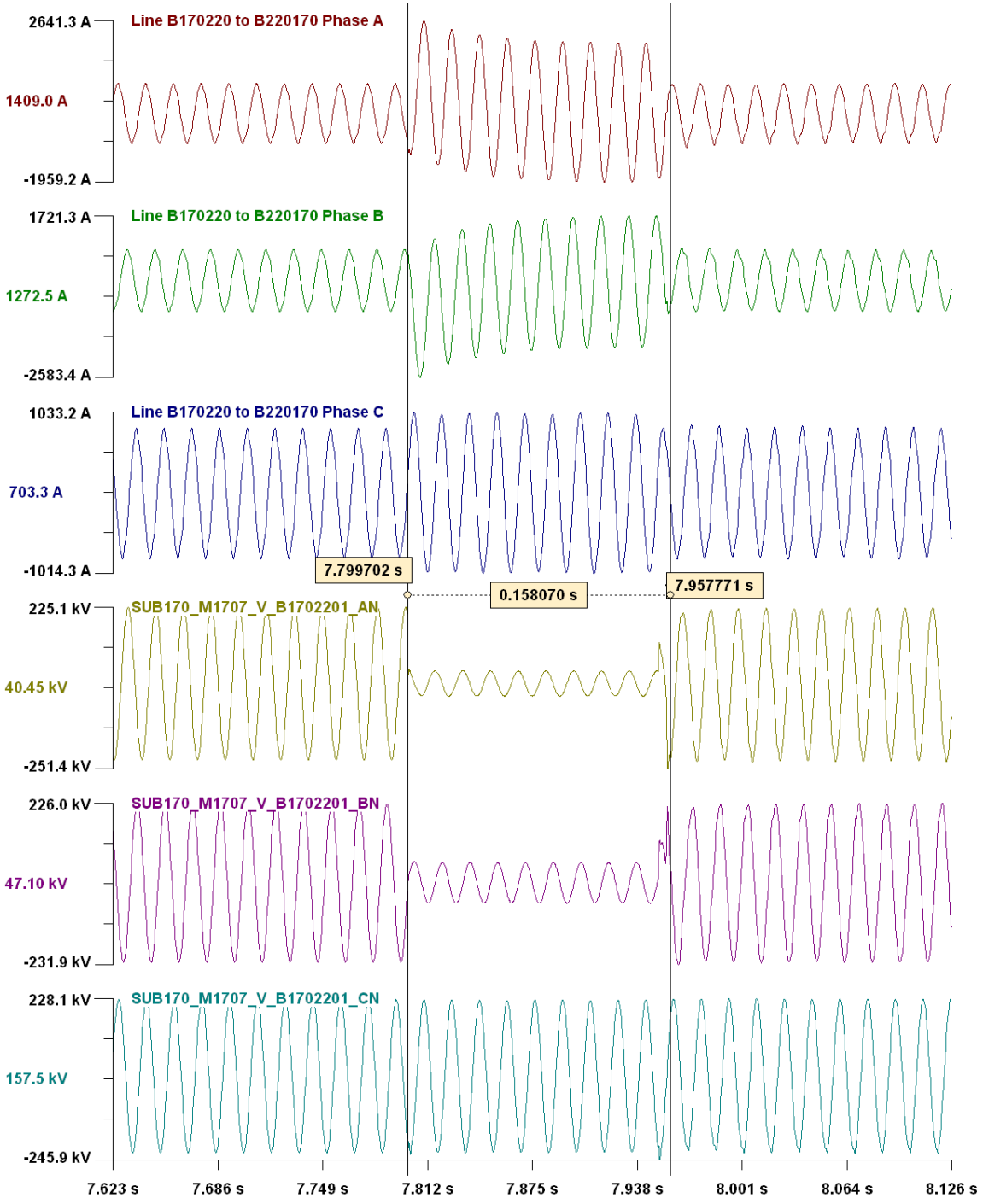


Figure B-2.1E1.29 Currents and Voltage observed in 170PZ3 for subevent 5. Merging Unit 1707.

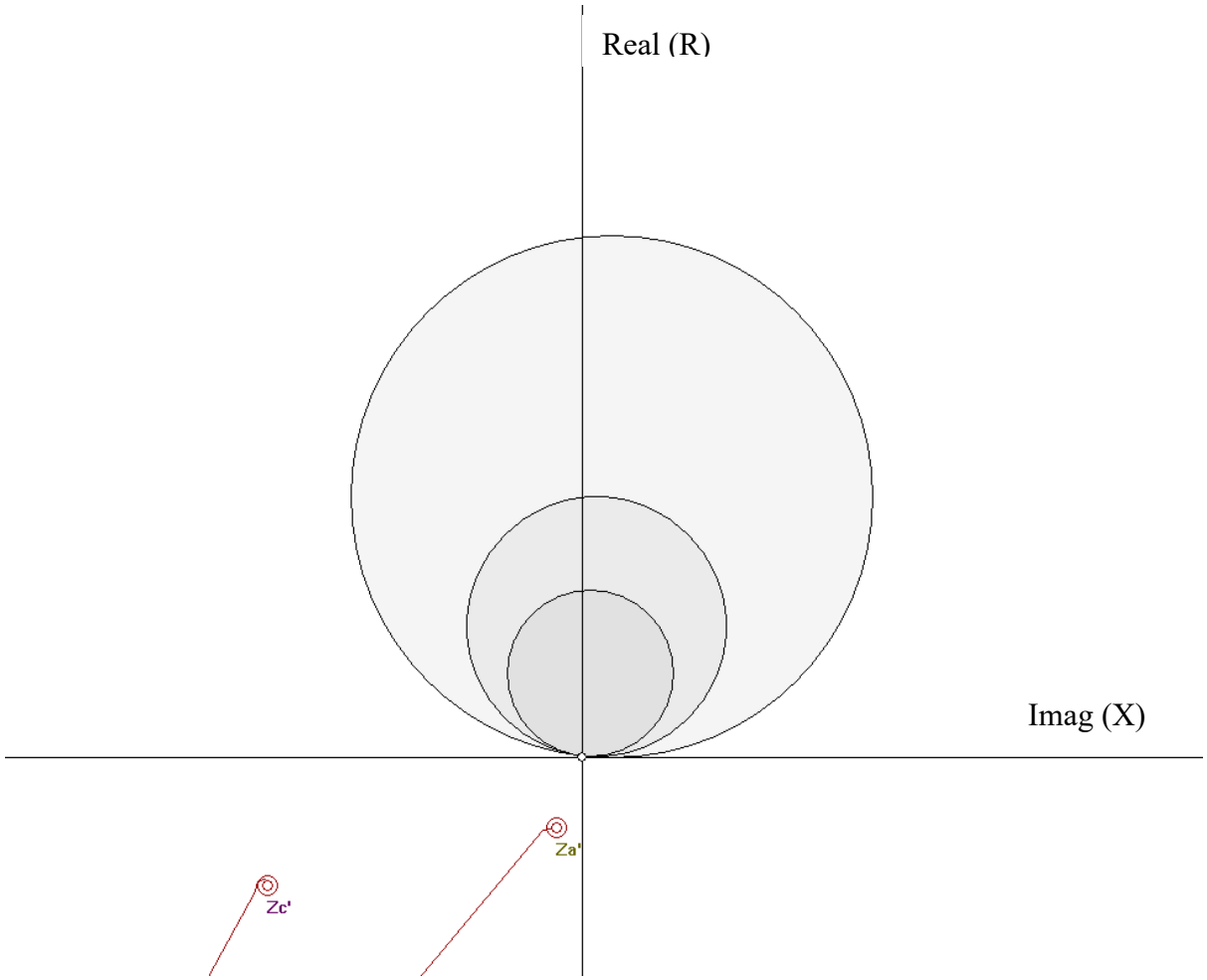


Figure B-2.1E1.30 Distance relay response of 170PZ3 for subevent 5.

Figure B-2.1E1.29 shows the currents and voltages of 170PZ3 for subevent 5, and Figure B-2.1E1.30 shows the performance of this relay in WinXFM (Note: We have shown only the minimum value for the line-to-line equation and not the line to ground equation). Note that this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Event-2:

As described in section B-1.2 Event-2 is an event performed on Substation-240. The performance of the legacy protection and control of some of the protection zones is given below:

Performance of 240PZ1 Protection and Control

For Event 2, there are two subevents as listed in Table B-1.2. We can observe that subevent 1 is an A-G fault happening on the transmission line B240150 to B150240 at 27 miles from Substation -240 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B24030 to B30240 at 13.2883 miles from Substation 240 which is 75% of the line length of the transmission line B24030 to B30240 In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B240150 to B150240 for subevent 1**.

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-1 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

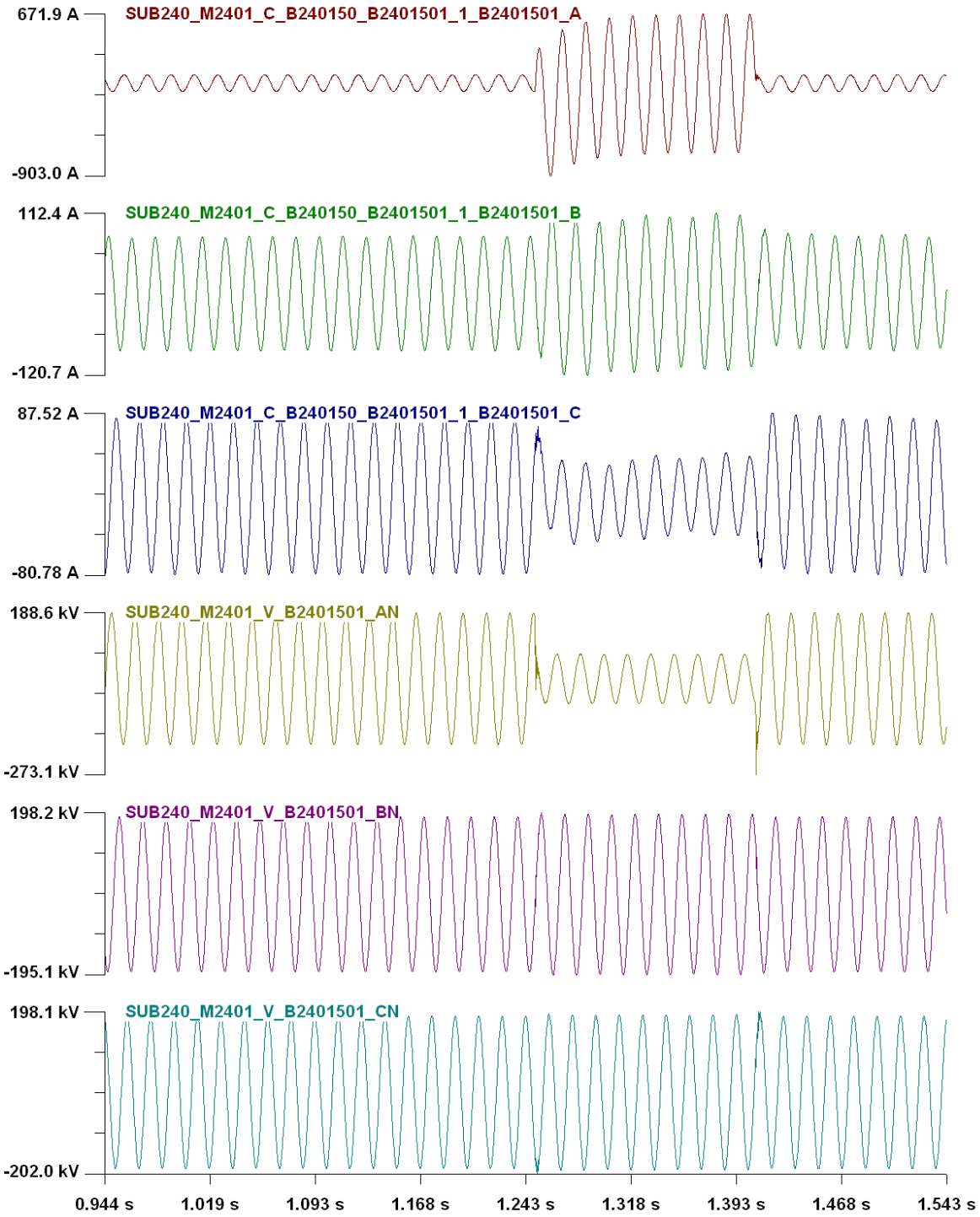


Figure B-2.1E2.1 Currents and Voltage observed in 240PZ1 for subevent 1. Merging Unit 2401.

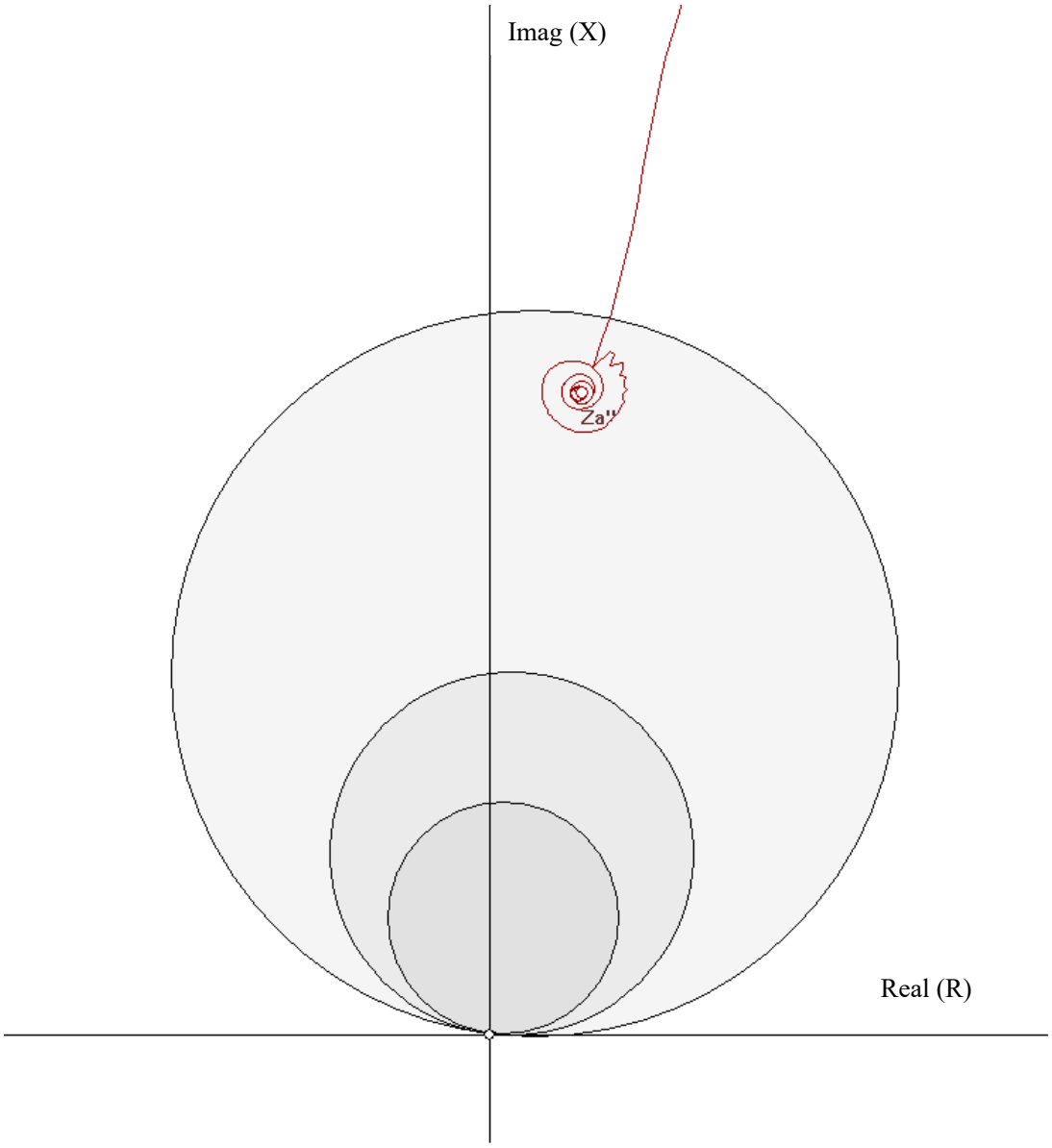


Figure B-2.1E2.2 Distance relay response of 240PZ1 for subevent 1.

Figure B-2.1E2.1 shows the currents and voltages of 240PZ1 for subevent 1, and Figure B-2.1E2.2 shows the performance of the distance relay in WinXFM. It can be observed that the relay "sees" the fault in zone 3 (delay of 30 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 30 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Subevent-2:

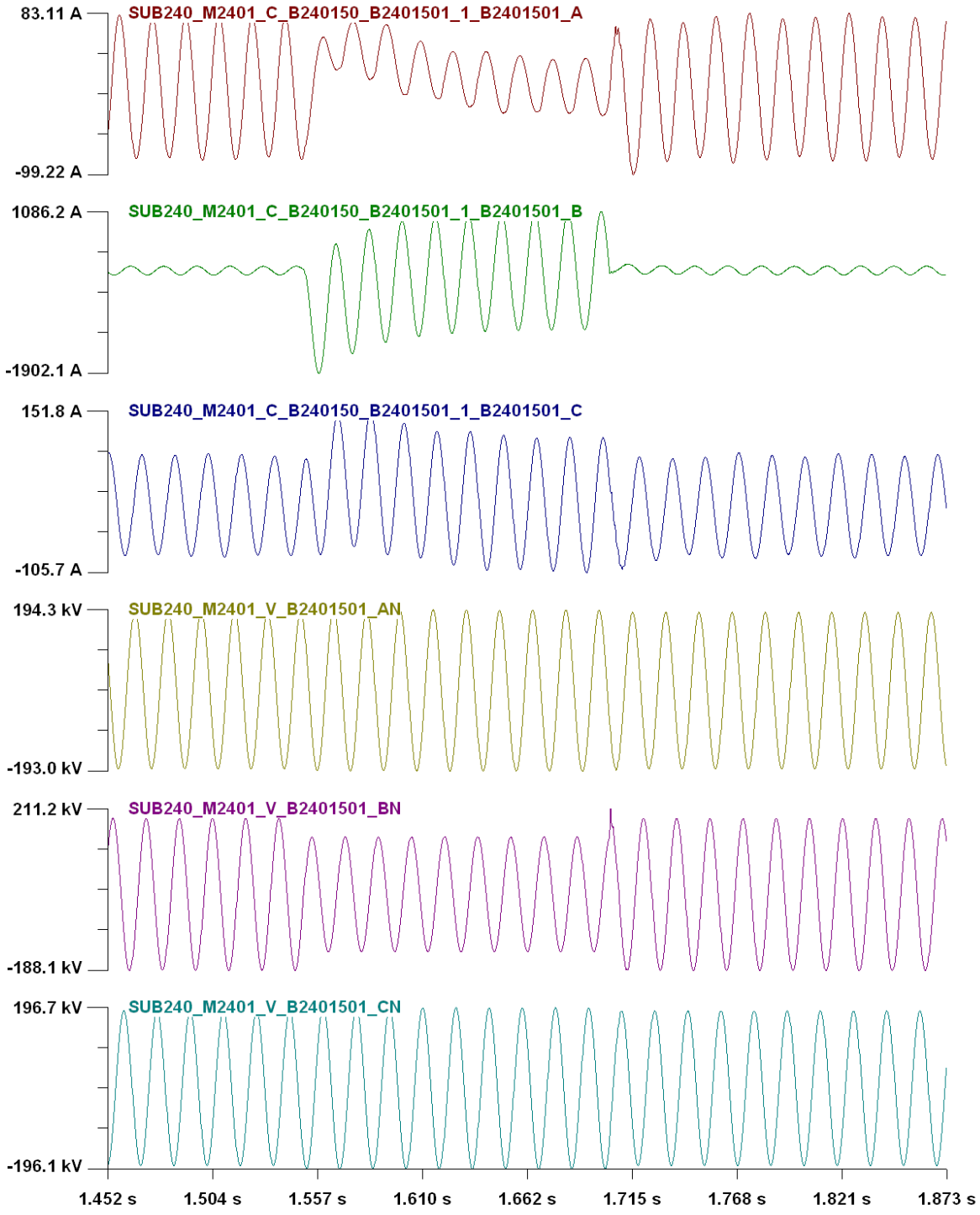


Figure B-2.1E2.3 Currents and Voltage observed in 240PZ1 for subevent 2. Merging Unit 2401.

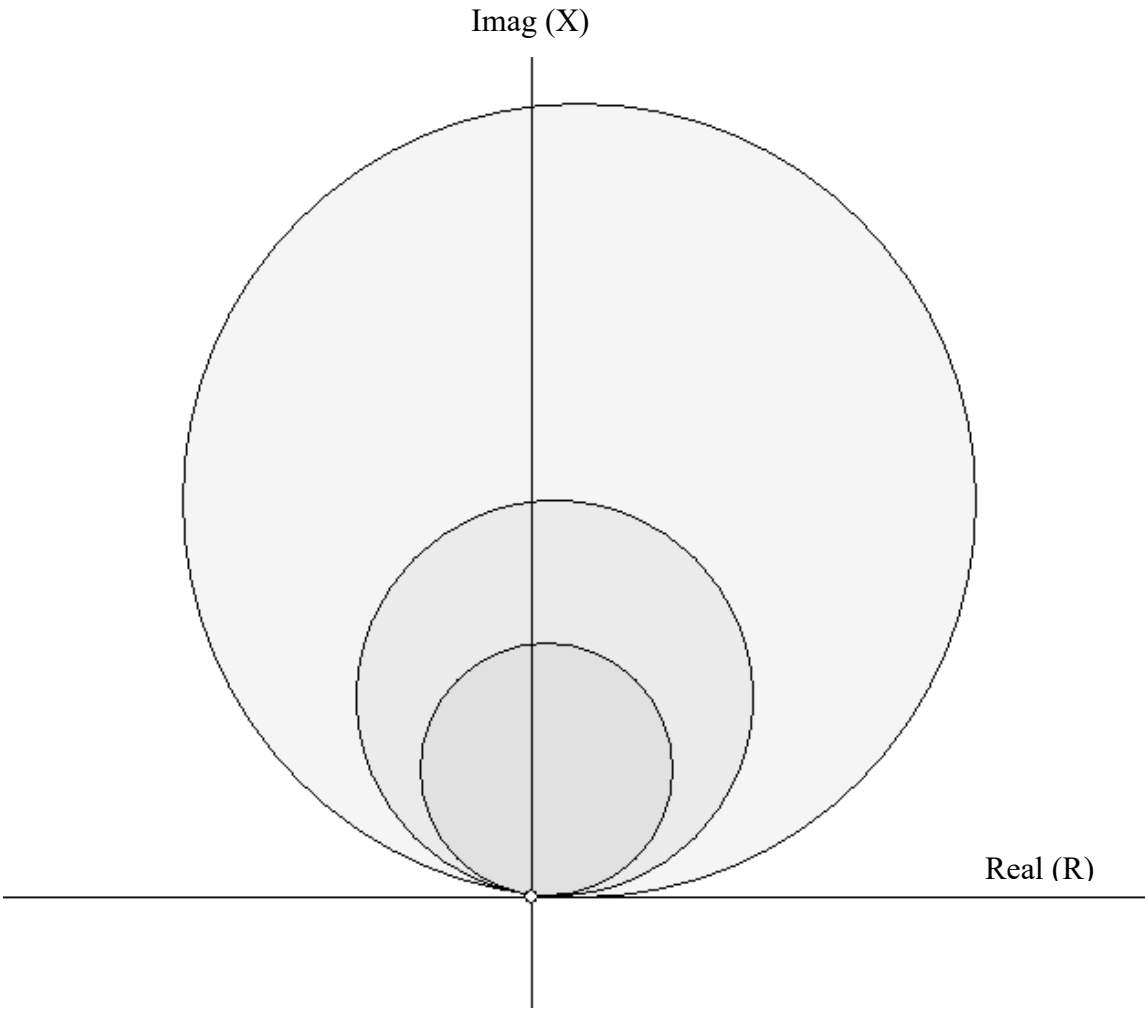


Figure B-2.1E2.4 Distance relay response of 240PZ1 for subevent 2.

Figure B-2.1E2.3 shows the currents and voltages of 240PZ1 for subevent 2, and Figure B-2.1E2.4 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Performance of 240PZ3 Protection and Control

For Event 2, we can observe that subevent 1 is an A-G fault happening on the transmission line B240150 to B150240 at 27 miles from Substation -240 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B24030 to B30240 at 13.2883 miles from Substation 240 which is 75% of the line length of the transmission line B24030 to B30240 In this case the correct action of the protection and control system is that **only the protective relay for protection zone 3 acts to isolate the line B24030 to B30240 for subevent 2**.

The voltages and currents measured by the MUs in protection zone-3 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

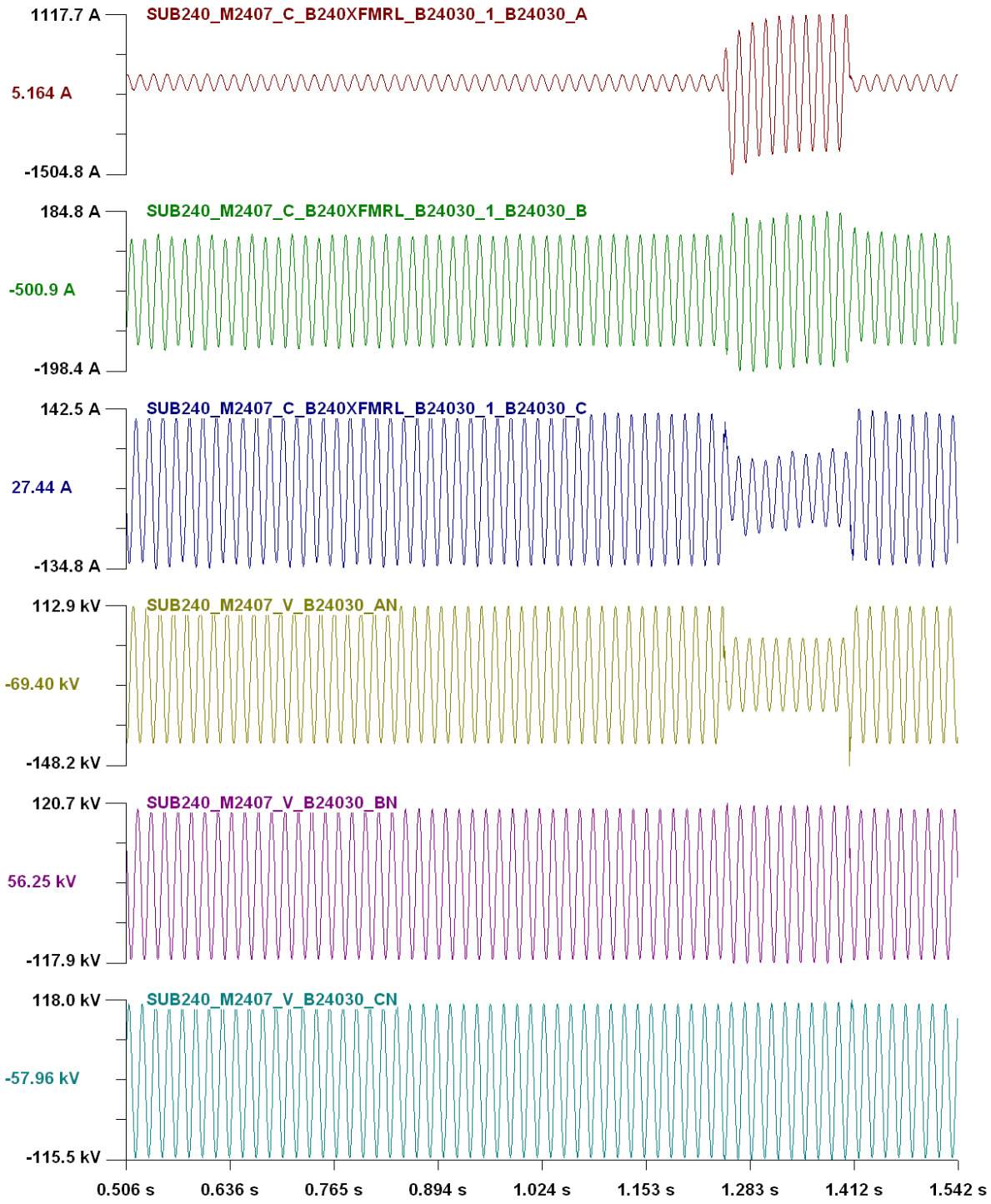


Figure B-2.1E2.5 Currents and Voltage observed in 240PZ3 for subevent 1. Merging Unit 2407.

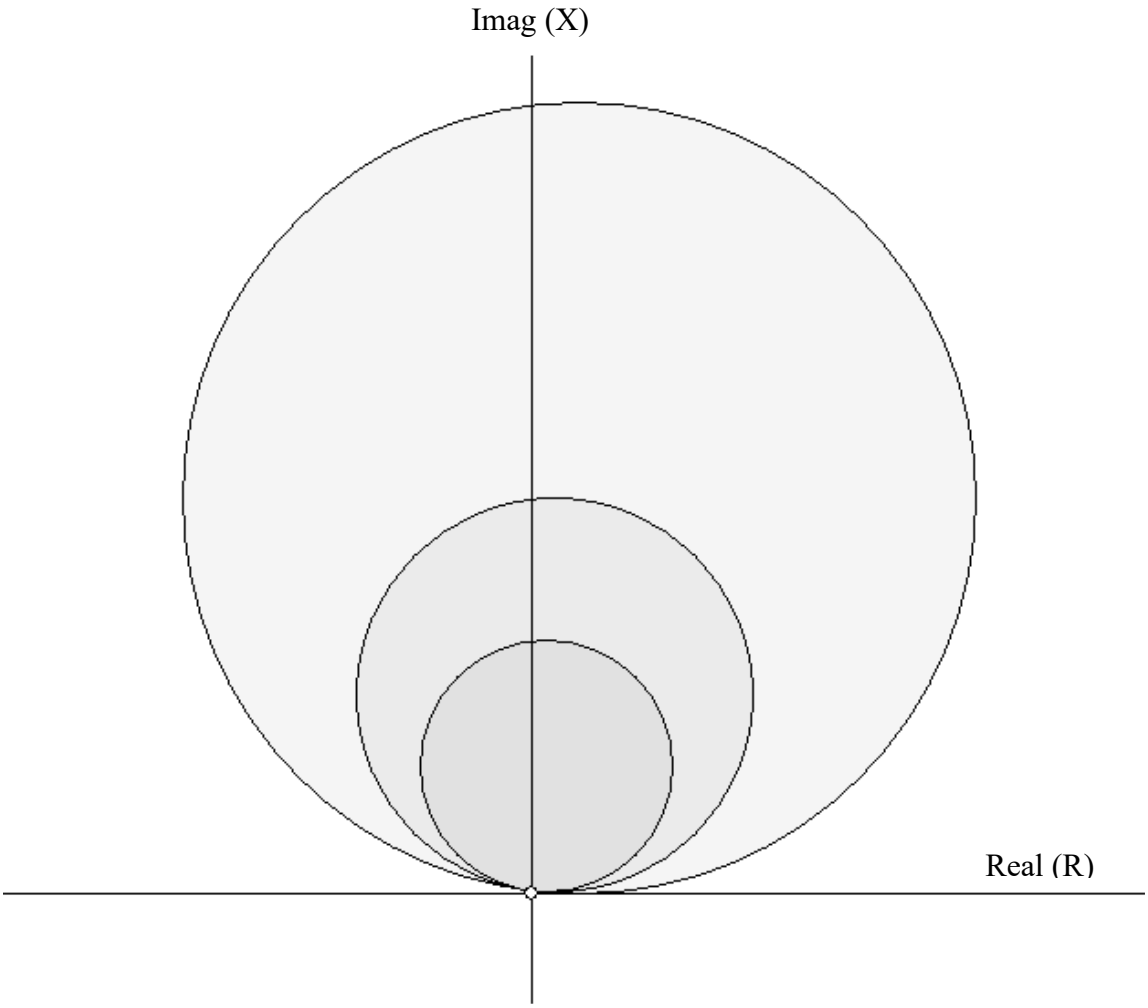


Figure B-2.1E2.6 Distance relay response of 240PZ3 for subevent 1.

Figure B-2.1E2.5 shows the currents and voltages of 240PZ3 for subevent 1, and Figure B-2.1E2.6 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line B24030 to B30240. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

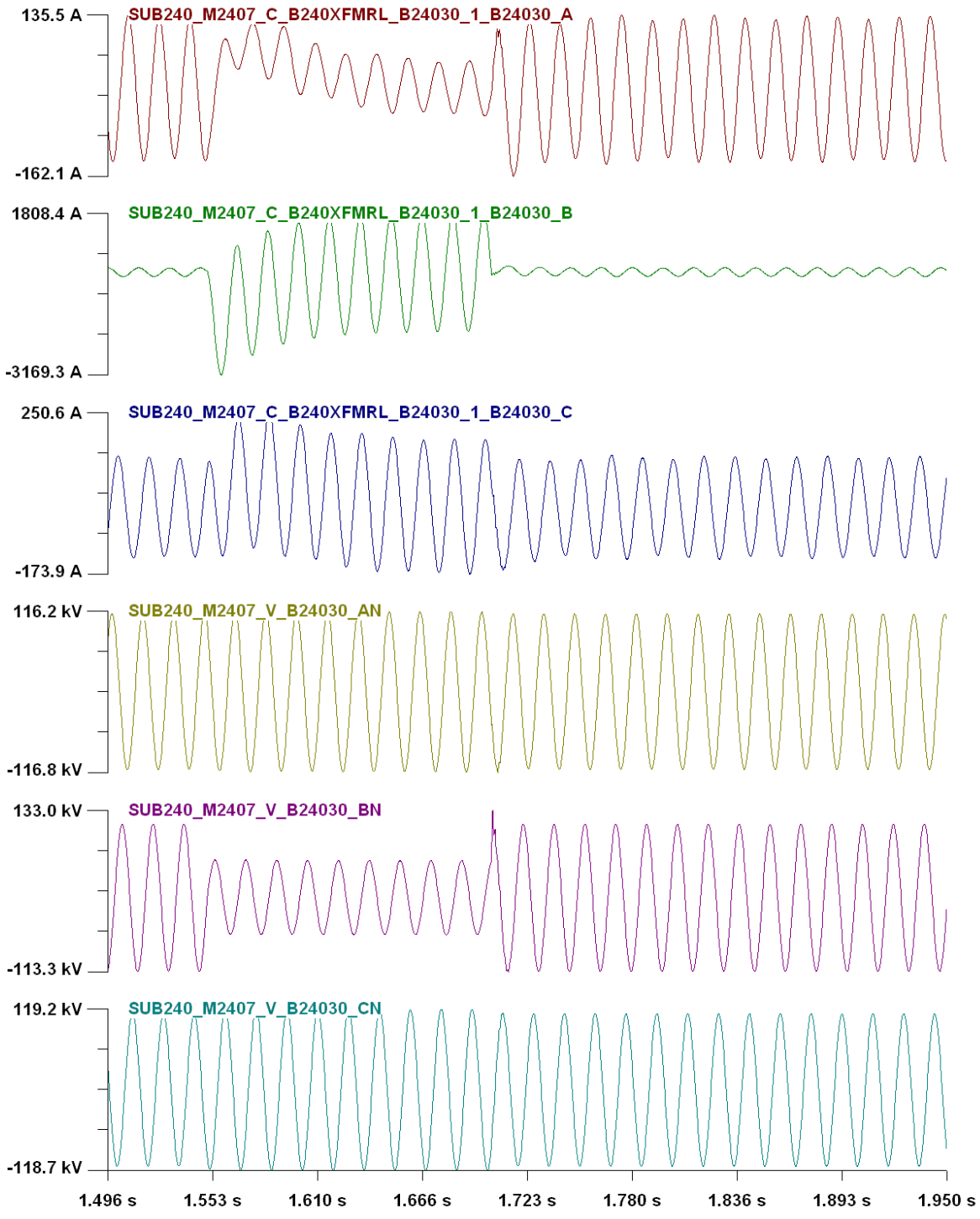


Figure B-2.1E2.7 Currents and Voltage observed in 240PZ3 for subevent 2. Merging Unit 2407.

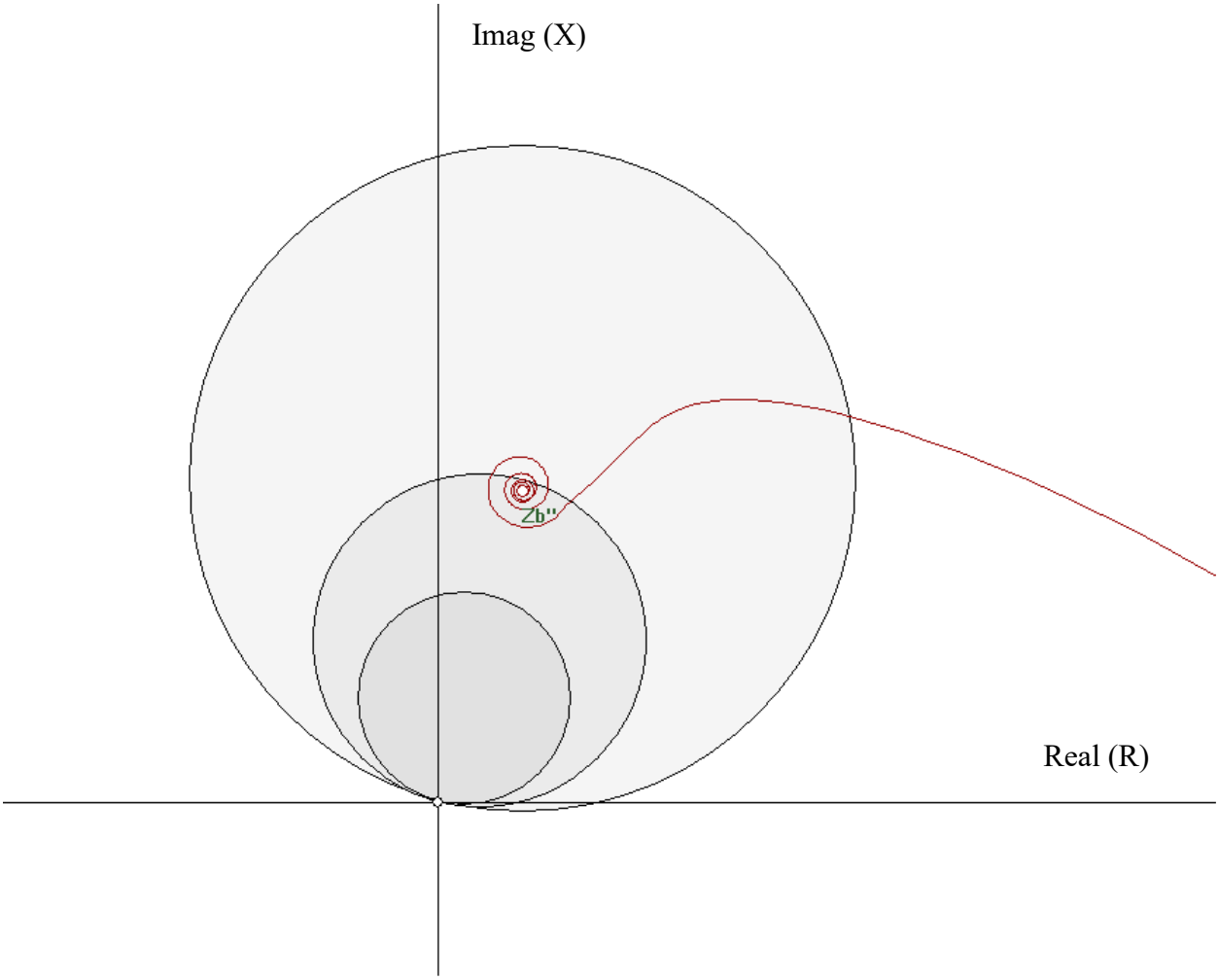


Figure B-2.1E2.8 Distance relay response of 240PZ3 for subevent 2.

Figure B-2.1E2.7 shows the currents and voltages of 240PZ3 for subevent 2, and Figure B-2.1E2.8 shows the performance of the distance relay in WinXFM. It can be observed that the relay "sees" the fault in zone 2 (delay of 10 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 10 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Event-3:

As described in section B-1.3 Event-3 is an event performed on Substation-50. The performance of the legacy protection and control of some of the protection zones is given below:

Performance of 50PZ1 Protection and Control

For Event 3, there are two subevents as listed in B-1.3. We can observe that subevent 1 is an A-G fault happening on the transmission line B5010 to B1050 at 16.5 miles from Substation-50 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B50100 to B10050 at 17.7175 miles from Substation-50 which is 75% of the line length of the transmission line B50100 to B10050. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B5010 to B1050 for subevent 1**.

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-1 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

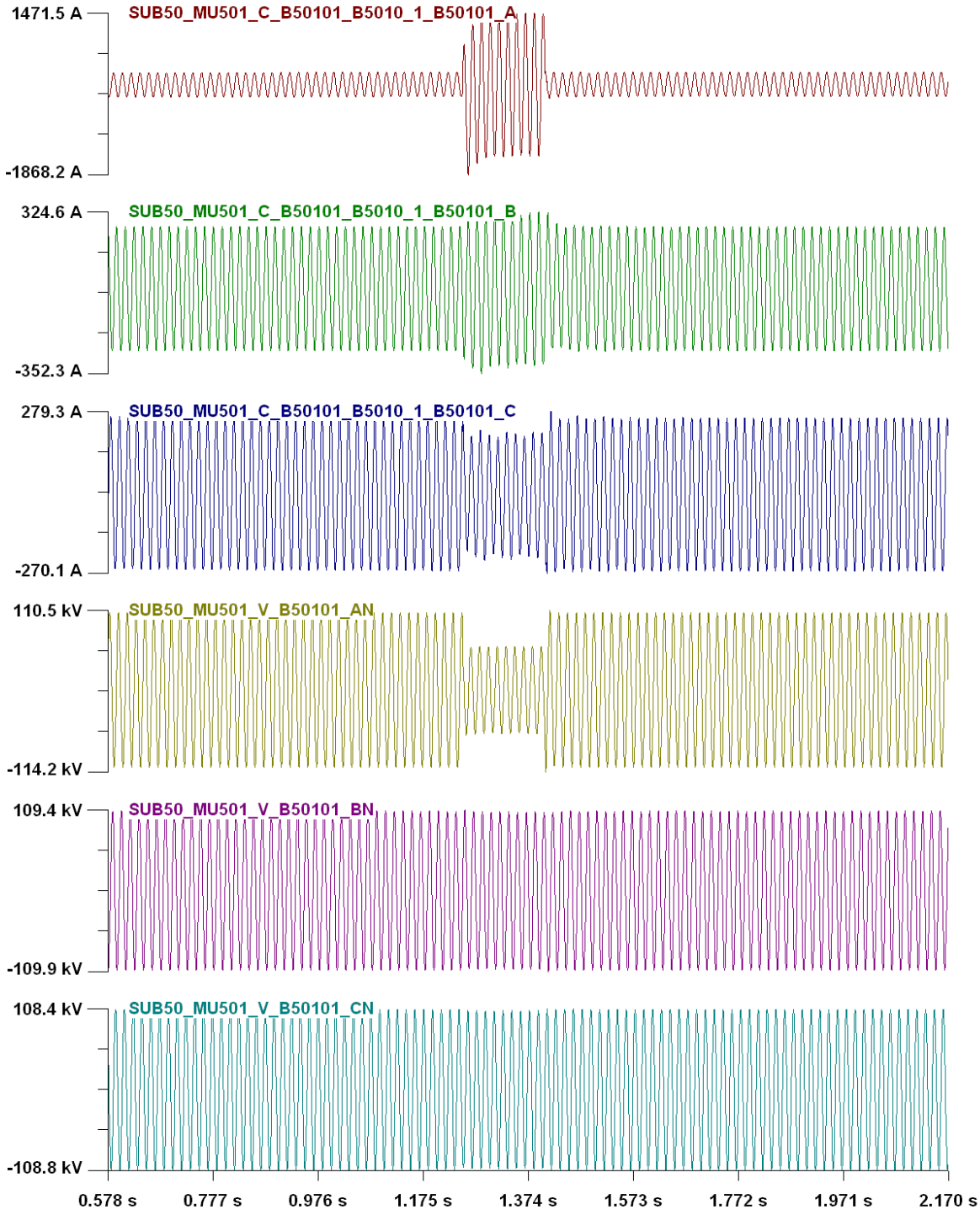


Figure B-2.1E3.1 Currents and Voltage observed in 50PZ1 for subevent 1. Merging Unit 501.

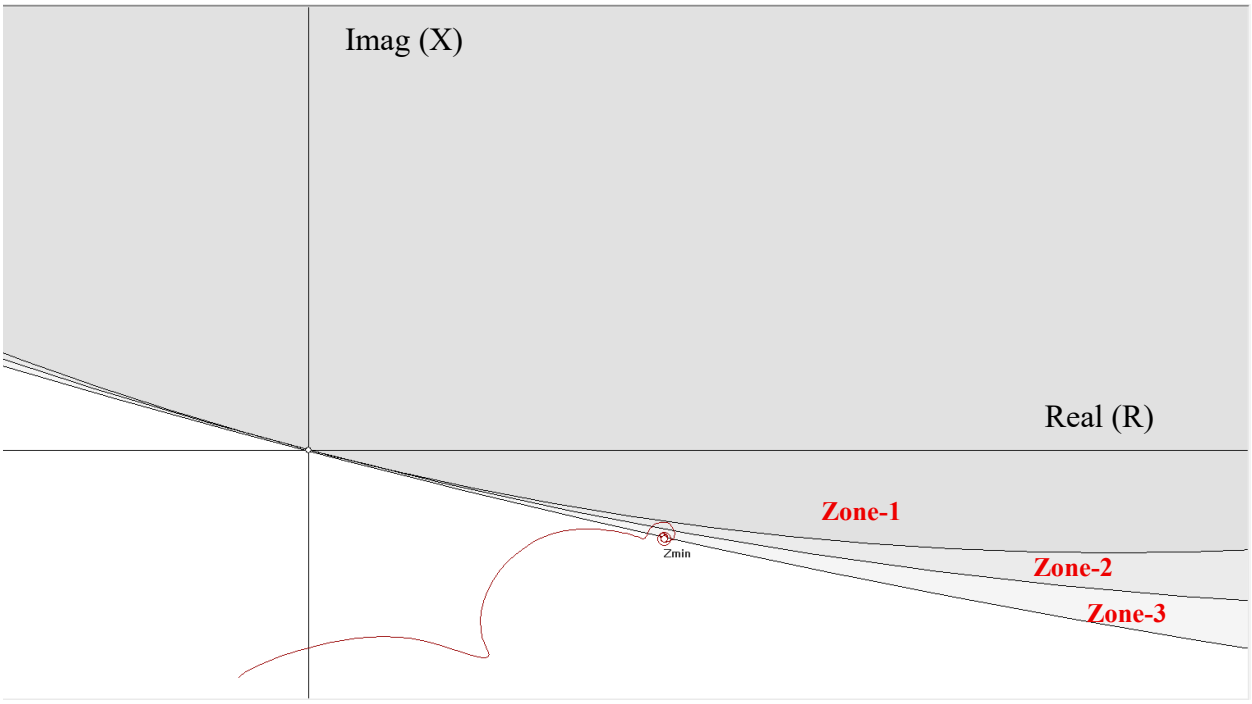


Figure B-2.1E3.2 Distance relay response of 50PZ1 for subevent 1.

Figure B-2.1E3.1 shows the currents and voltages of 50PZ1 for subevent 1, and Figure B-2.1E3.2 shows the performance of the distance relay in WinXFM. It can be observed that the relay "sees" the fault in zone 3 (delay of 30 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 30 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Subevent-2:

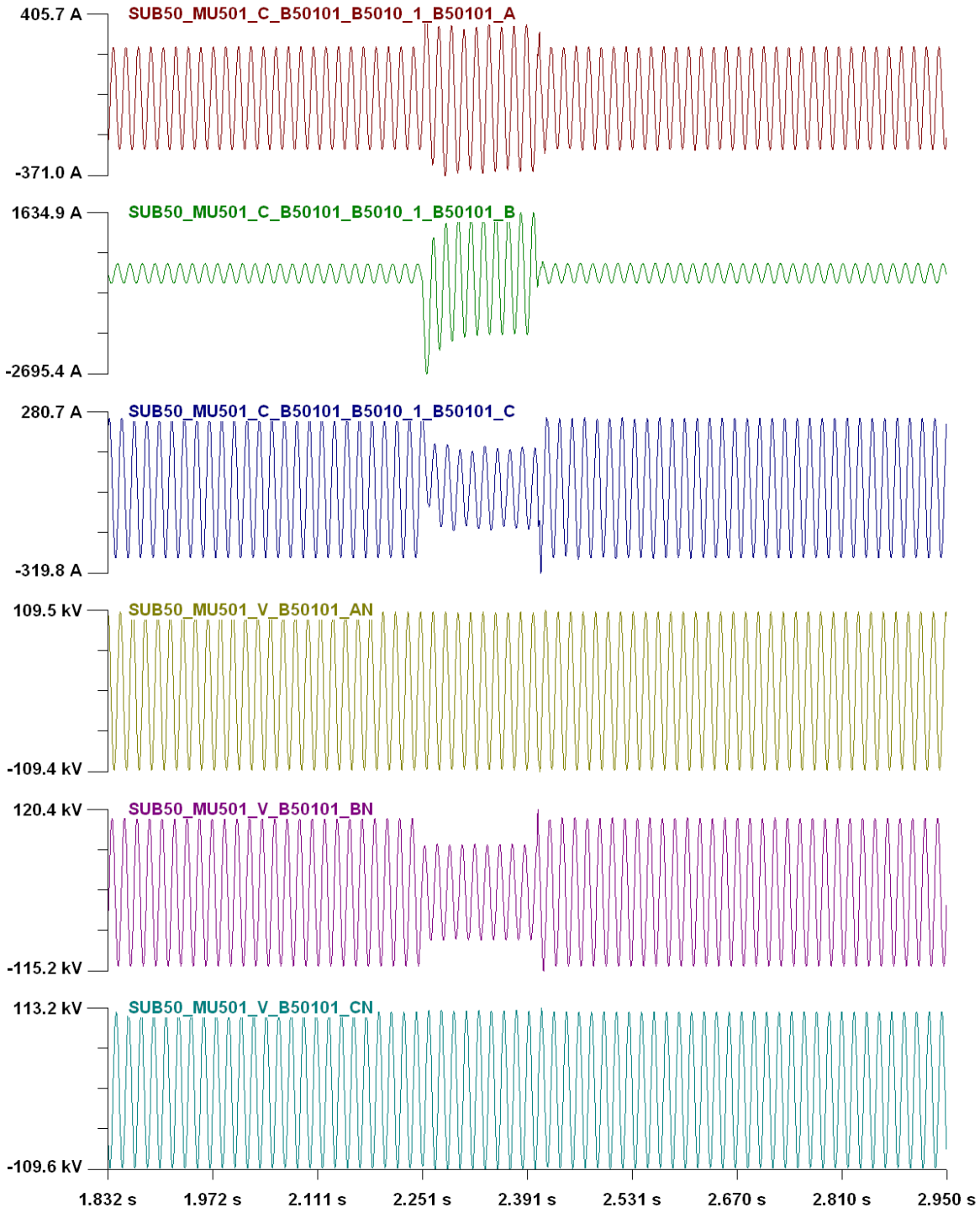


Figure B-2.1E3.3 Currents and Voltage observed in 50PZ1 for subevent 2. Merging Unit 501.

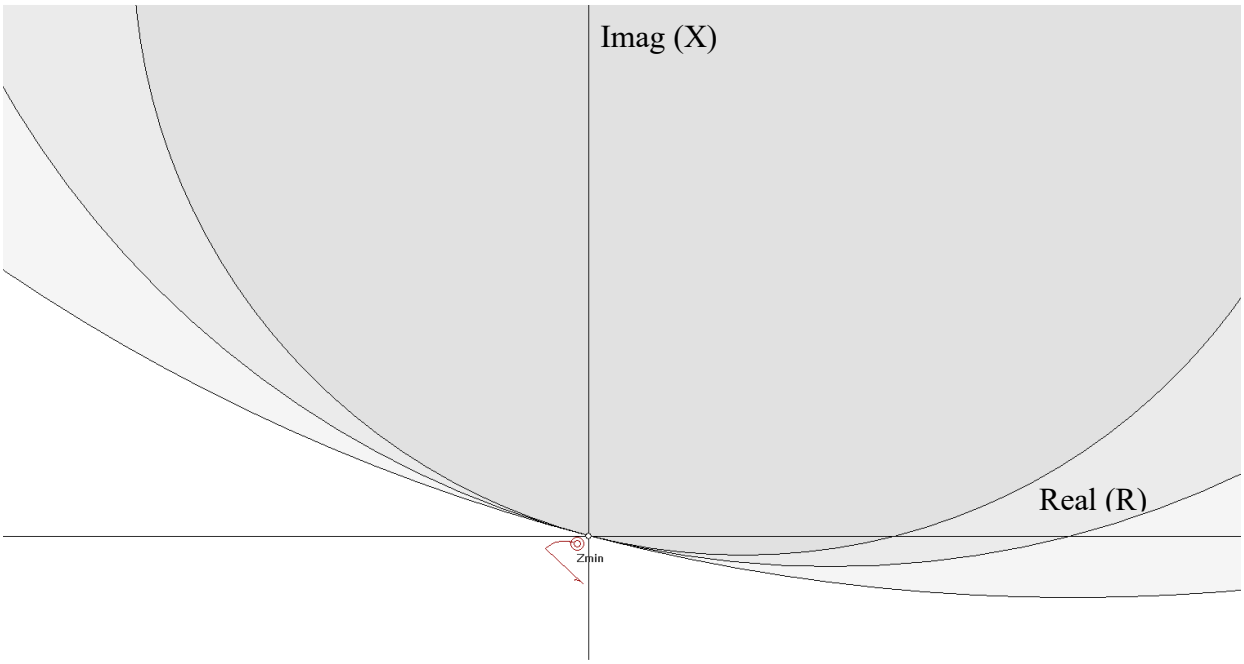


Figure B-2.1E3.4 Distance relay response of 50PZ1 for subevent 2.

Figure B-2.1E3.3 shows the currents and voltages of 50PZ1 for subevent 2, and Figure B-2.1E3.4 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Performance of 50PZ2 Protection and Control

For Event 3, we can observe that subevent 1 is an A-G fault happening on the transmission line B5010 to B1050 at 16.5 miles from Substation-50 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B50100 to B10050 at 17.7175 miles from Substation-50 which is 75% of the line length of the transmission line B50100 to B10050. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the line B50100 to B10050 for subevent 2**.

The voltages and currents measured by the MUs in protection zone-2 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

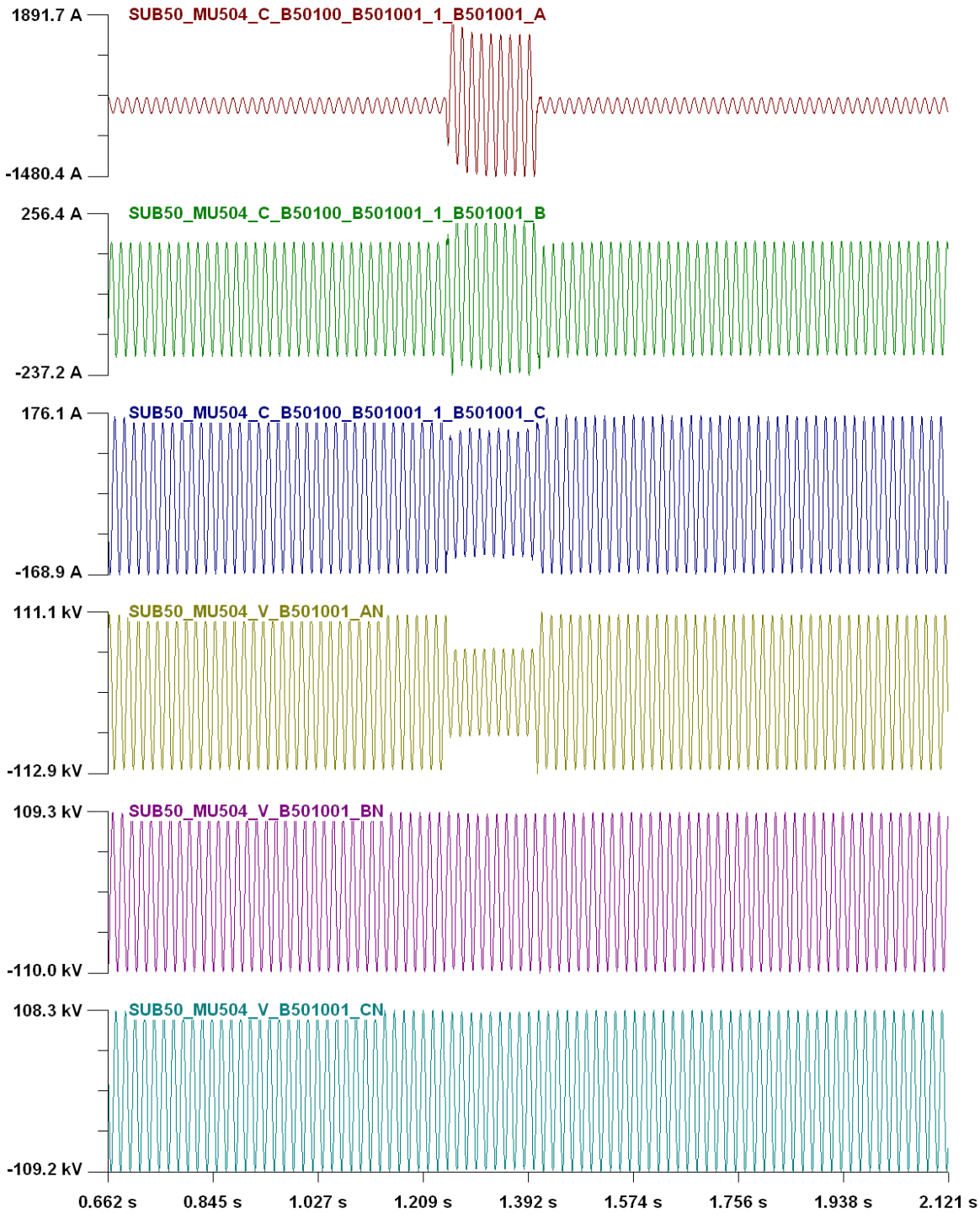


Figure B-2.1E3.5 Currents and Voltage observed in 50PZ2 for subevent 1. Merging Unit 504.

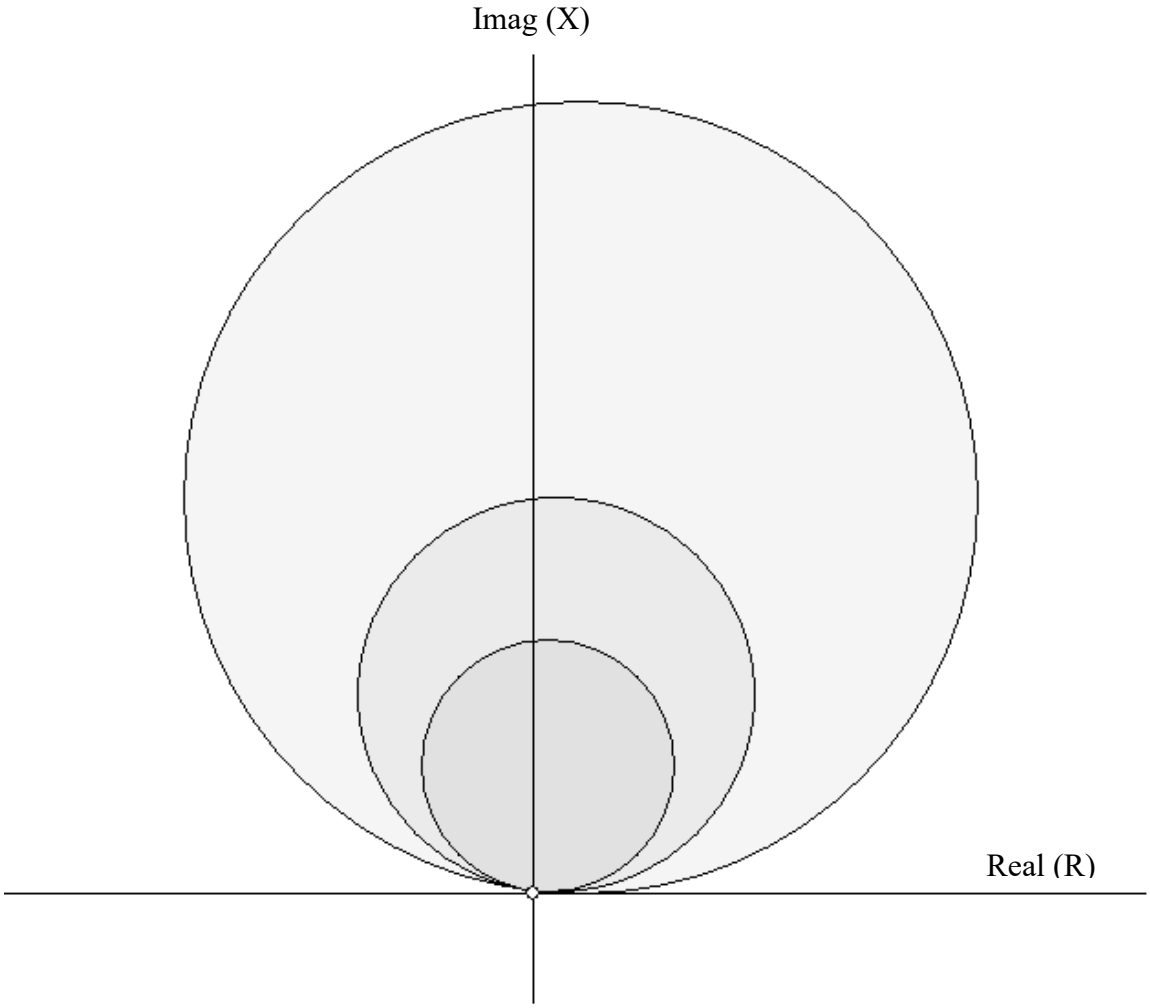


Figure B-2.1E3.6 Distance relay response of 50PZ2 for subevent 1.

Figure B-2.1E3.5 shows the currents and voltages of 50PZ2 for subevent 1, and Figure B-2.1E3.6 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

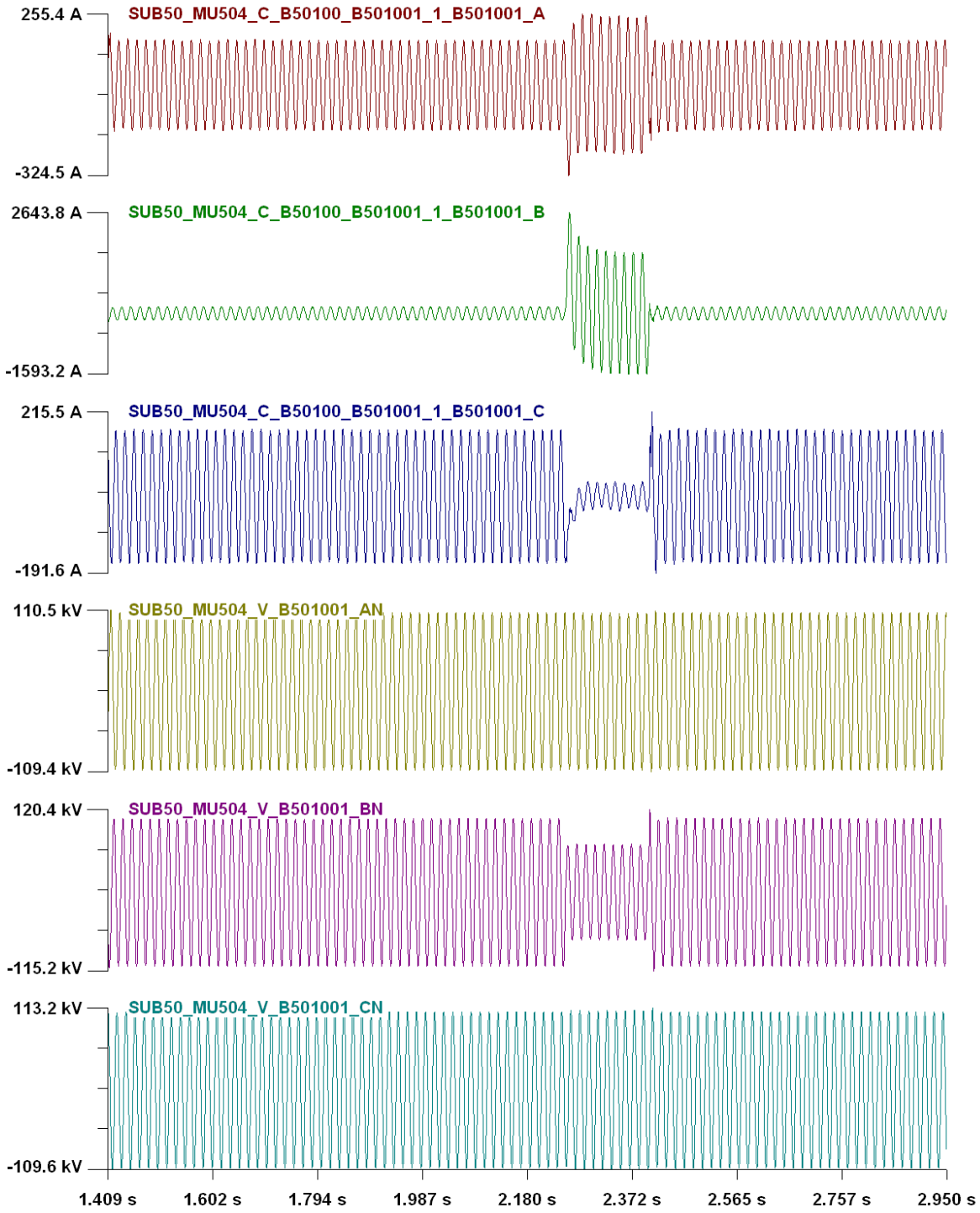


Figure B-2.1E3.7 Currents and Voltage observed in 50PZ2 for subevent 2. Merging Unit 504.

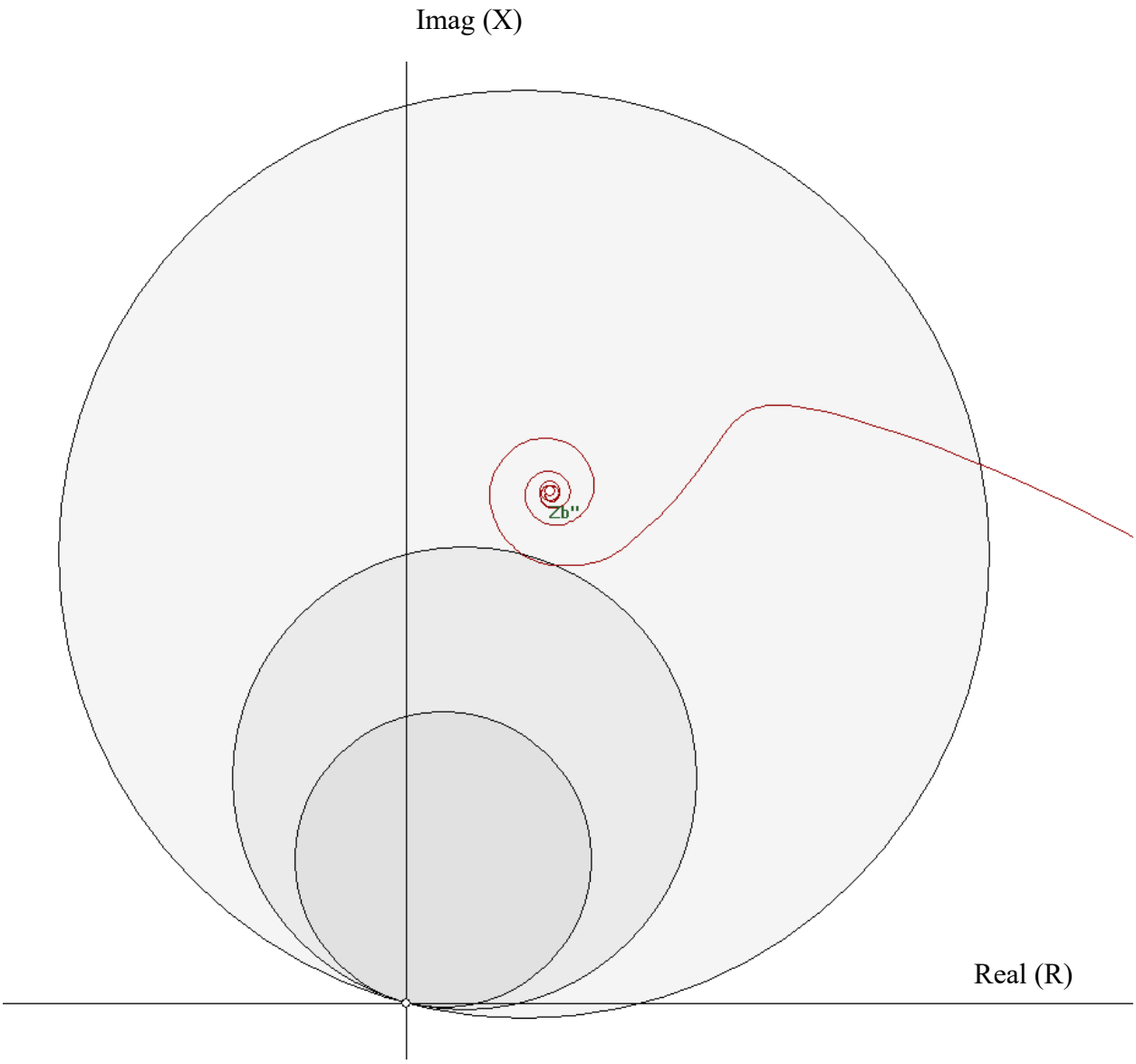


Figure B-2.1E3.8 Distance relay response of 50PZ2 for subevent 2.

Figure B-2.1E3.7 shows the currents and voltages of 50PZ2 for subevent 2, and Figure B-2.1E3.8 shows the performance of the distance relay in WinXFM. It can be observed that the relay "sees" the fault in zone 3 (delay of 30 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 30 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined

"setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Event-4:

As described in section B-1.4. Event-4 is an event performed on Substation-40. The performance of the legacy protection and control of some of the protection zones is given below:

Performance of 40PZ1 Protection and Control

For Event 4, there are two subevents as listed in Table B-1.4. We can observe that subevent 1 is an A-G fault happening on the transmission line B4020 to B2040 at 24.75 miles from Substation-40 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B4090 to B9040 at 19.875 miles from Substation-40 which is 75% of the line length of the transmission line B4090 to B9040. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B4090 to B9040 for subevent 2.**

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-1 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

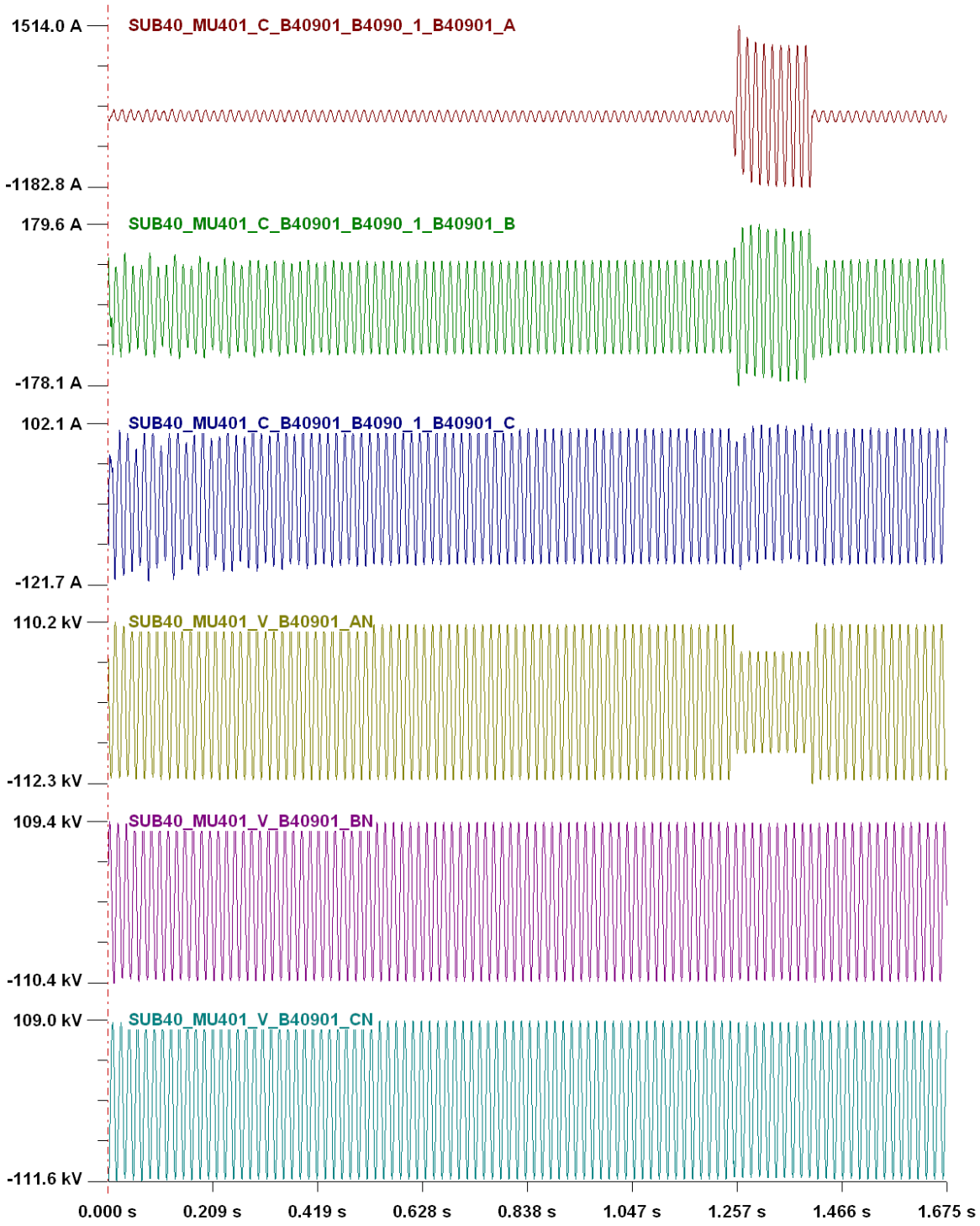


Figure B-2.1E4.1 Currents and Voltage observed in 40PZ1 for subevent 1. Merging Unit 401.

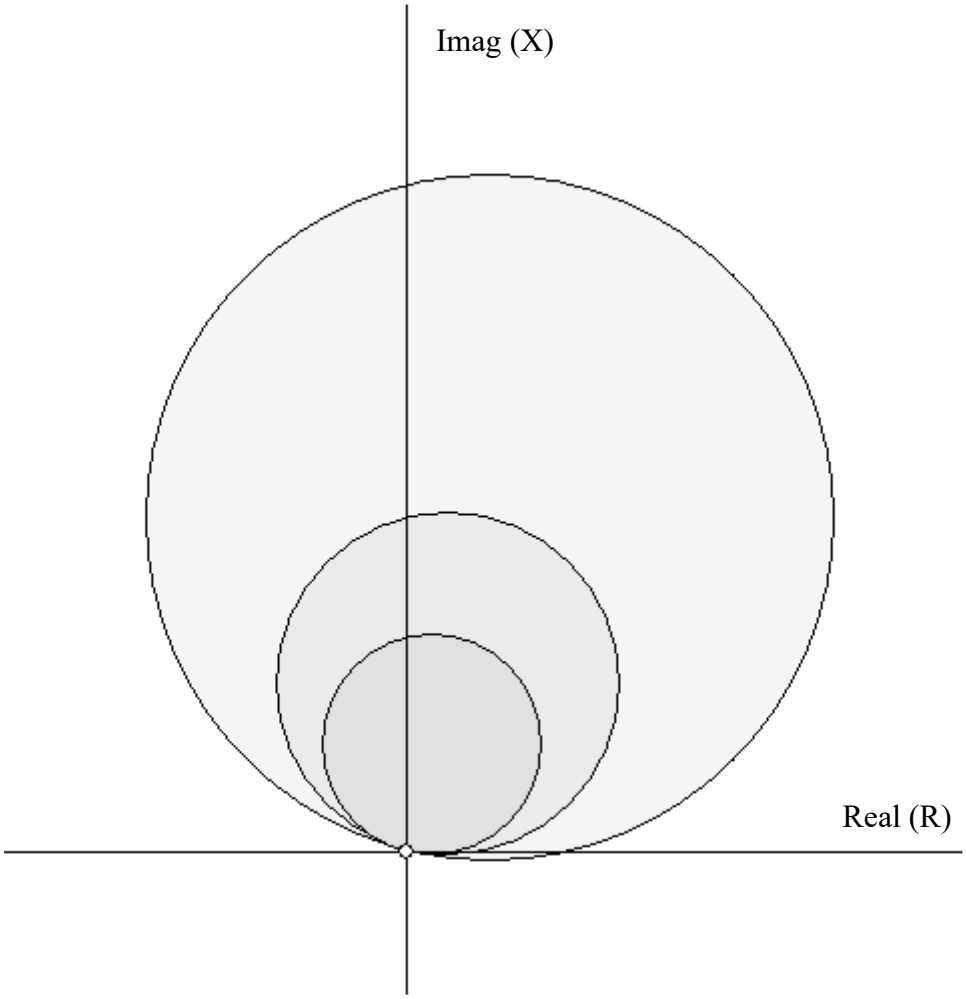


Figure B-2.1E4.2 Distance relay response of 40PZ1 for subevent 1.

Figure B-2.1E4.1 shows the currents and voltages of 40PZ1 for subevent 1, and Figure B-2.1E4.2 shows the performance of the distance relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Subevent-2:

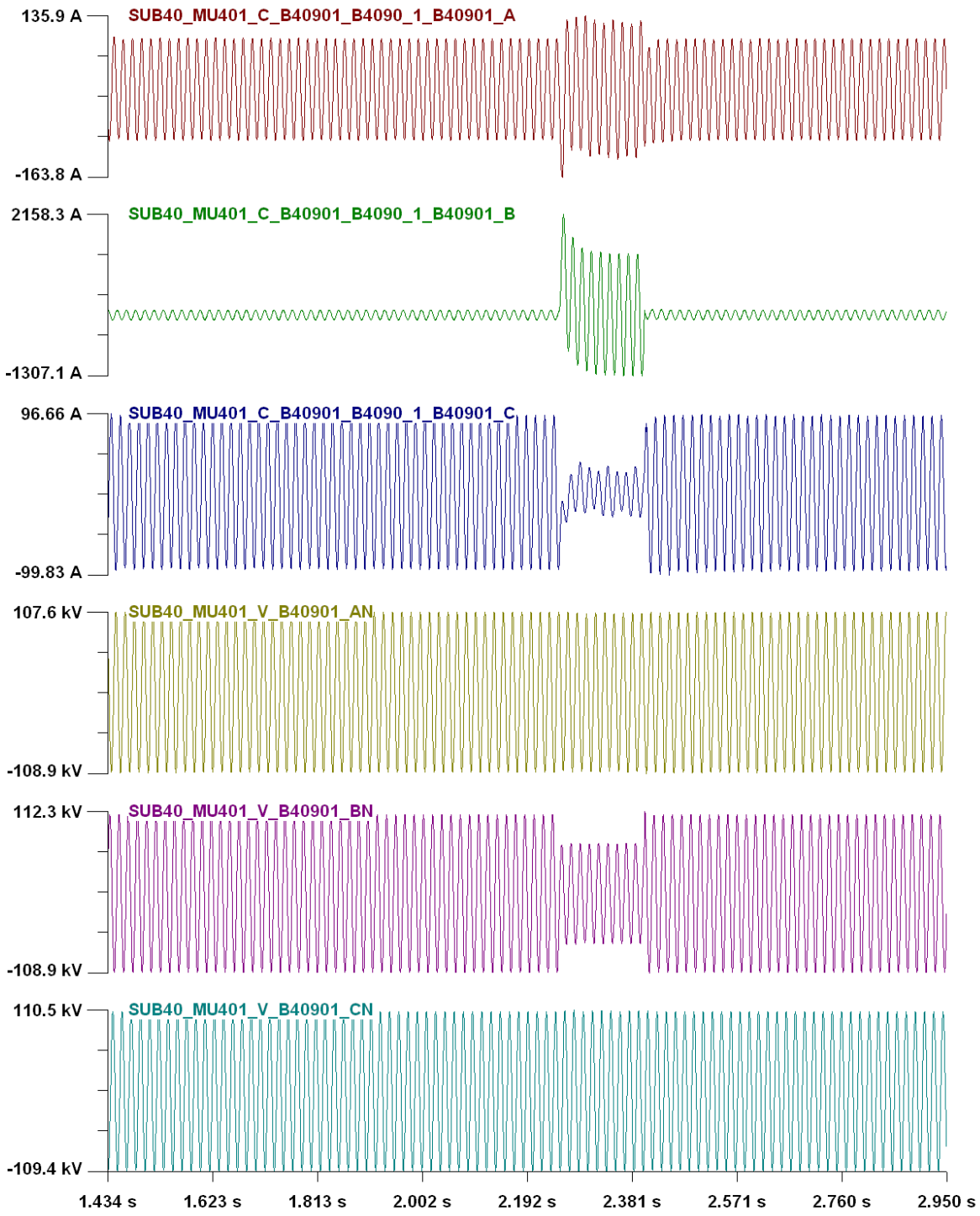


Figure B-2.1E4.3 Currents and Voltage observed in 40PZ1 for subevent 2. Merging Unit 401.

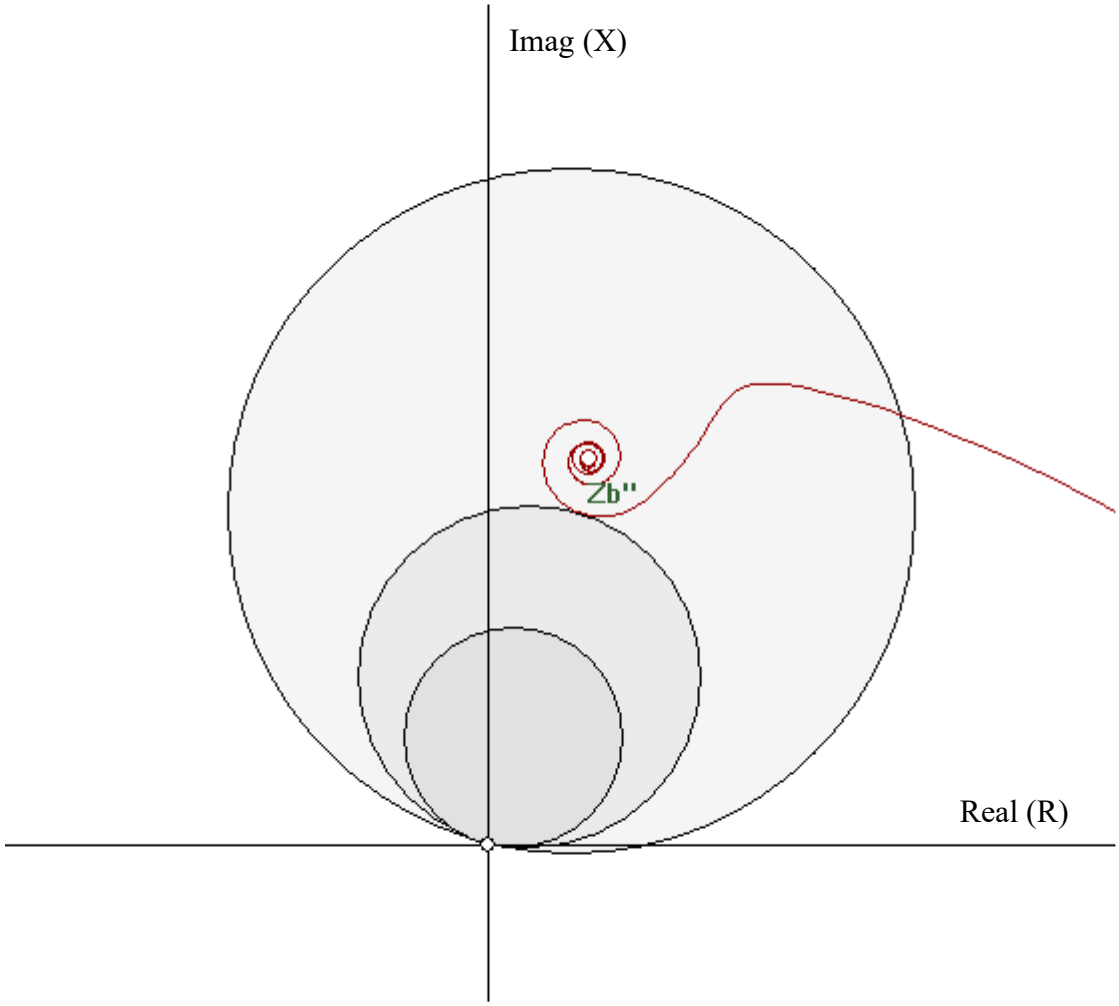


Figure B-2.1E4.4 Distance relay response of 40PZ1 for subevent 2.

Figure B-2.1E4.3 shows the currents and voltages of 40PZ1 for subevent 2, and Figure B-2.1E4.4 shows the performance of this relay in WinXFM.

It can be observed that the relay "sees" the fault in zone 3 (delay of 30 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 30 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Performance of 40PZ2 Protection and Control

For Event 4, we can observe that subevent 1 is an A-G fault happening on the transmission line B4020 to B2040 at 24.75 miles from Substation-40 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B4090 to B9040 at 19.875 miles from Substation-40 which is 75% of the line length of the transmission line B4090 to B9040. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the line B4020 to B2040 for subevent 1.**

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-2 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

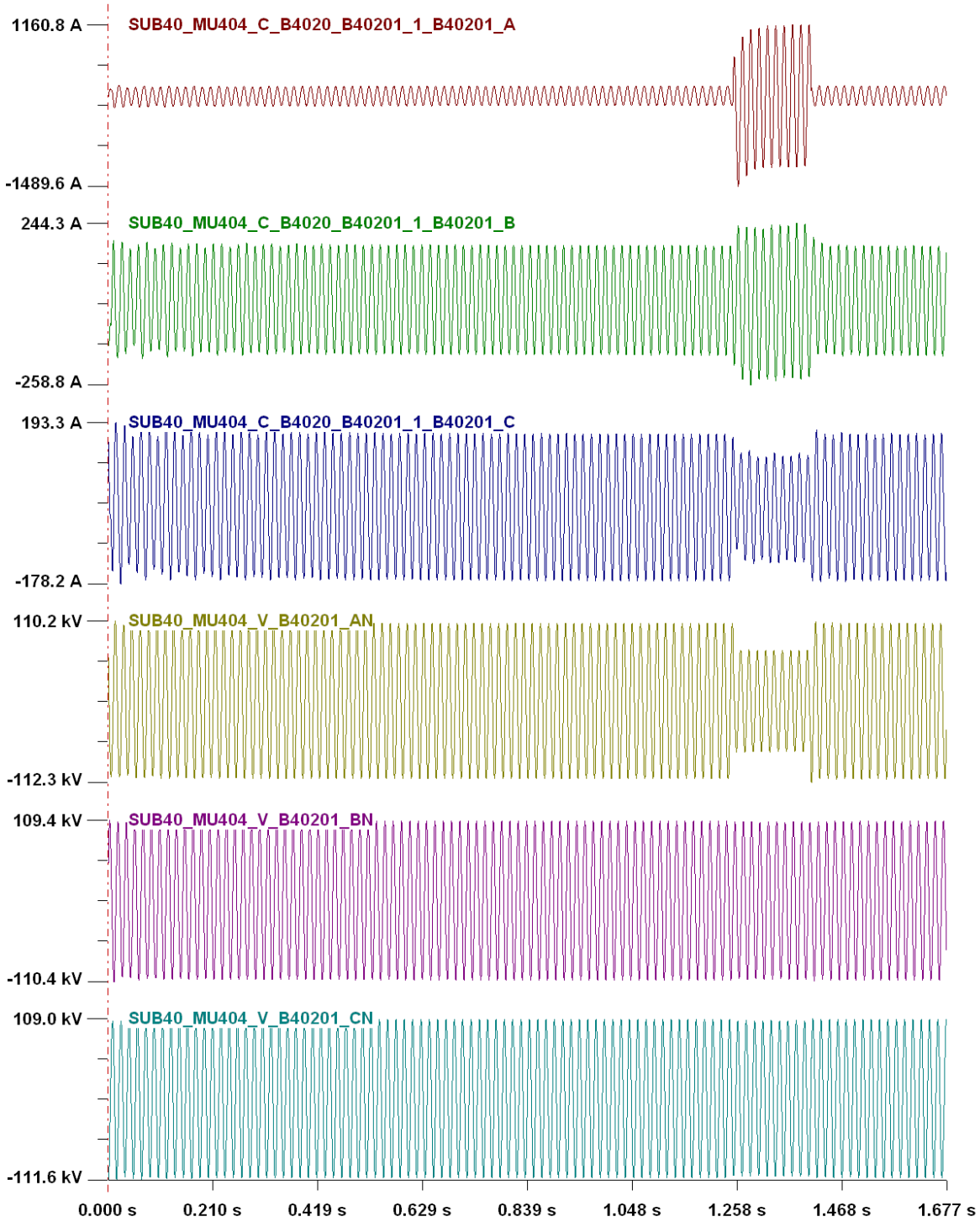


Figure B-2.1E4.5 Currents and Voltage observed in 40PZ2 for subevent 1. Merging Unit 404.

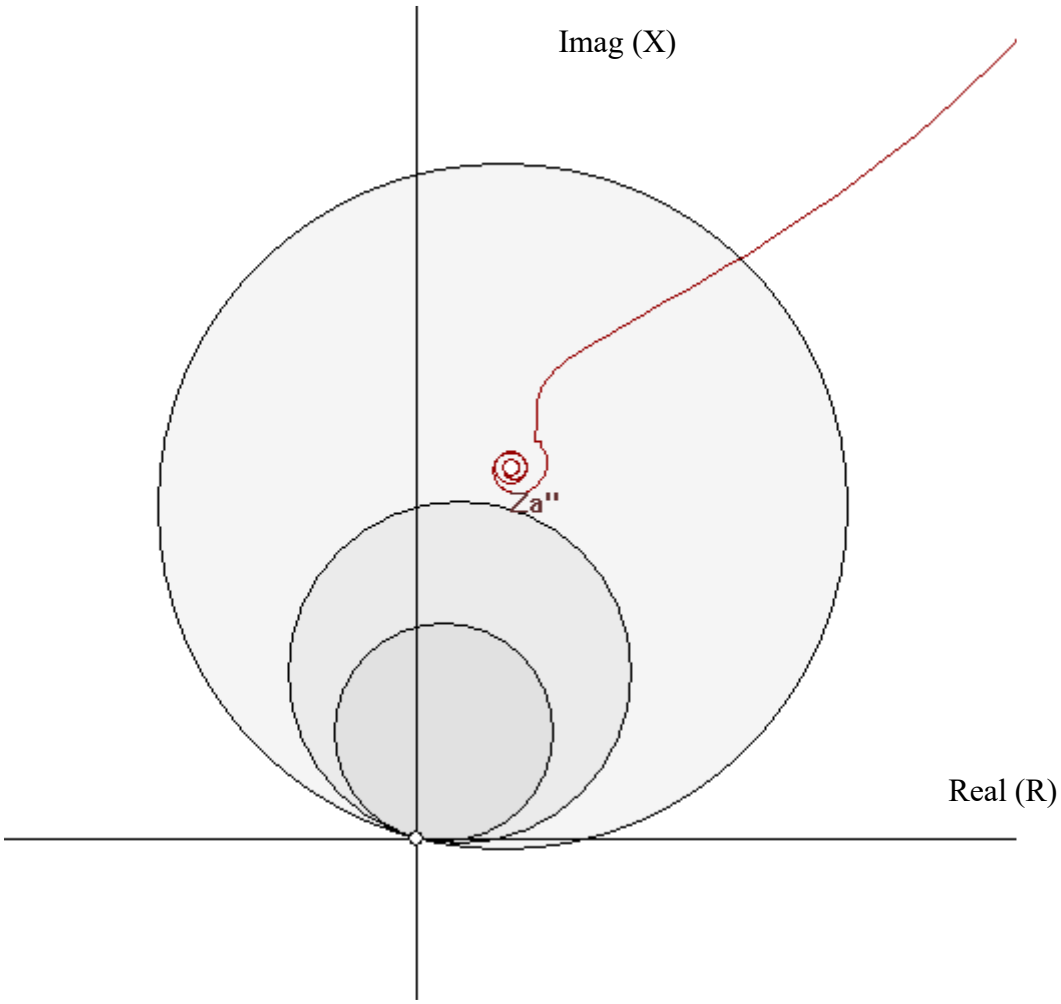


Figure B-2.1E4.6 Distance relay response of 40PZ2 for subevent 1.

Figure B-2.1E4.5 shows the currents and voltages of 40PZ2 for subevent 1, and Figure B-2.1E4.6 shows the performance of this relay in WinXFM.

It can be observed that the relay "sees" the fault in zone 3 (delay of 30 cycles). Note that this relay does not immediately disconnect the line and acts to disconnect the line with a significant delay of 30 cycles. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Subevent-2:

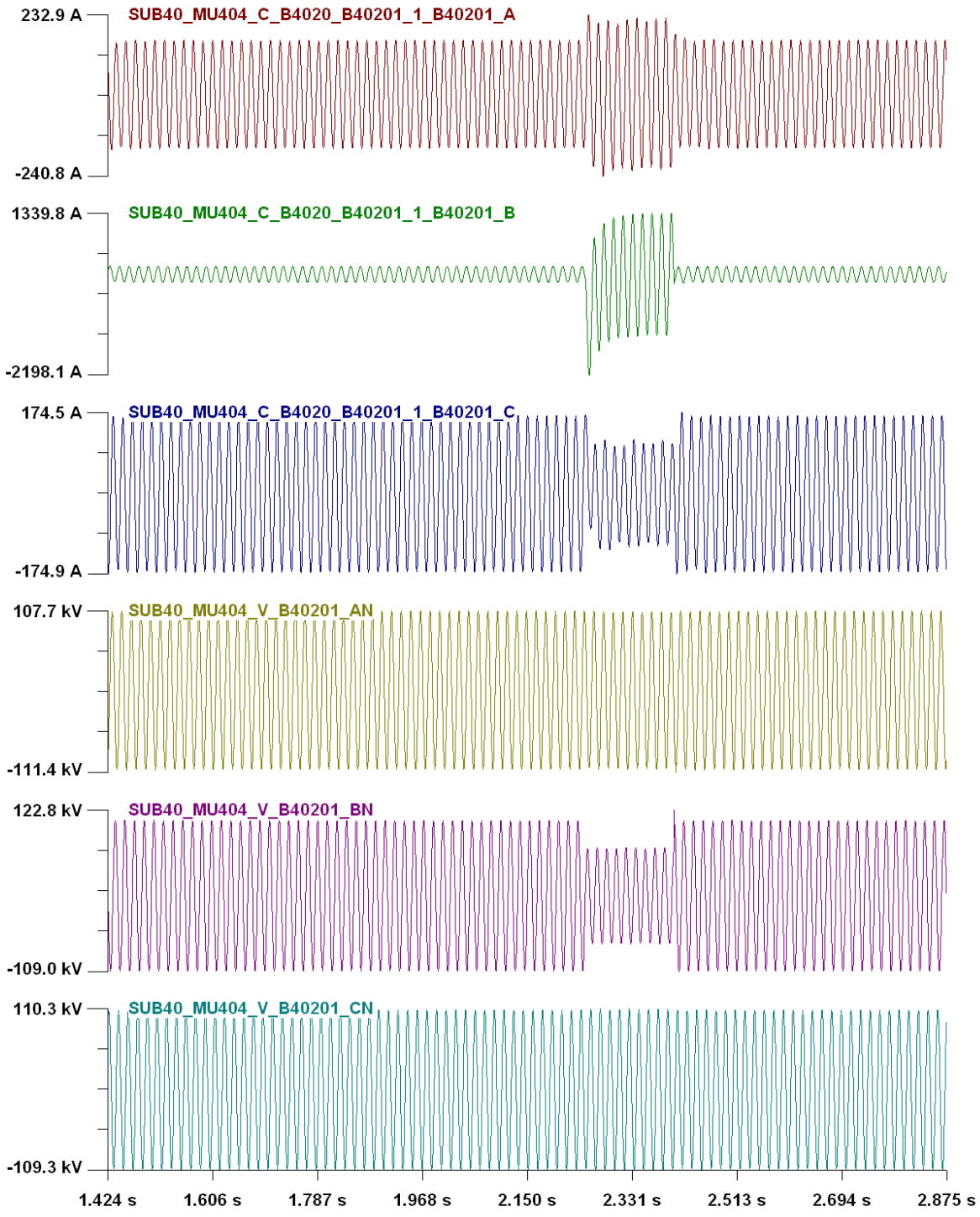


Figure B-2.1E4.7 Currents and Voltage observed in 40PZ2 for subevent 2. Merging Unit 404.

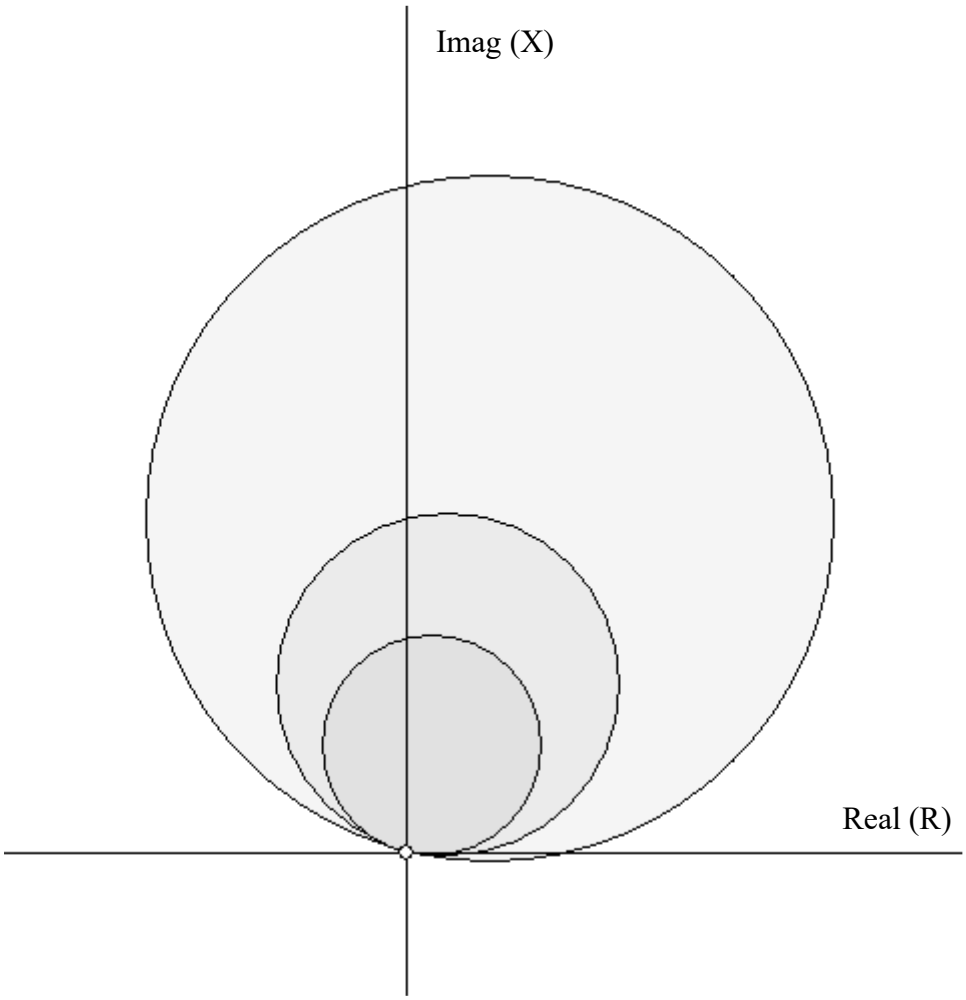


Figure B-2.1E4.8 Distance relay response of 40PZ2 for subevent 2.

Figure B-2.1E4.7 shows the currents and voltages of 40PZ2 for subevent 2, and Figure B-2.1E4.8 shows the performance of the distance relay in WinXFM. Note that this relay will not act to disconnect the line B4020 to B2040. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Event-5:

As described in section B-1.5 Event-5 is an event performed on Substation-70. The performance of the legacy protection and control of some of the protection zones is given below:

Performance of 70PZ1 Protection and Control

For Event 5, there are two subevents as listed in Table B-1.5. We can observe that subevent 1 is an A-G fault happening on the transmission line B7080 to B8070 at 12 miles from Substation-70 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the high side of the transformer XFMR70L to XFMR70H. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B7080 to B8070 for subevent 1**.

As discussed in section 3.6.1 the distance relay requires measurements from the MUs monitoring the voltages and currents within the protection zone to calculate the minimum impedance. The voltages and currents measured by the MUs in protection zone-1 can be seen along with the response of the distance relay for each subevent:

Subevent-1:

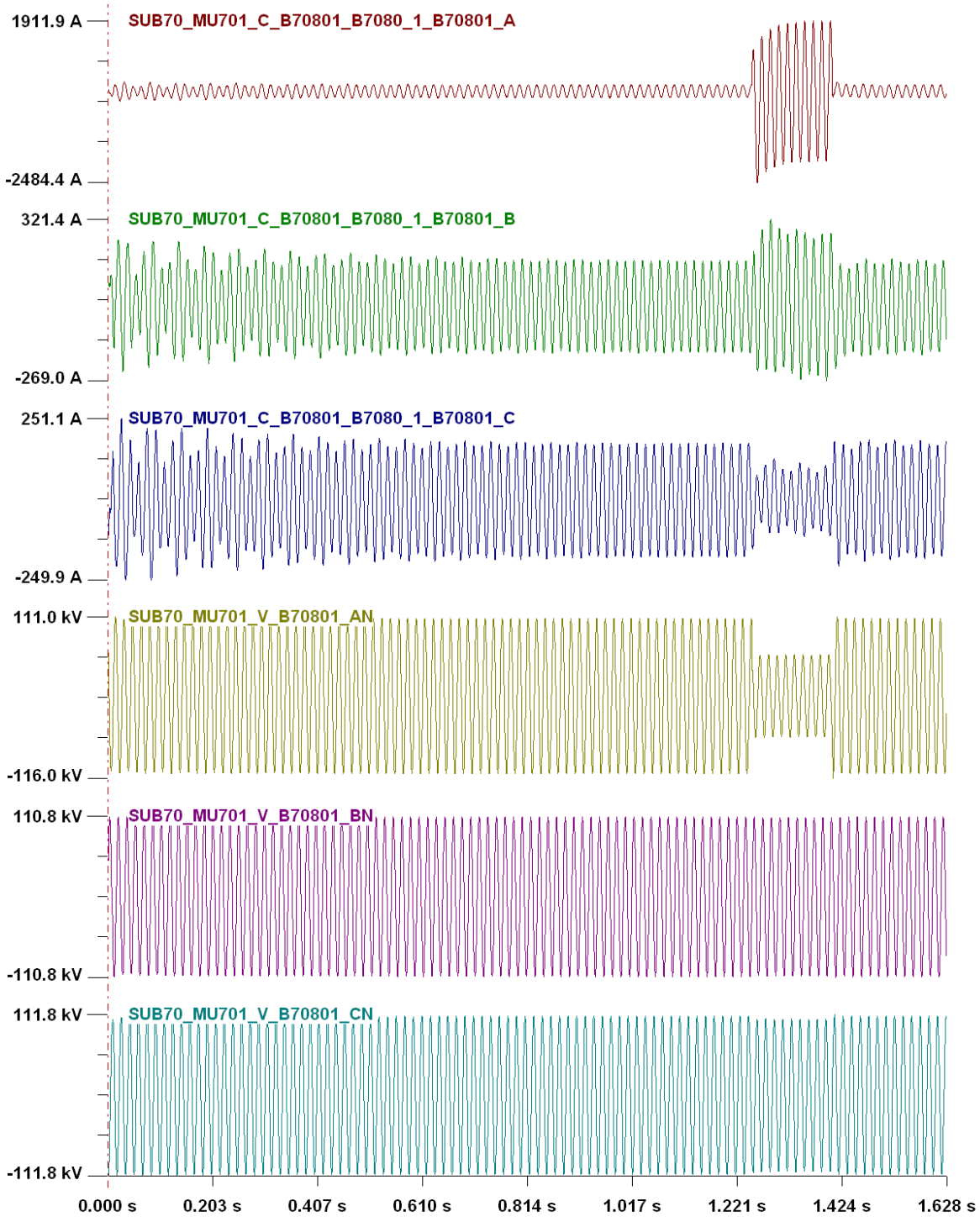


Figure B-2.1E5.1 Currents and Voltage observed in 70PZ1 for subevent 1. Merging Unit 701.

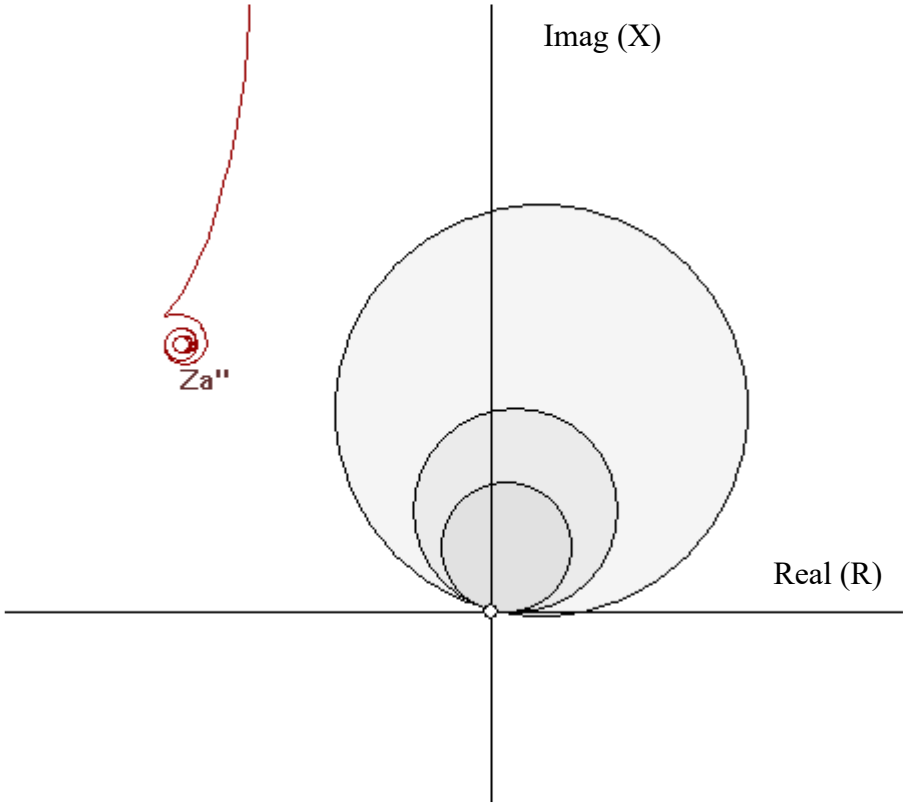


Figure B-2.1E5.2 Distance relay response of 70PZ1 for subevent 1.

Figure B-2.1E5.1 shows the currents and voltages of 70PZ1 for subevent 1, and Figure B-2.1E5.2 shows the performance of the distance relay in WinXFM.

It can be observed that the relay does not even see the fault in any zone and this relay does not act to disconnect the line. This is an incorrect action for this relay and the relay misoperated.

The root cause of this misoperation is that the IBRs suppress the negative- and zero-sequence components of the fault current. As a result, the distance relay, which relies on predefined "setting," interprets the fault currents as if they originated from a conventional generator-based system that contributes significantly to fault currents, leading to incorrect operation.

Subevent-2:

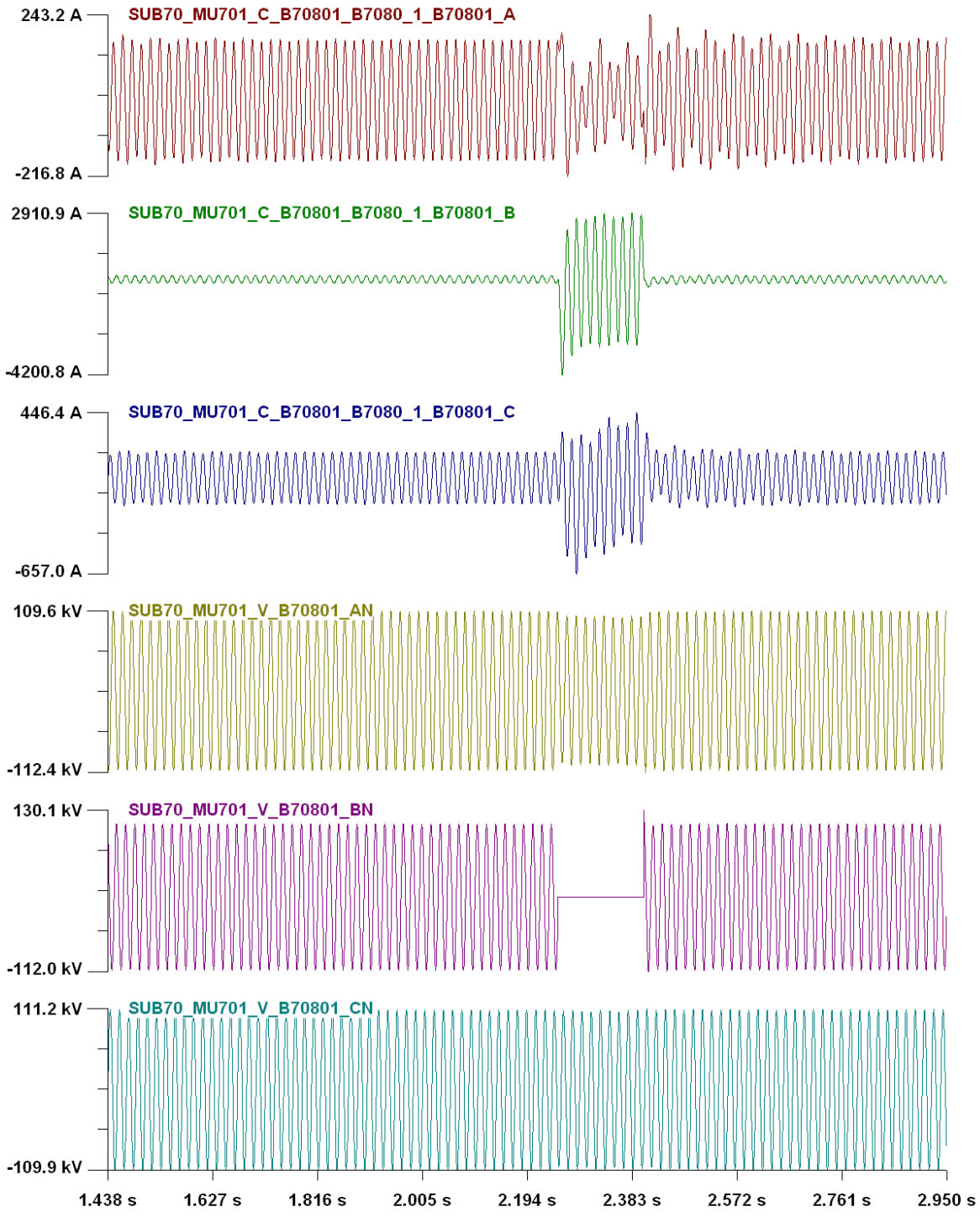


Figure B-2.1E5.3 Currents and Voltage observed in 70PZ1 for subevent 2. Merging Unit 701.

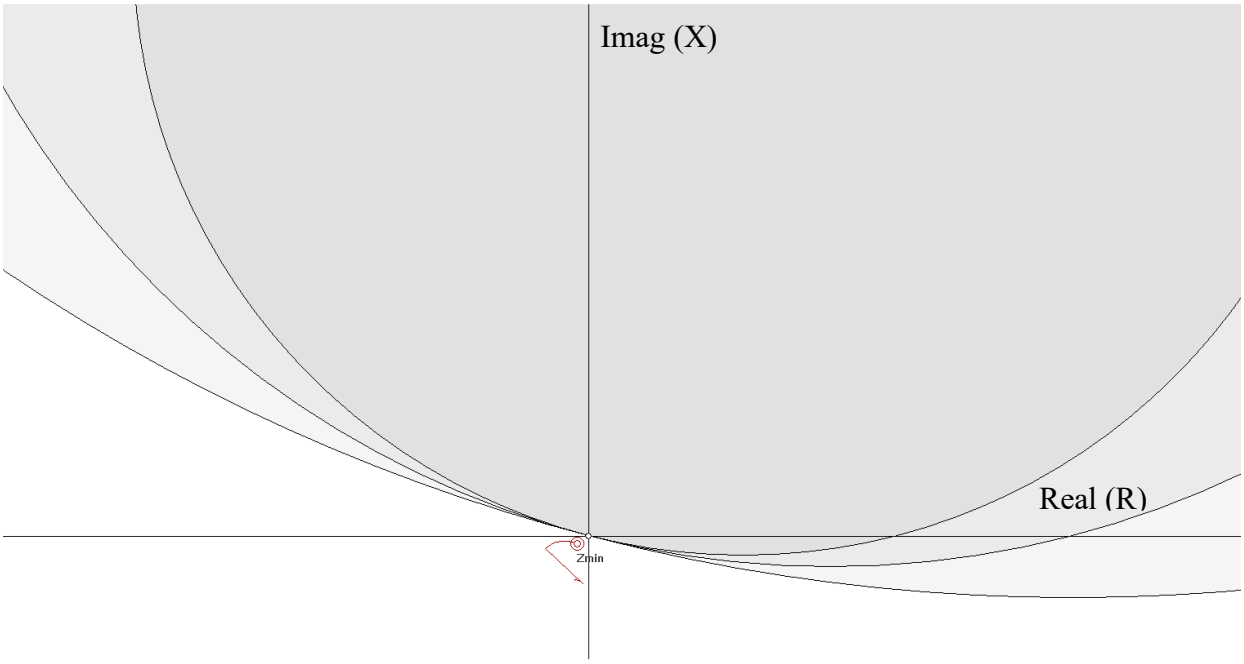


Figure 3.60 Distance relay response of 70PZ1 for subevent 2.

Figure B-2.1E5.4 shows the currents and voltages of 70PZ1 for subevent 2, and Figure 3.60 shows the performance of this relay in WinXFM. Note that this relay will not act to disconnect the line. This is the correct action for this relay.

Note that in this case the relay operated correctly.

Performance of 70PZ2 Protection and Control

For Event 5, we can observe that subevent 1 is an A-G fault happening on the transmission line B7080 to B8070 at 12 miles from Substation-70 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the high side of the transformer XFMR70L to XFMR70H. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the transformer XFMR70H to XFMR70L for subevent 2**.

The voltages and currents measured by the MUs in protection zone-2 can be seen along with the response of the differential relay for each subevent:

Subevents-1 and 2:

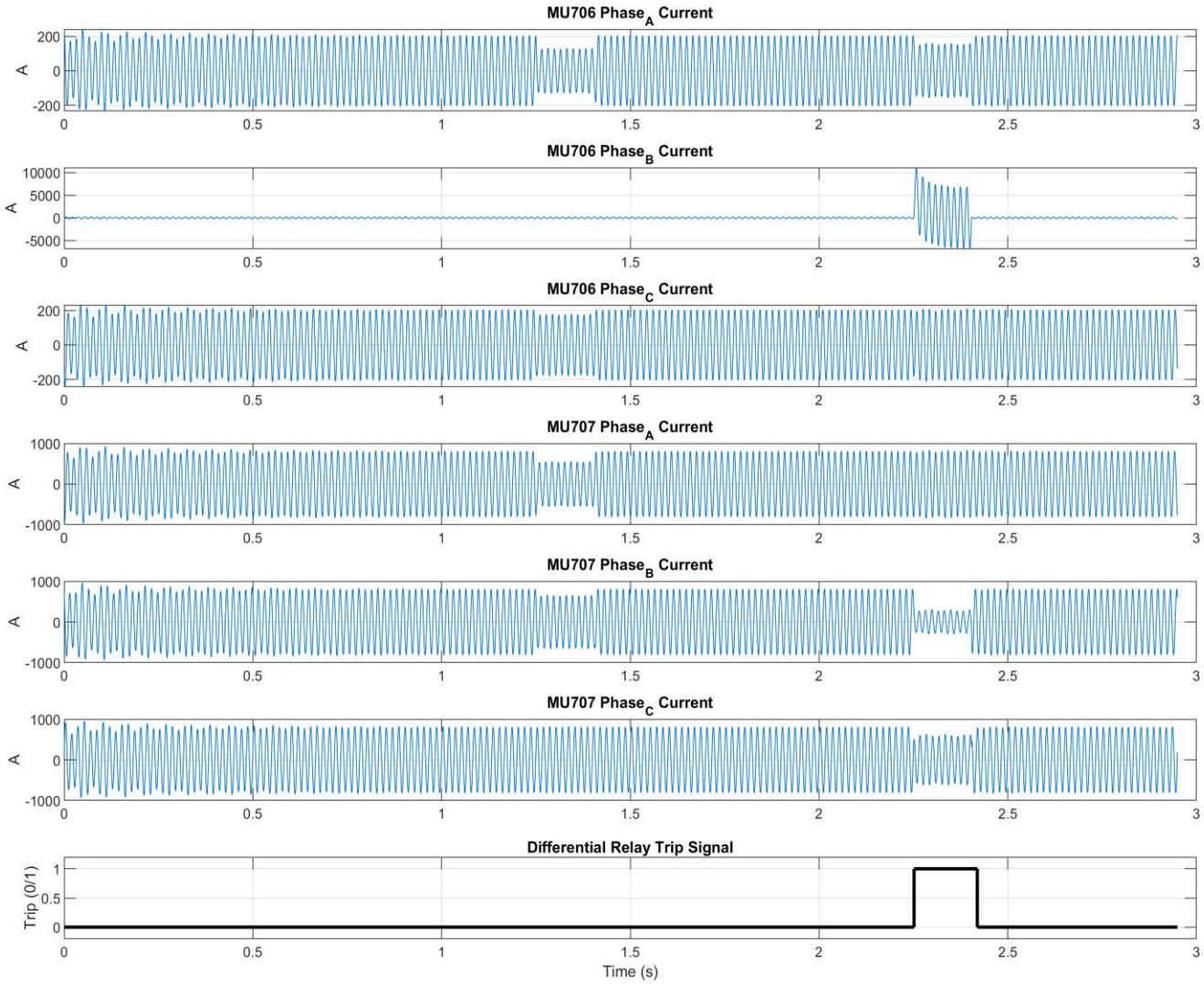


Figure B-2.1E5.5 Differential relay response for protection zone 70PZ2 for subevents 1 and 2.

Figure B-2.1E5.5 shows the differential relay response for protection zone 70PZ2 for subevents 1 and 2. It can be noted that the relay does not generate a trip signal for subevent 1. This is the correct action for this relay.

For subevent 2 the differential relay generates a trip signal to open the circuit breakers protecting the transformer XFMR70L to XFMR70H. This is the correct action for this relay.

Note that in this case the relay operated correctly.

B-2.2. Response of Estimation Based Protection and Control Systems

We analyze the response of the Estimation based protection system within selected protection zones, focusing on the protective relays installed at the substations. Each protection zone is equipped with a corresponding relay, and the performance of selected relays is documented to assess whether they operate as expected or result in a mis-operation. In cases of mis-operation, the root cause is identified and examined.

Event-1:

As described in section B-1.1 Event-1 is an event performed on Substation-170. The performance of the estimation-based protection and control of some of the protection zones is given below:

Performance of Estimation-based Protection and Control monitoring LineB170180-B180170

For Event 1, there are multiple subevents as listed in Table B-1.1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180 to B180170. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line for subevents 4 and 5**.

Subevent-1:

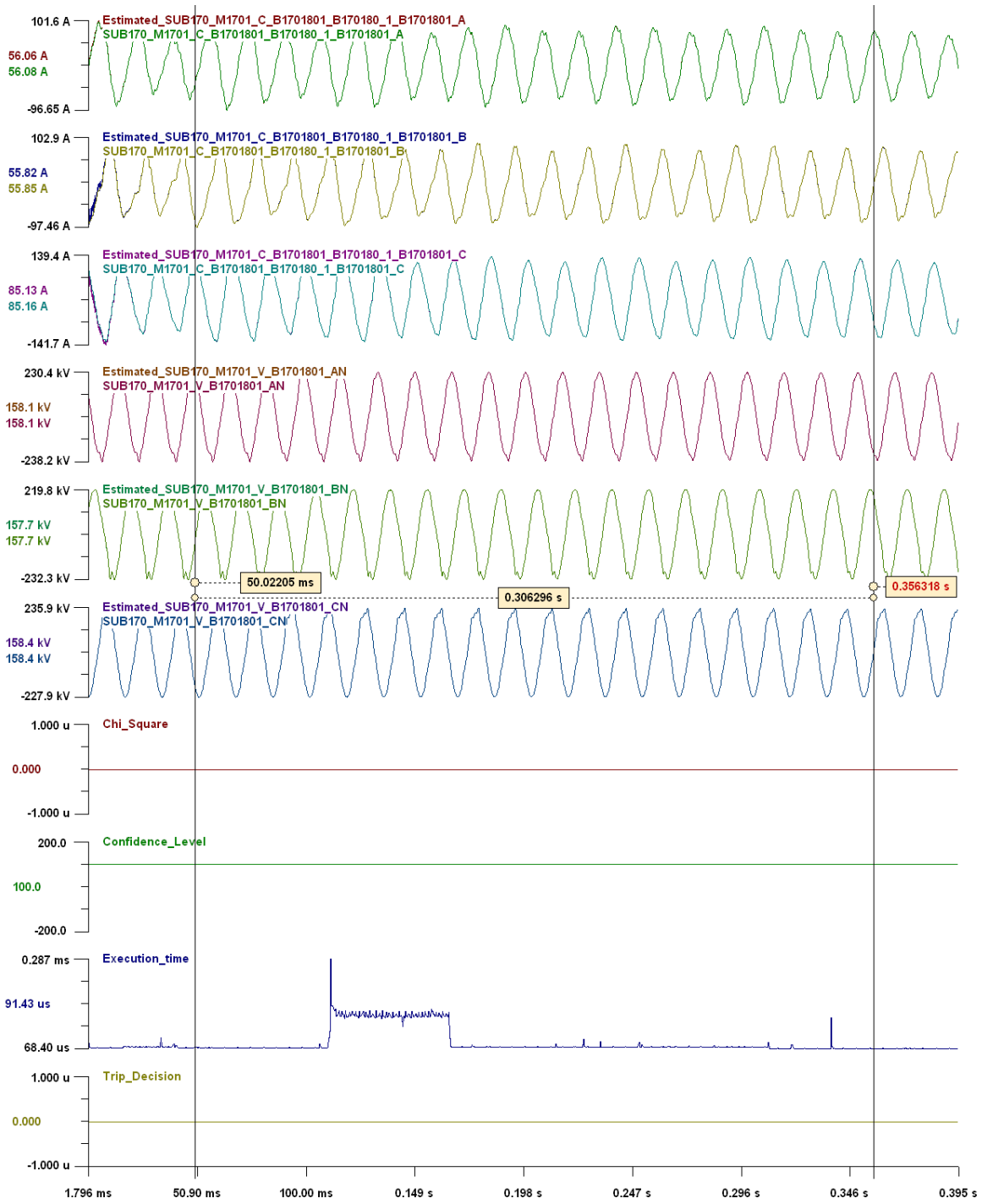


Figure B-2.2E1.1 EBP relay response monitoring Line B170180 to B180170 for subevent 1.

Figure B-2.2E1.1 shows the response of the EBP relay monitoring the line B170180 to B180170 for subevent 1. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP

relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal (detailed explanation of the working of EBP relay is given in the reference [25] and [29]). Therefore, this relay will not act to disconnect the line B170180 to B180170. This is the correct action for this relay.

Subevent-2:

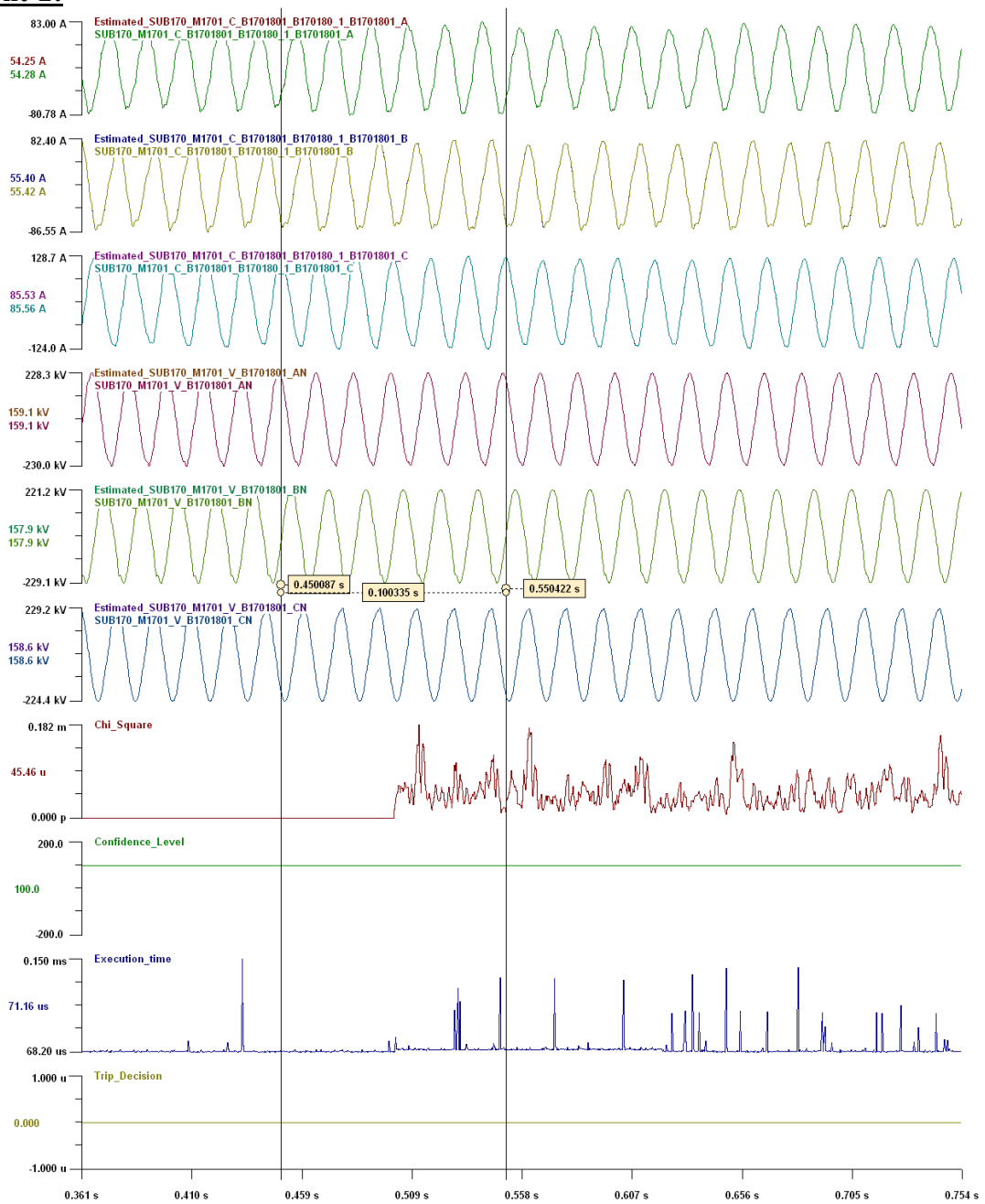


Figure B-2.2E1.2 EBP relay response monitoring Line B170180 to B180170 for subevent 2.

Figure B-2.2E1.2 shows the response of the EBP relay monitoring the line B170180 to B180170 for subevent 2. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170180 to B180170. This is the correct action for this relay.

Subevent-3:

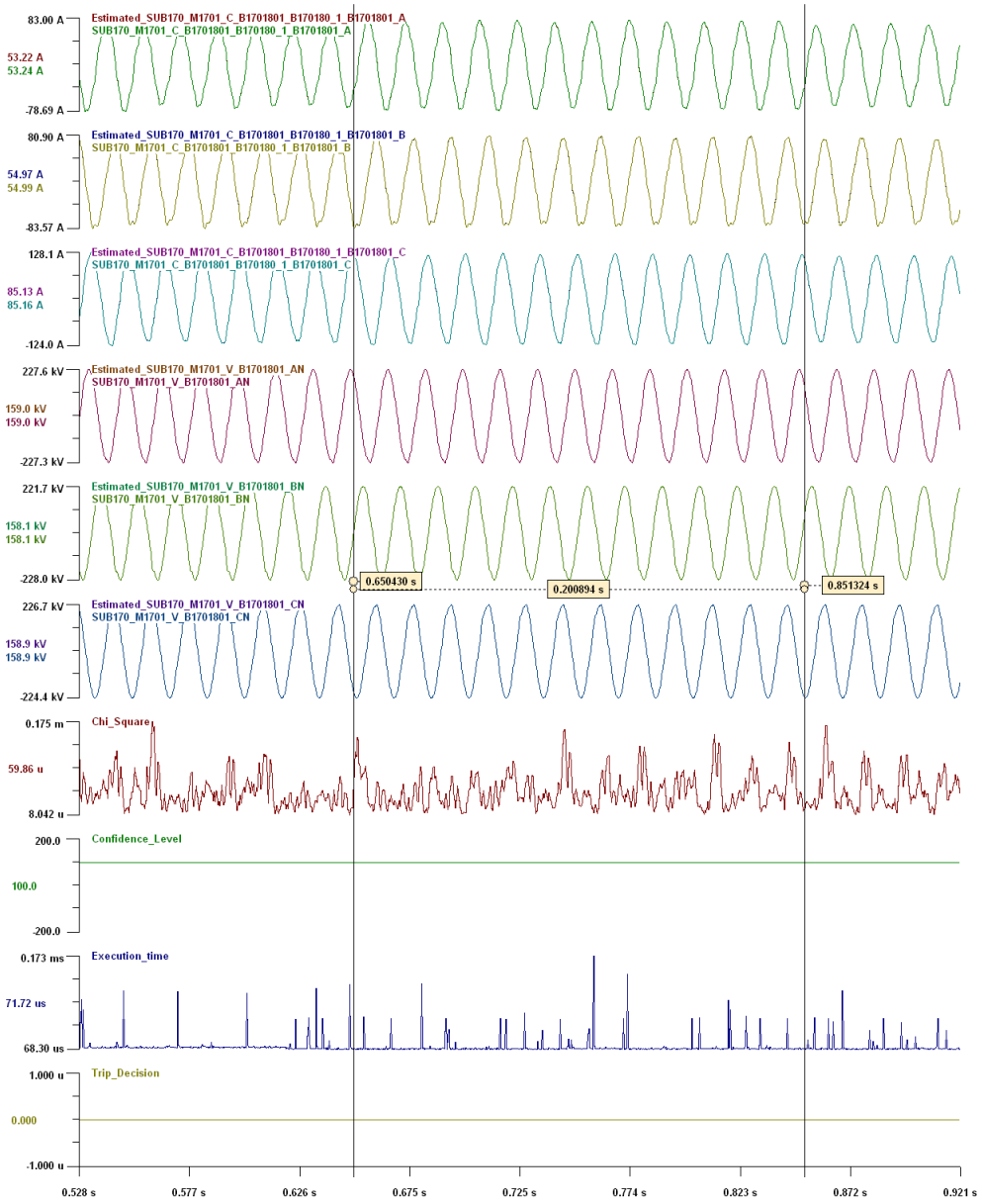


Figure B-2.2E1.3 EBP relay response monitoring Line B170180 to B180170 for subevent 3.

Figure B-2.2E1.3 shows the response of the EBP relay monitoring the line B170180 to B180170 for subevent 3. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170180 to B180170. This is the correct action for this relay.

Subevent-4:

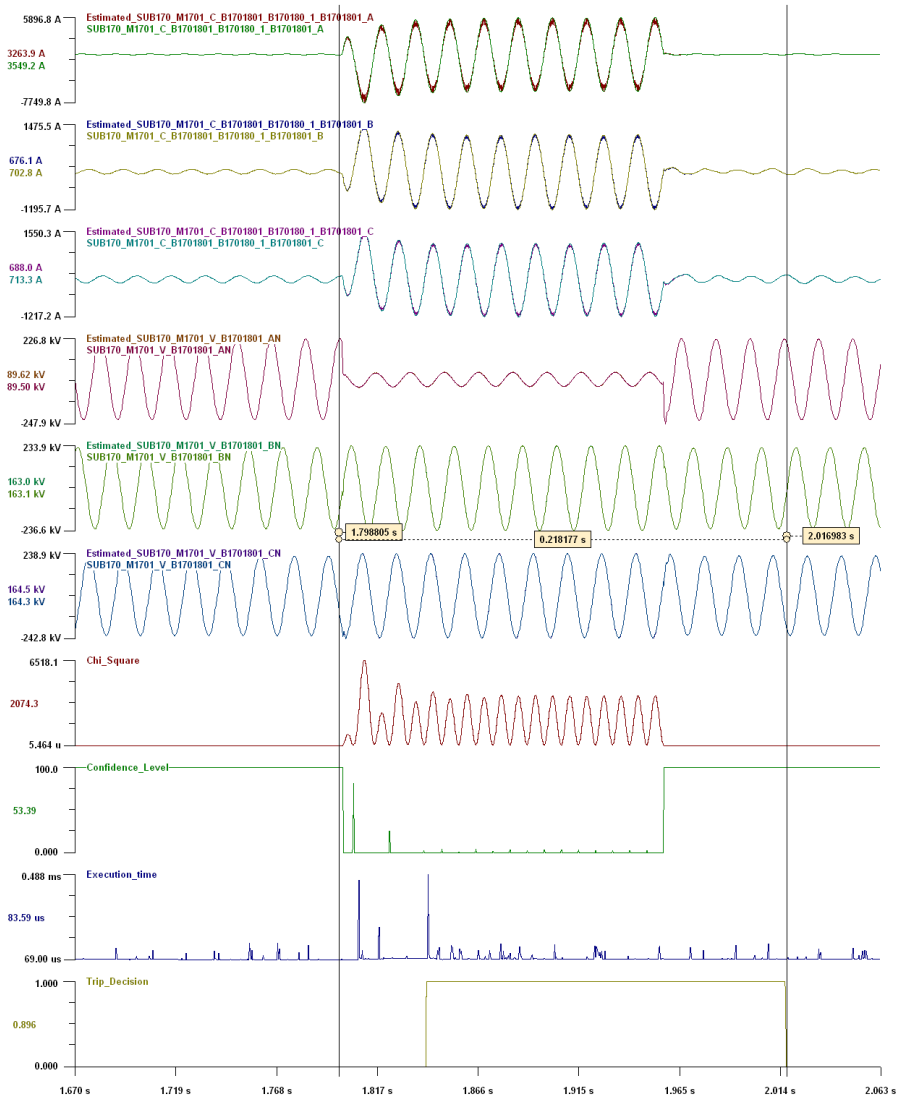


Figure B-2.2E1.4 EBP relay response monitoring Line B170180 to B180170 for subevent 4.

Figure B-2.2E1.4 shows the response of the EBP relay monitoring the line B170180 to B180170 for subevent 4. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line B170180 to B180170. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Subevent-5:

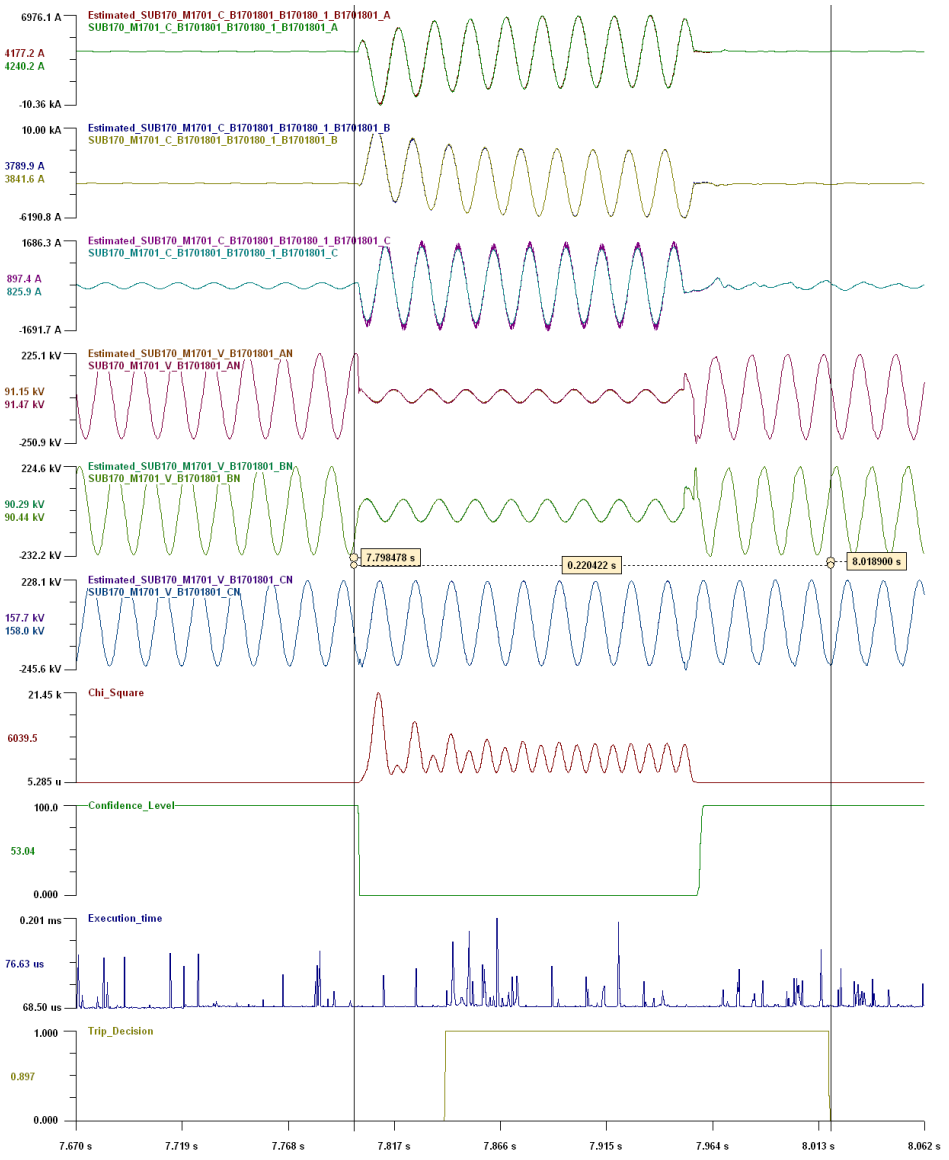


Figure B-2.2E1.5 EBP relay response monitoring Line B170180 to B180170 for subevent 5.

Figure B-2.2E1.5 shows the response of the EBP relay monitoring the line B170180 to B180170 for subevent 5. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line B170180 to B180170. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Performance of Estimation-based Protection and Control monitoring LineB170160-B160170

For Event 1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180 to B180170. In this case the correct action of the protection and control system is that **the protective relay for protection zone 2 does not operate**.

Subevent-1:

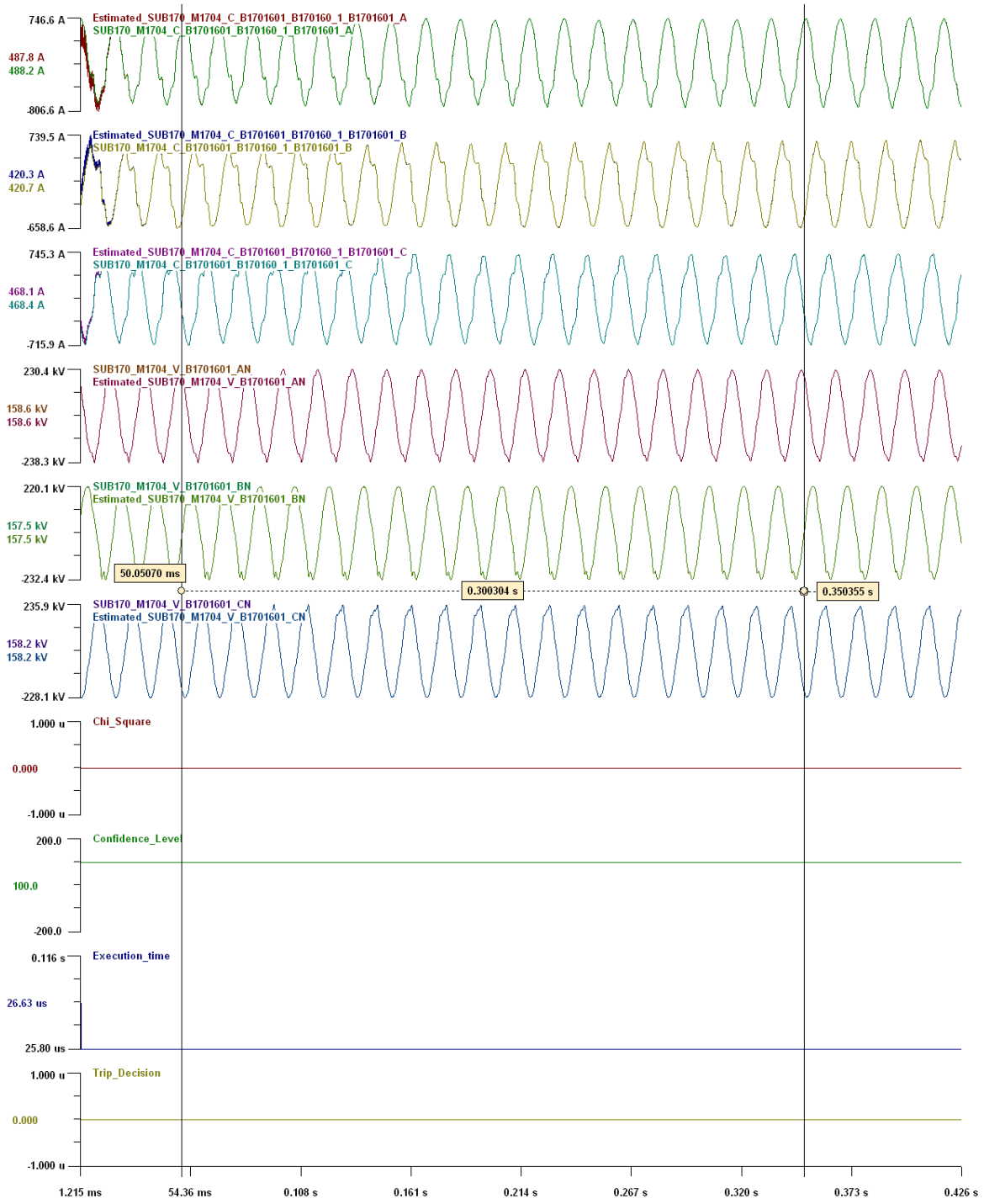


Figure B-2.2E1.6 EBP relay response monitoring Line B170160 to B160170 for subevent 1.

Figure B-2.2E1.6 shows the response of the EBP relay monitoring the line B170160 to B160170 for subevent 1. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Subevent-2:

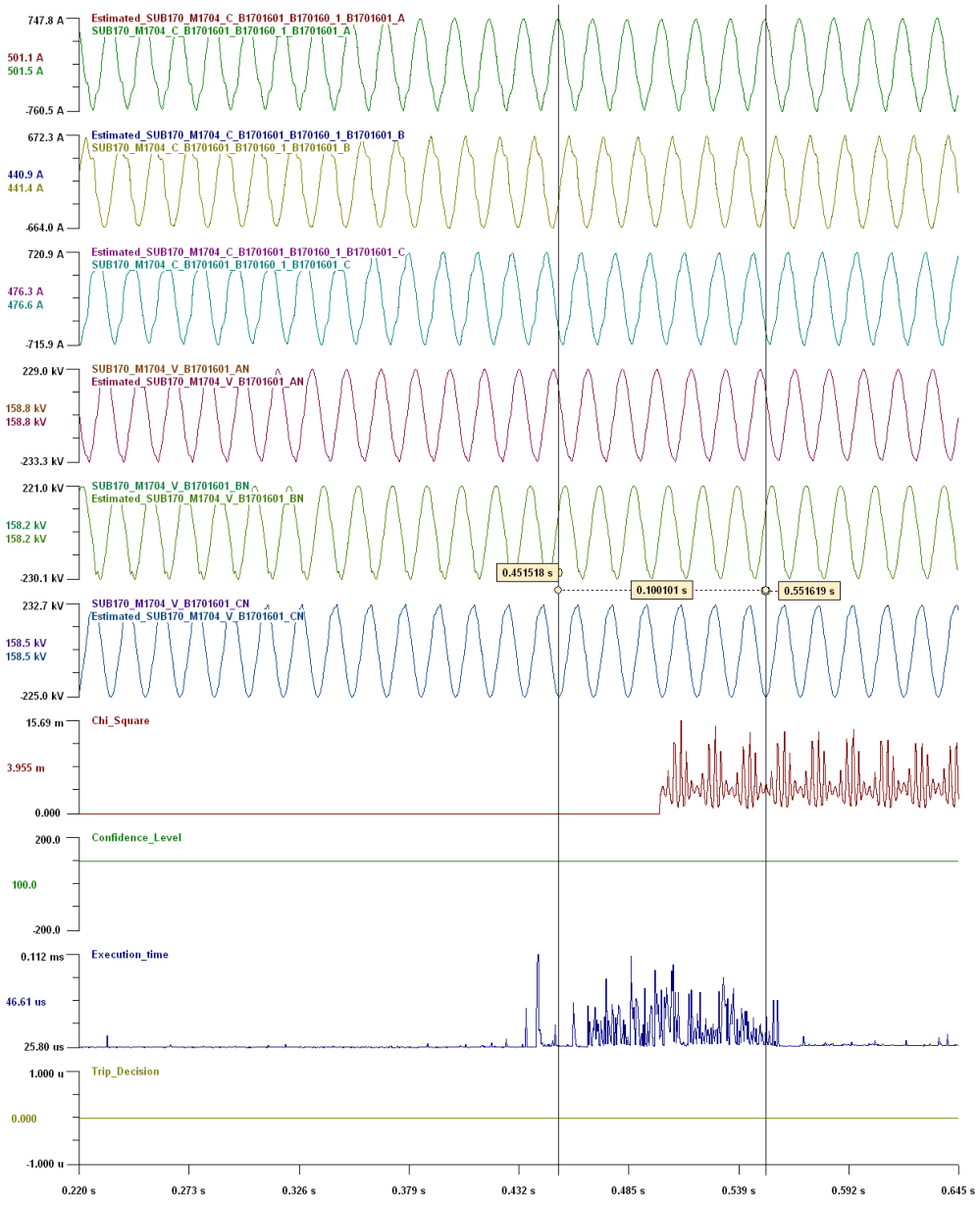


Figure B-2.2E1.7 EBP relay response monitoring Line B170160 to B160170 for subevent 2.

Figure B-2.2E1.7 shows the response of the EBP relay monitoring the line B170160 to B160170 for subevent 2. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Subevent-3:

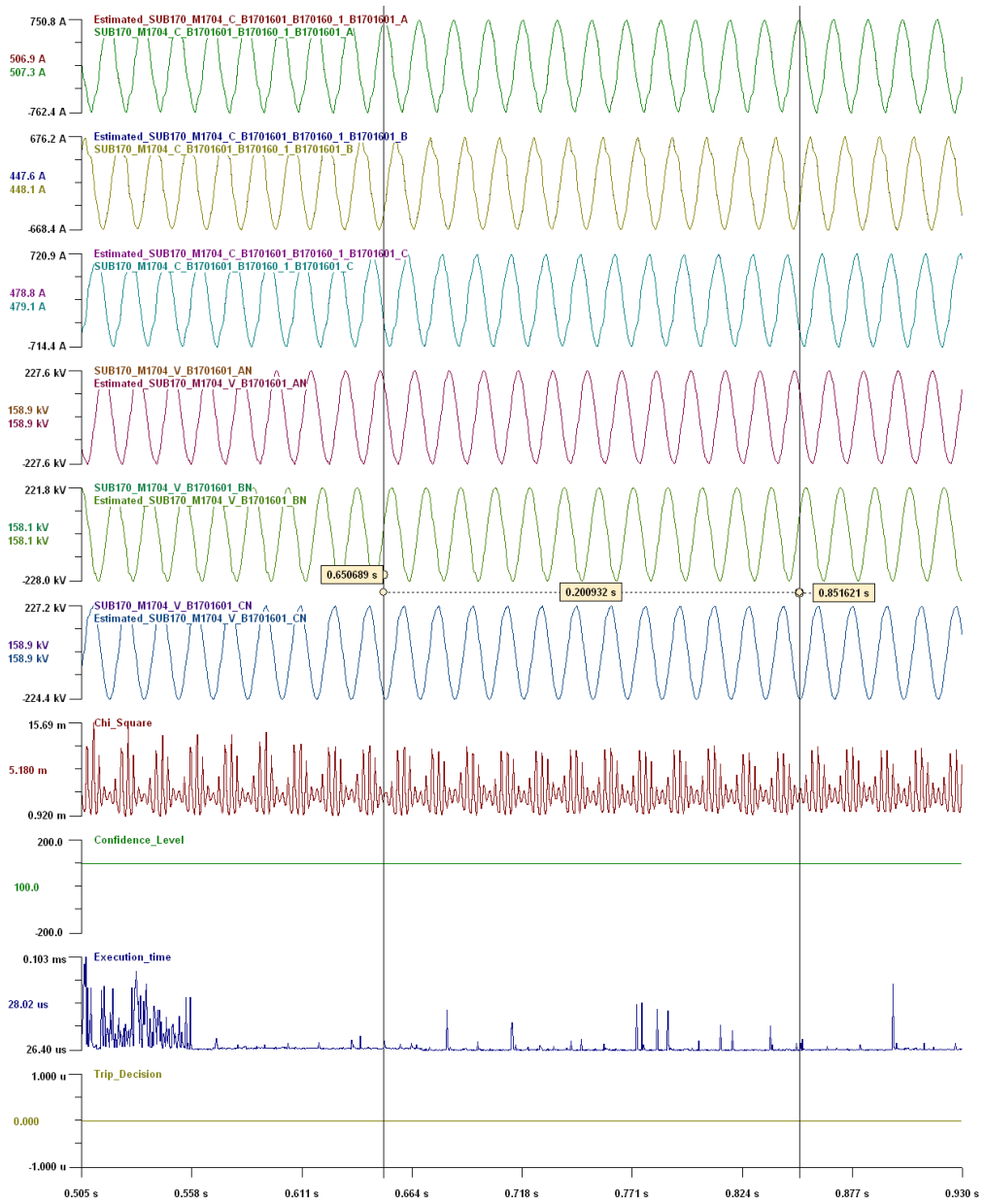


Figure B-2.2E1.8 EBP relay response monitoring Line B170160 to B160170 for subevent 3.

Figure B-2.2E1.8 shows the response of the EBP relay monitoring the line B170160 to B160170 for subevent 3. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Subevent-4:

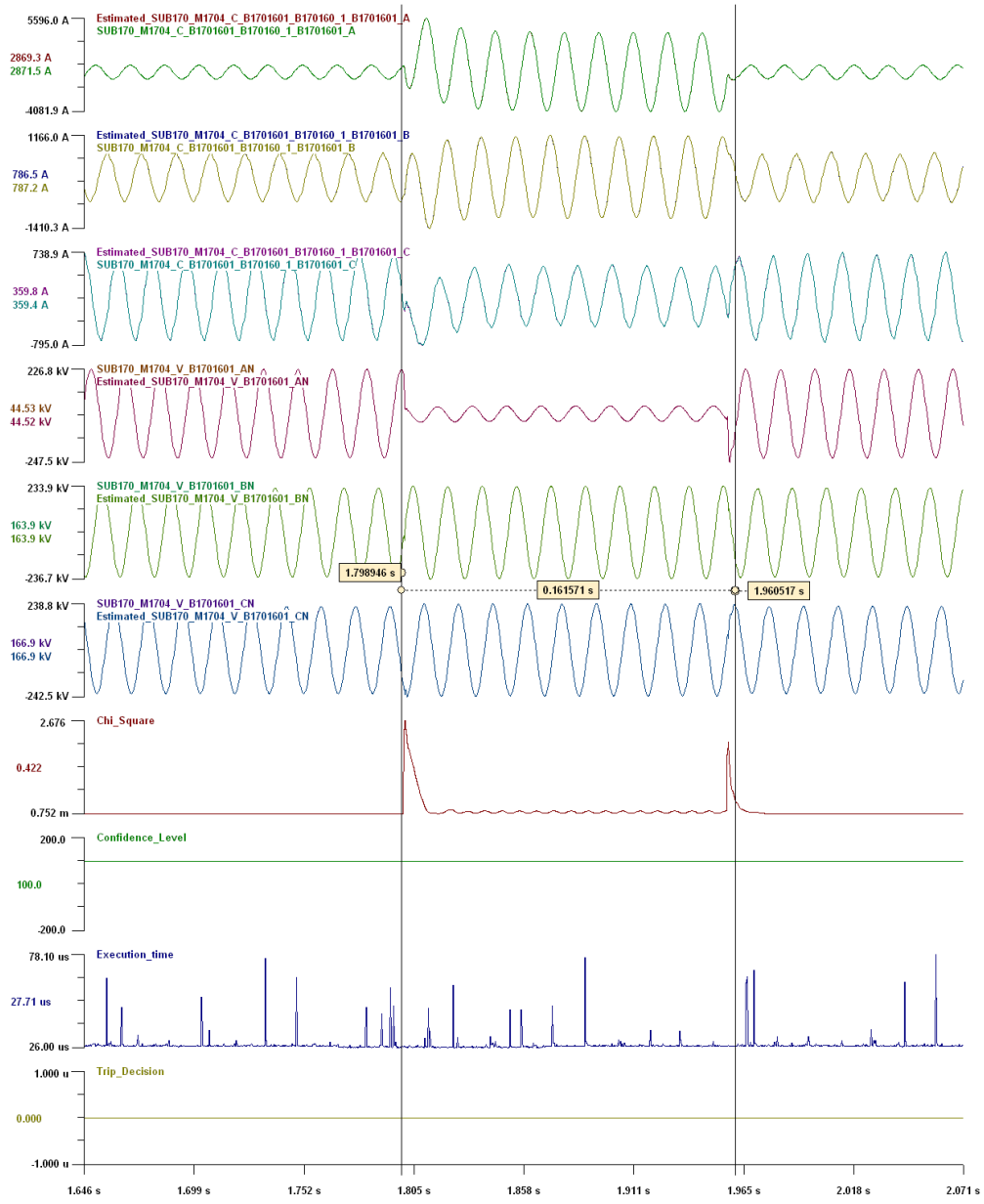


Figure B-2.2E1.9 EBP relay response monitoring Line B170160 to B160170 for subevent 4.

Figure B-2.2E1.9 shows the response of the EBP relay monitoring the line B170160 to B160170 for subevent 4. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Subevent-5:

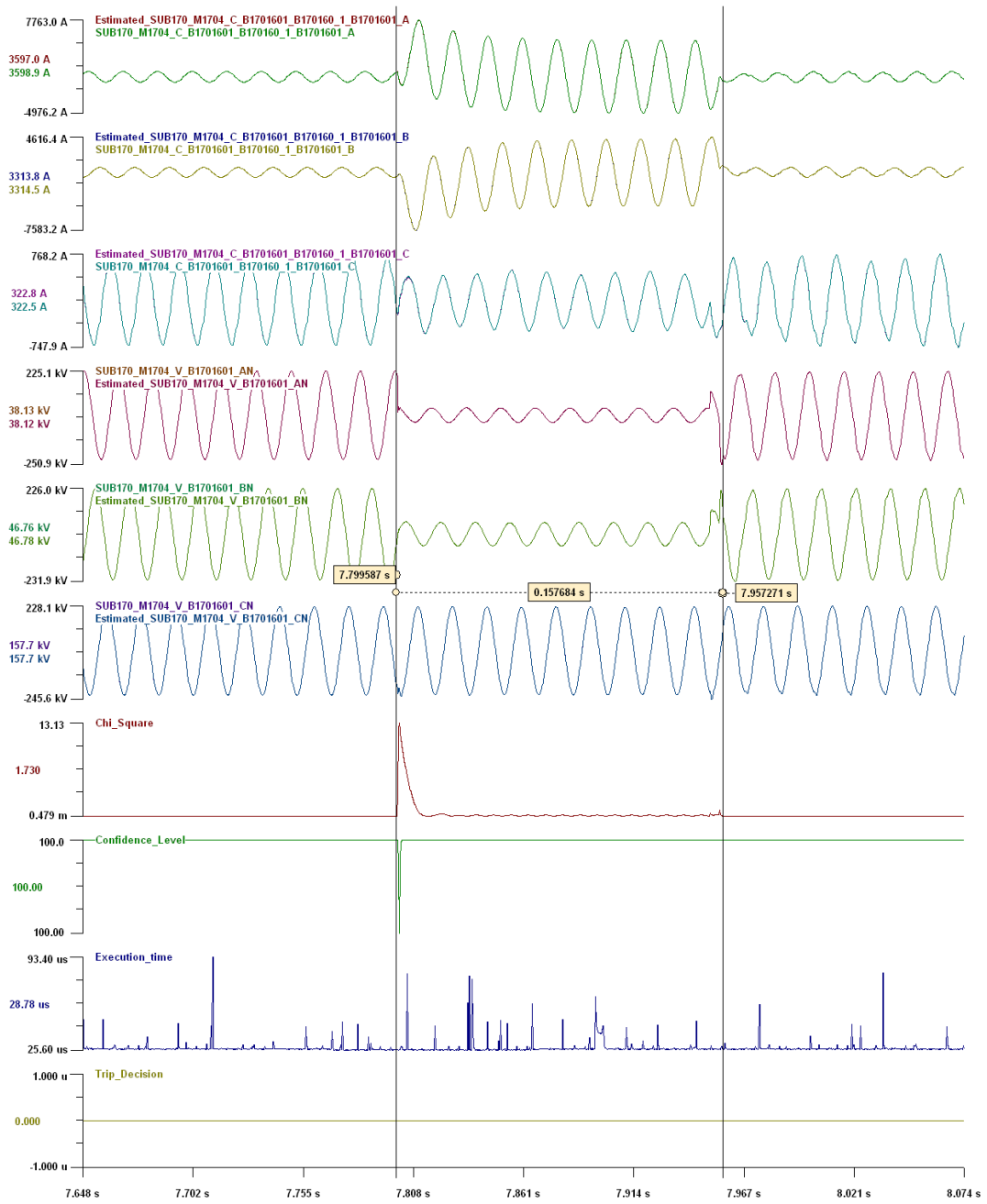


Figure B-2.2E1.10 EBP relay response monitoring Line B170160 to B160170 for subevent 5.

Figure B-2.2E1.10 shows the response of the EBP relay monitoring the line B170160 to B160170 for subevent 5. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal (detailed explanation of the working of EBP relay is given in the reference [16]). Therefore, this

relay will not act to disconnect the line B170160 to B160170. This is the correct action for this relay.

Performance of Estimation-based Protection and Control monitoring LineB170220-B220170

For Event 1, we can observe that the subevents occur on the transmission line B170180 to B180170. It can also be observed that events 1 through 3 are load changes which is a normal occurrence within the power system, the **protective relays should not act for these subevents**.

For subevents 4 and 5 there is a single-line to ground fault happening on the transmission line B170180 to B180170 at 5 miles from Substation-170 which is 50% of the line length of the transmission line B170180 to B180170 and double-line to ground fault happening on the line at 7.5 miles from Substation-170 which is 75% of the line length of the transmission line B170180 to B180170. In this case the correct action of the protection and control system is that **the protective relay for protection zone 3 does not operate**.

Subevent-1:

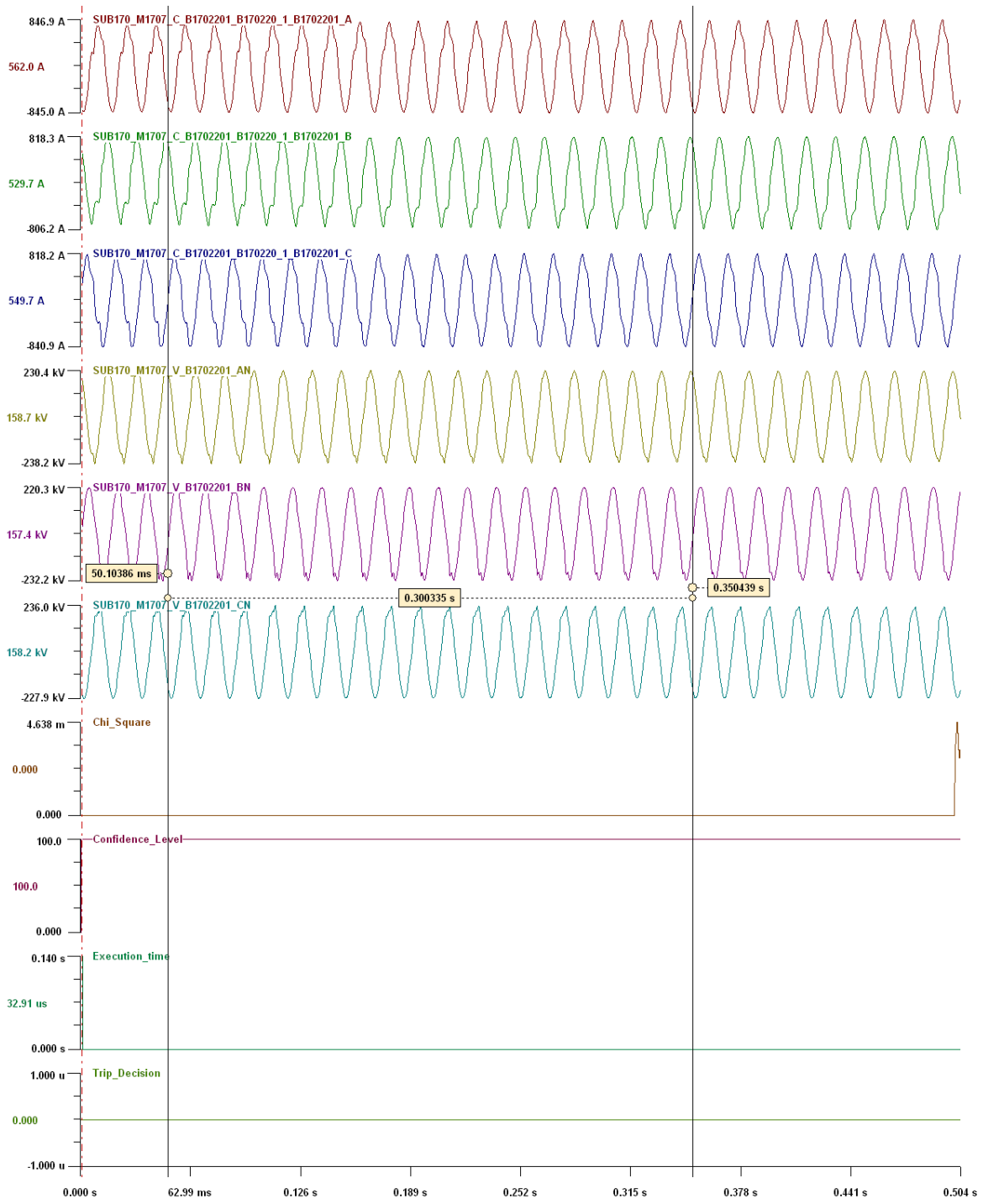


Figure B-2.2E1.11 EBP relay response monitoring Line B170220 to B220170 for subevent 1.

Figure B-2.2E1.11 shows the response of the EBP relay monitoring the line B170220 to B220170 for subevent 1. We can observe that the confidence level generated by the state estimator of the

EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Subevent-2:

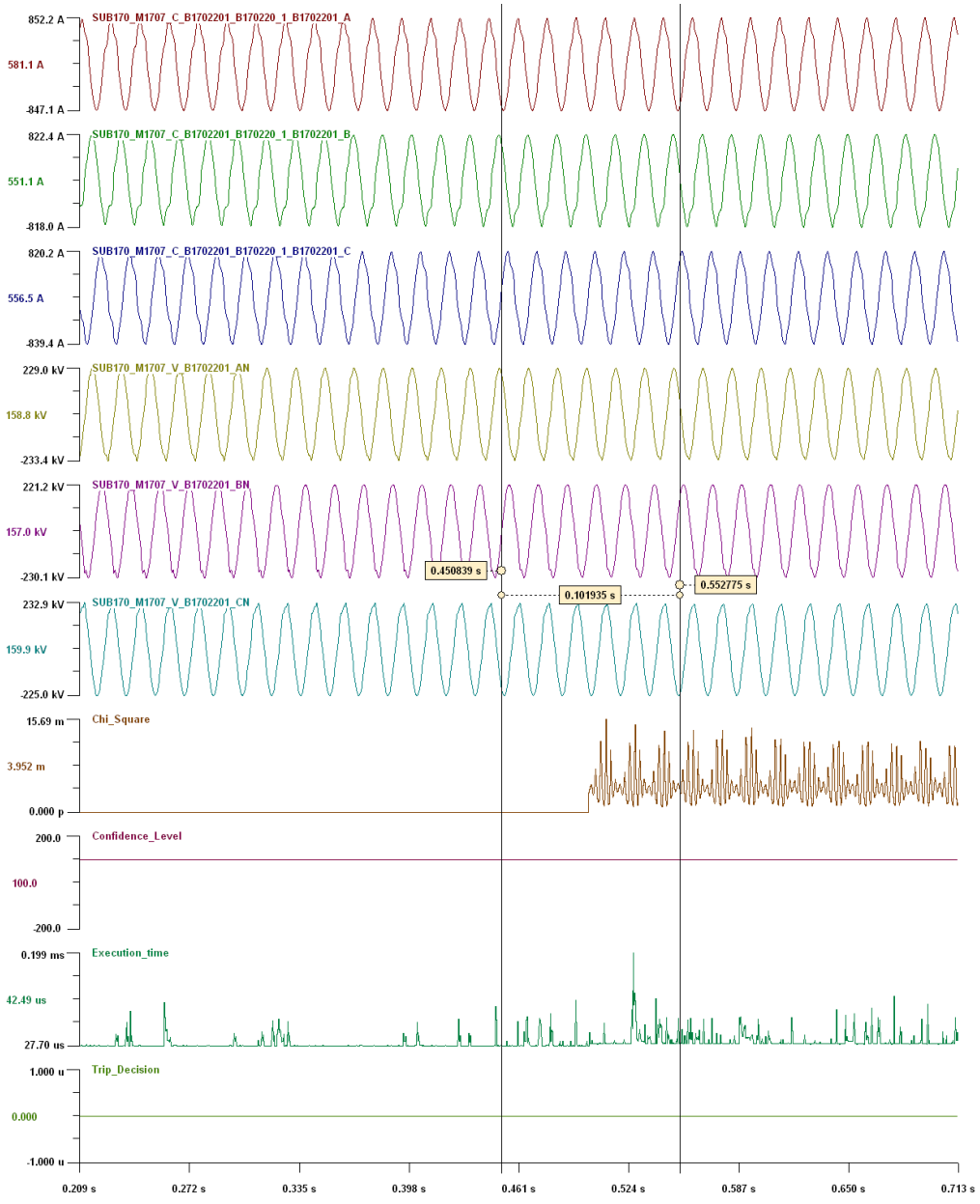


Figure B-2.2E1.12 EBP relay response monitoring Line B170220 to B220170 for subevent 2

Figure B-2.2E1.12 shows the response of the EBP relay monitoring the line B170220 to B220170 for subevent 2. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Subevent-3:

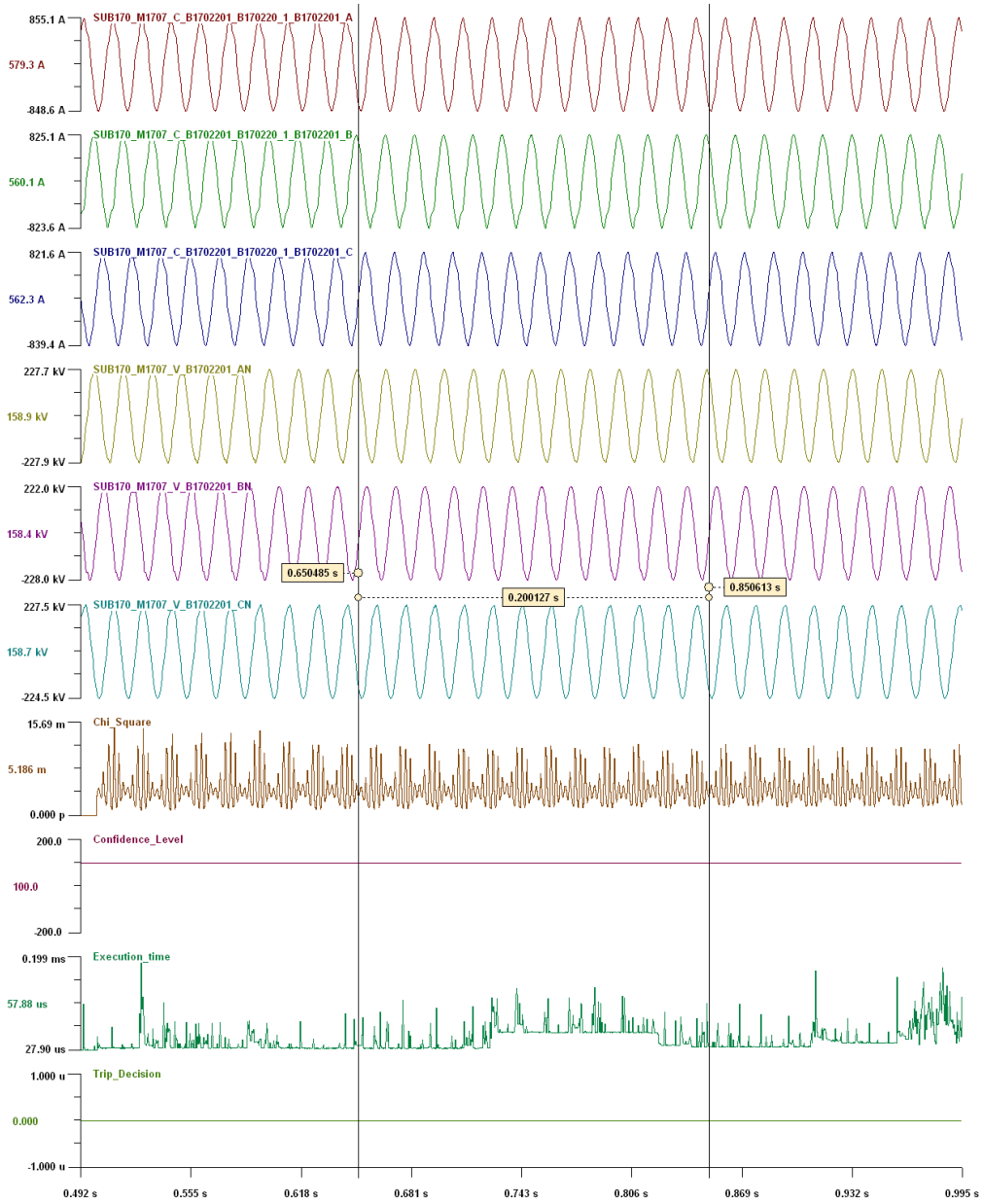


Figure B-2.2E1.13 EBP relay response monitoring Line B170220 to B220170 for subevent 3.

Figure B-2.2E1.13 shows the response of the EBP relay monitoring the line B170220 to B220170 for subevent 3. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Subevent-4:

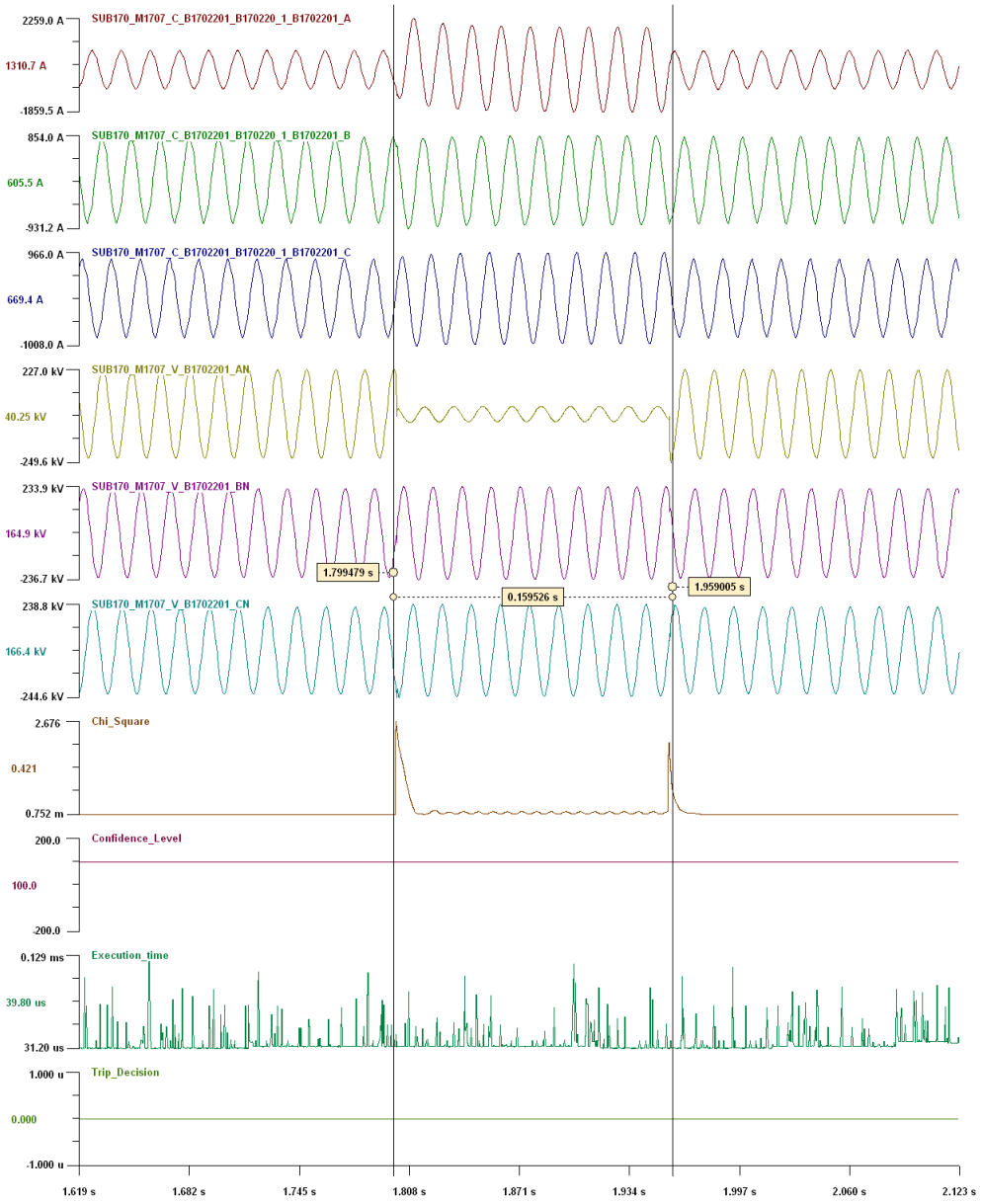


Figure B-2.2E1.14 EBP relay response monitoring Line B170220 to B220170 for subevent 4.

Figure B-2.2E1.14 shows the response of the EBP relay monitoring the line B170220 to B220170 for subevent 4. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Subevent-5:

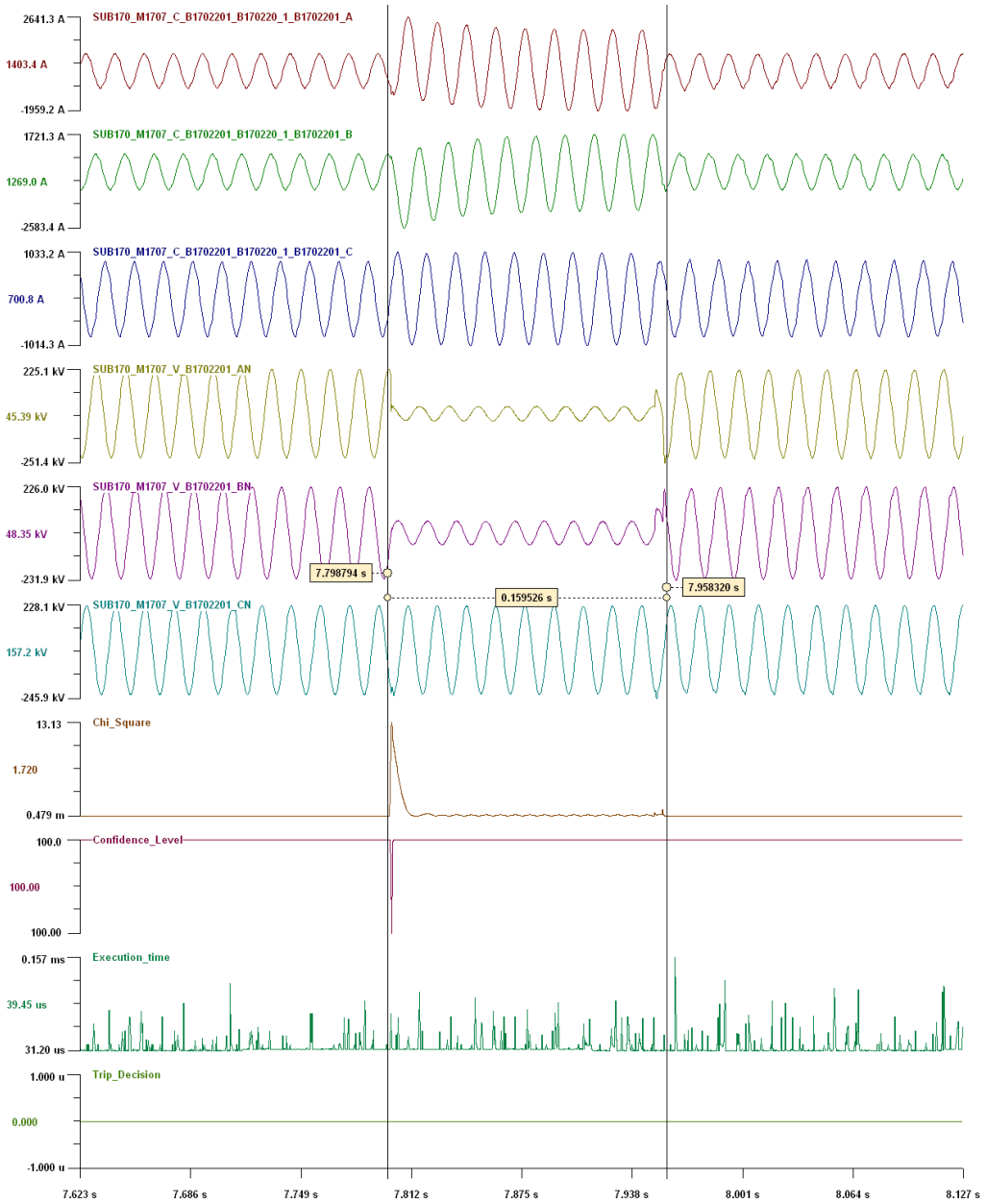


Figure B-2.2E1.15 EBP relay response monitoring Line B170220 to B220170 for subevent 5.

Figure B-2.2E1.15 shows the response of the EBP relay monitoring the line B170220 to B220170 for subevent 5. We can observe that the confidence level generated by the state estimator of the EBP relay is at 100%, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability the EBP generates a trip signal. Therefore, this relay will not act to disconnect the line B170220 to B220170. This is the correct action for this relay.

Event-2:

As described in section B-1.2 Event-2 is an event performed on Substation-240. The performance of the estimation-based protection and control of some of the protection zones is given below:

Performance of Estimation-based Protection and Control monitoring LineB240150-B150240

For Event 2, there are two subevents as listed in Table B-1.2. We can observe that subevent 1 is an A-G fault happening on the transmission line B240150 to B150240 at 27 miles from Substation -240 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B24030 to B30240 at 13.2883 miles from Substation 240 which is 75% of the line length of the transmission line B24030 to B30240 In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B240150 to B150240 for subevent 1**.

Subevents-1 and 2:

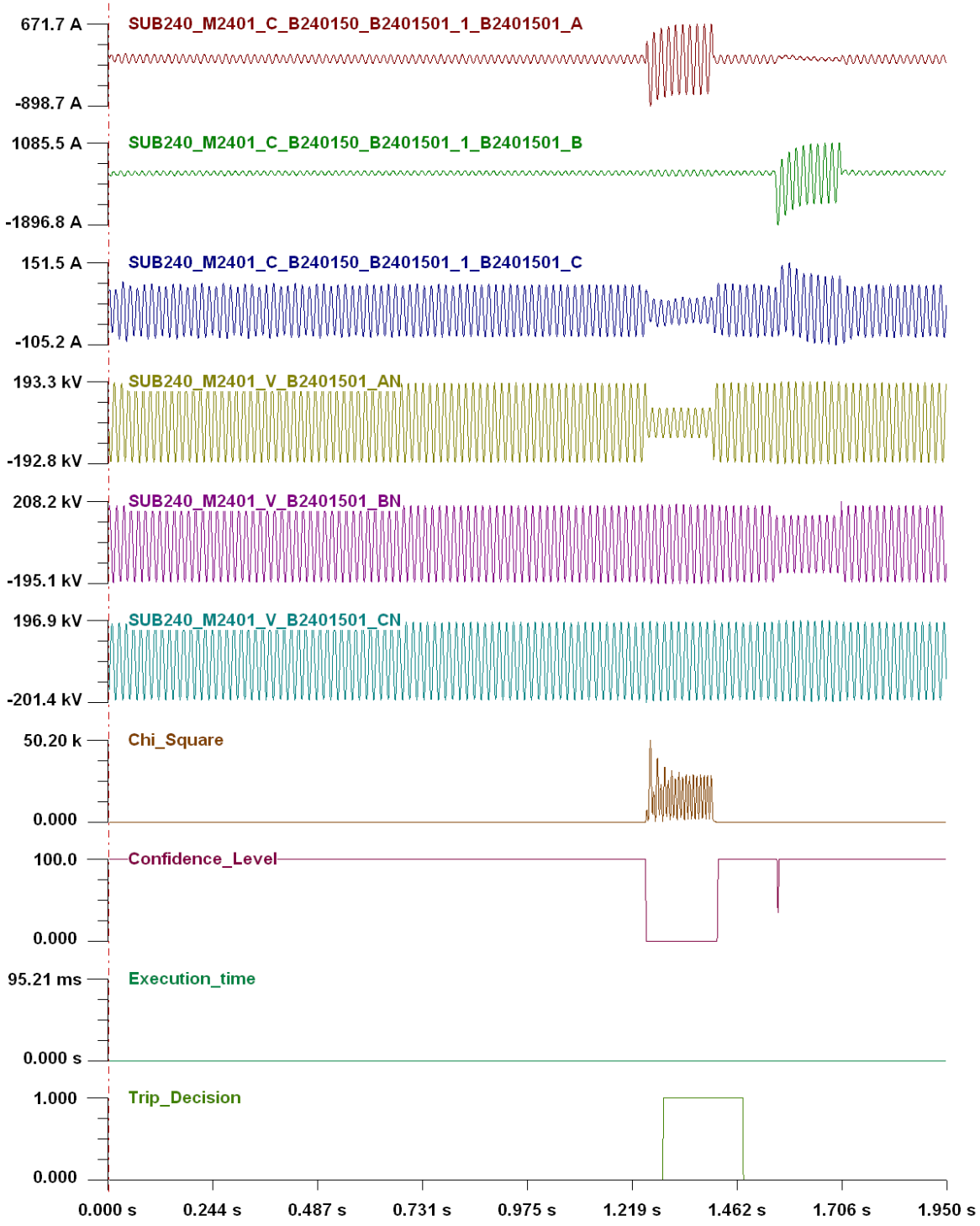


Figure B-2.2E2.1 EBP relay response monitoring Line B240150 to B150240 for subevents 1 and 2.

Figure B-2.2E2.1 shows the response of the EBP relay monitoring the line B240150 to B150240 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 1, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Consequently, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 2, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Performance of Estimation-based Protection and Control monitoring LineB24030-B30240

For Event 2, we can observe that subevent 1 is an A-G fault happening on the transmission line B240150 to B150240 at 27 miles from Substation -240 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B24030 to B30240 at 13.2883 miles from Substation 240 which is 75% of the line length of the transmission line B24030 to B30240 In this case the correct action of the protection and control system is that **only the protective relay for protection zone 3 acts to isolate the line B240150 to B150240 for subevent 2**.

Subevents-1 and 2:

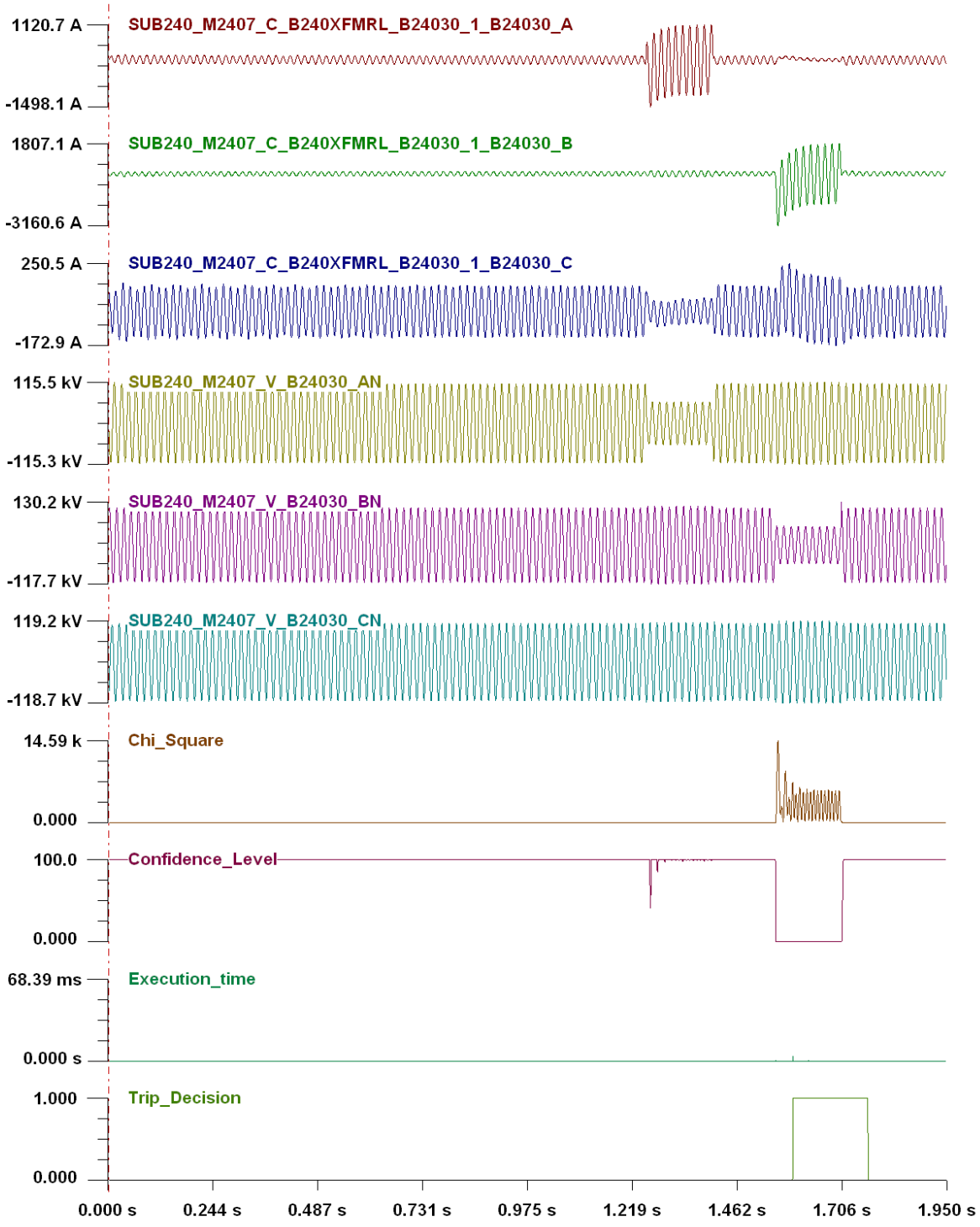


Figure B-2.2E2.2 EBP relay response monitoring Line B24030 to B30240 for subevents 1 and 2.

Figure B-2.2E2.2 shows the response of the EBP relay monitoring the line B24030 to B30240 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 2, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

However, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 1, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Event-3:

As described in section B-1.3 Event-3 is an event performed on Substation-50. The performance of the estimation-based protection and control of some of the protection zones is given below:

Performance of Estimation-based Protection and Control monitoring LineB5010-B1050

For Event 3, there are two subevents as listed in Table B-1.3. We can observe that subevent 1 is an A-G fault happening on the transmission line B5010 to B1050 at 16.5 miles from Substation-50 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B50100 to B10050 at 17.7175 miles from Substation-50 which is 75% of the line length of the transmission line B50100 to B10050. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B5010 to B1050 for subevent 1**.

Subevents-1 and 2:

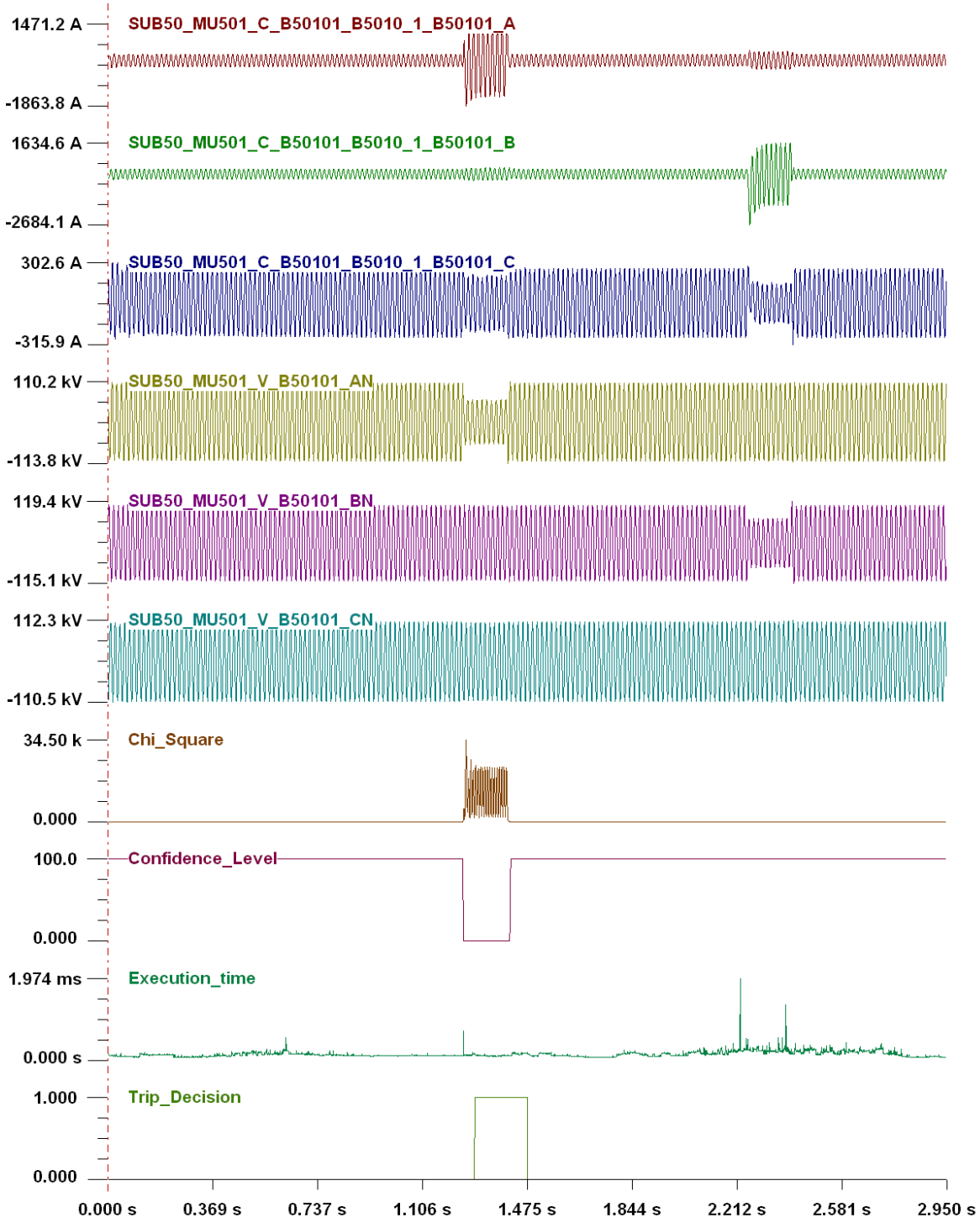


Figure B-2.2E3.1 EBP relay response monitoring Line B5010 to B1050 for subevents 1 and 2.

Figure B-2.2E3.1 shows the response of the EBP relay monitoring the line B5010 to B1050 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 1, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Consequently, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 2, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Performance of Estimation-based Protection and Control monitoring LineB50100-B10050

For Event 3, we can observe that subevent 1 is an A-G fault happening on the transmission line B5010 to B1050 at 16.5 miles from Substation-50 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B50100 to B10050 at 17.7175 miles from Substation-50 which is 75% of the line length of the transmission line B50100 to B10050. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the line B5010 to B1050 for subevent 2**.

Subevents-1 and 2:

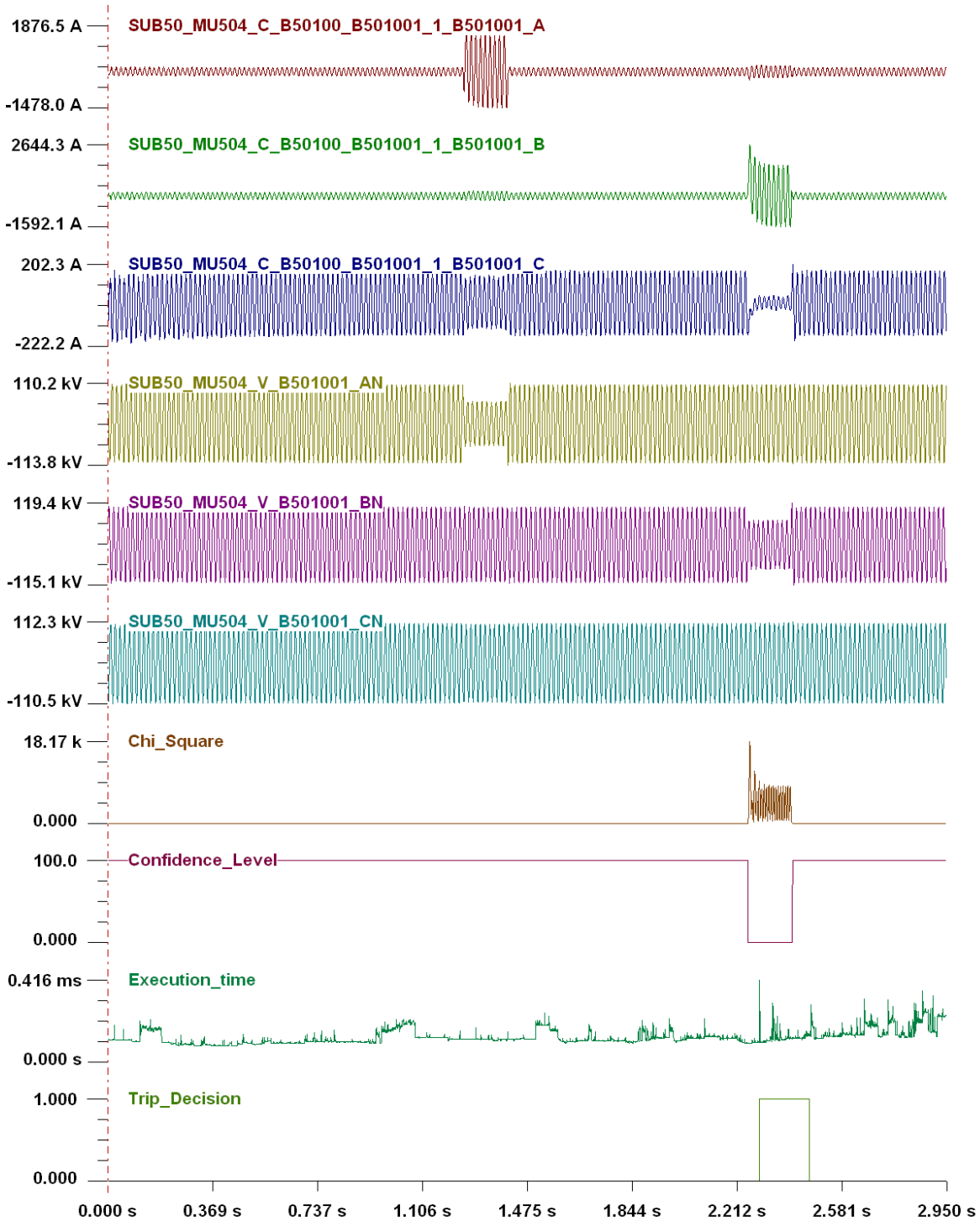


Figure B-2.2E3.2 EBP relay response monitoring Line B50100 to B10050 for subevents 1 and 2.

Figure B-2.2E3.2 shows the response of the EBP relay monitoring the line B50100 to B10050 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 2, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

However, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 1, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Event-4:

As described in section B-1.4. Event-4 is an event performed on Substation-40. The performance of the estimation-based protection and control of some of the protection zones is given below:

Performance of Estimation-based Protection and Control monitoring LineB4090-B9040

For Event 4, there are two subevents as listed in Table B-1.4. We can observe that subevent 1 is an A-G fault happening on the transmission line B4020 to B2040 at 24.75 miles from Substation-40 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B4090 to B9040 at 19.875 miles from Substation-40 which is 75% of the line length of the transmission line B4090 to B9040. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B4090 to B9040 for subevent 2.**

Subevents-1 and 2:

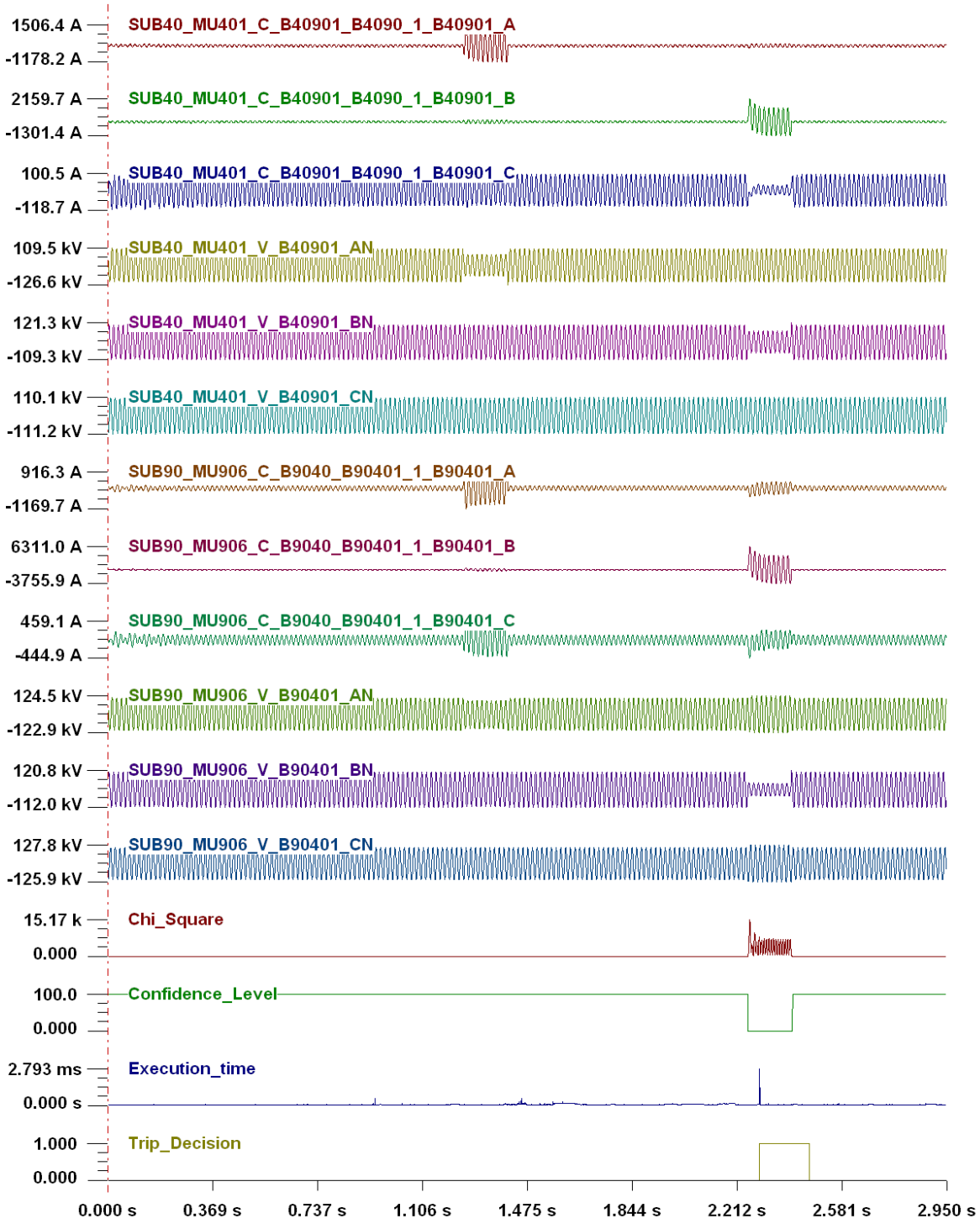


Figure B-2.2E4.1 EBP relay response monitoring Line B4090 to B9040 for subevents 1 and 2.

Figure B-2.2E4.1 shows the response of the EBP relay monitoring the line B4090 to B9040 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 2, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Consequently, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 1, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Performance of Estimation-based Protection and Control monitoring LineB4020-B2040

For Event 4, we can observe that subevent 1 is an A-G fault happening on the transmission line B4020 to B2040 at 24.75 miles from Substation-40 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the transmission line B4090 to B9040 at 19.875 miles from Substation-40 which is 75% of the line length of the transmission line B4090 to B9040. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the line B4020 to B2040 for subevent 1.**

Subevents-1 and 2:

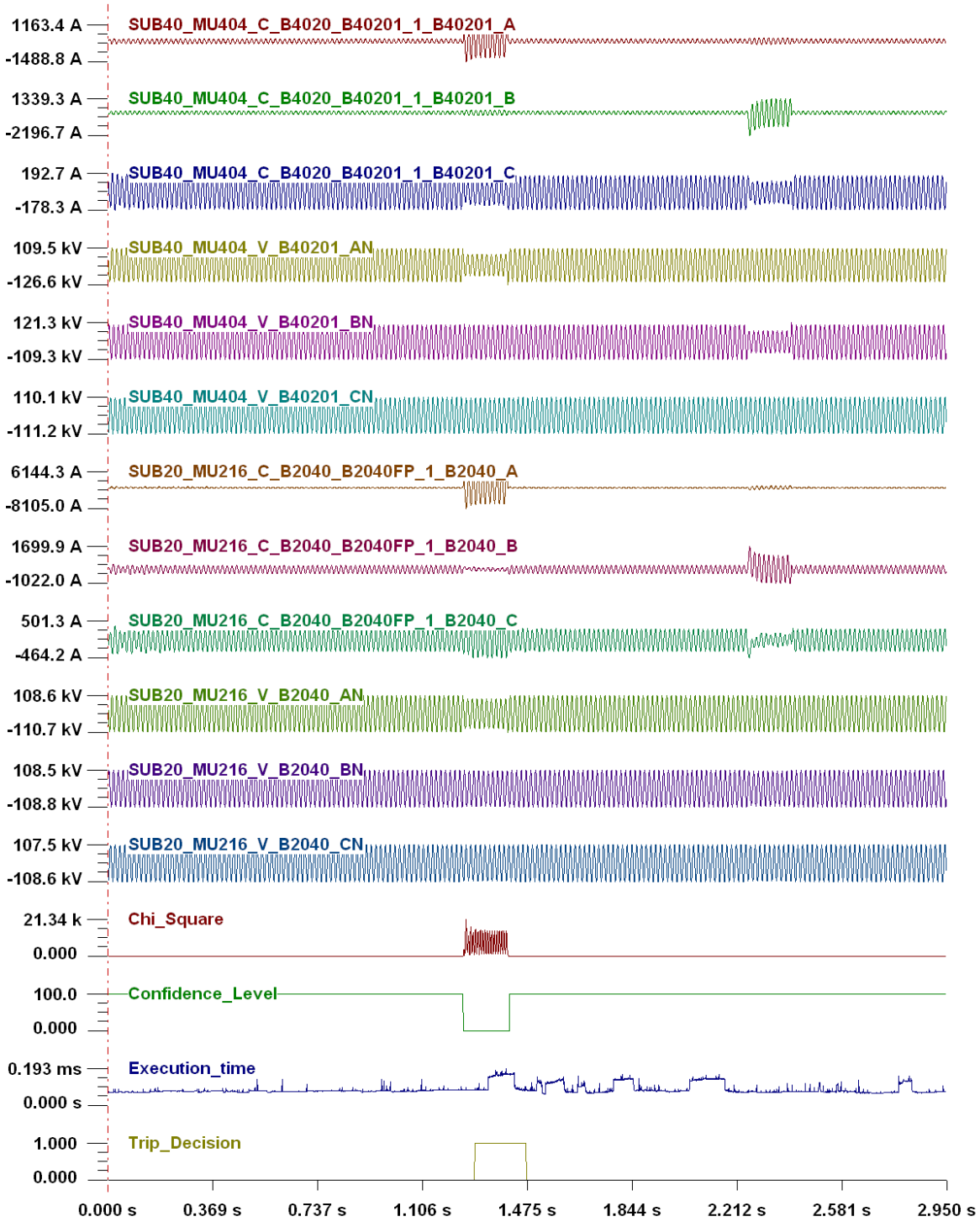


Figure B-2.2E4.2 EBP relay response monitoring Line B4020 to B2040 for subevents 1 and 2.

Figure B-2.2E4.2 shows the response of the EBP relay monitoring the line B4020 to B2040 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 1, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

However, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 2, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Event-5:

As described in section B-1.5. Event-5 is an event performed on Substation-70. The performance of the estimation-based protection and control of some of the protection zones is given below:

Performance of Estimation-based Protection and Control monitoring LineB7080-B8070

For Event 5, there are two subevents as listed in Table B-1.5. We can observe that subevent 1 is an A-G fault happening on the transmission line B7080 to B8070 at 12 miles from Substation-70 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the high side of the transformer XFMR70L to XFMR70H. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 1 acts to isolate the line B7080 to B8070 for subevent 1**.

Subevents-1 and 2:

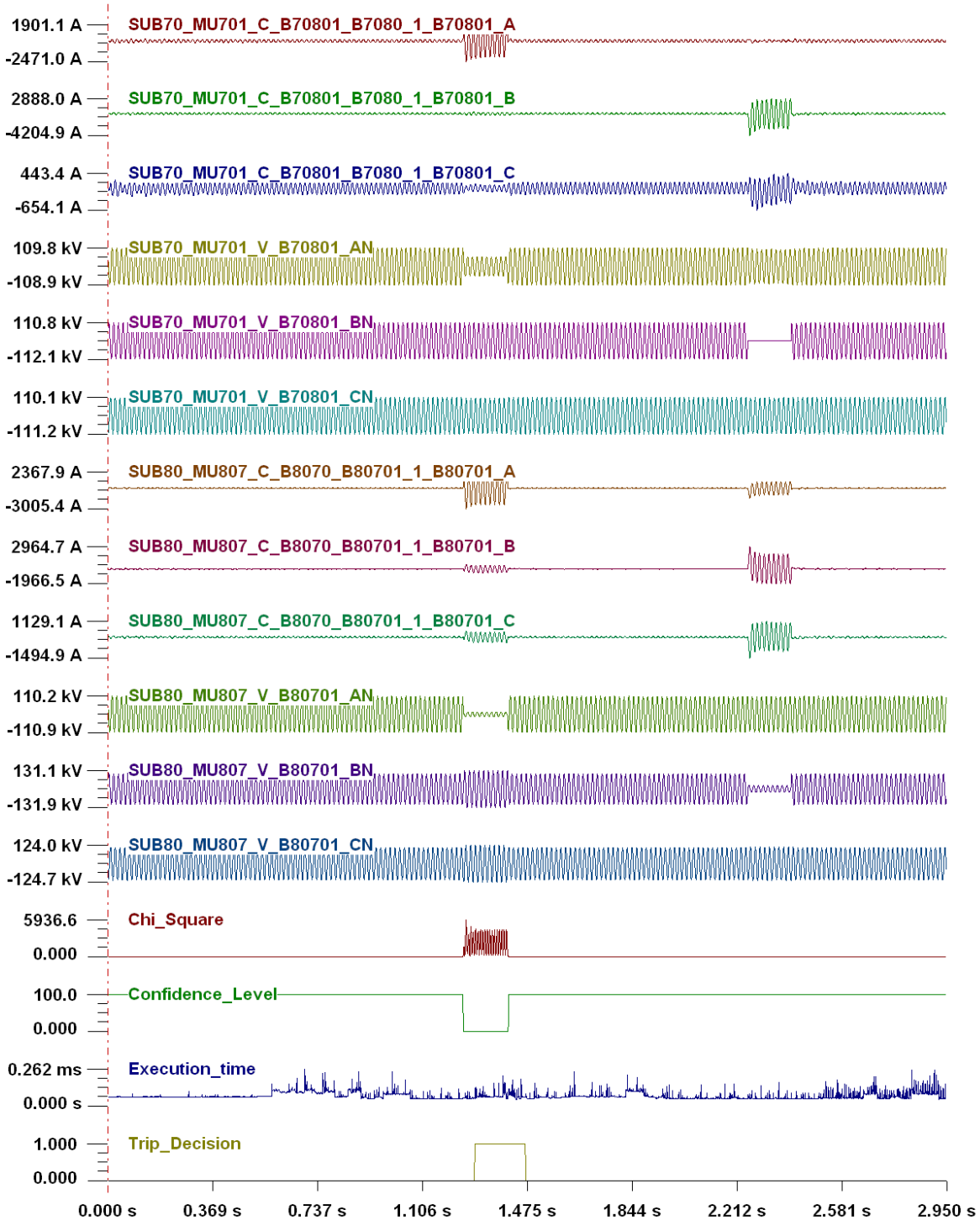


Figure B-2.2E5.1 EBP relay response monitoring Line B7080-B8070 for subevents 1 and 2.

Figure B-2.2E5.1 shows the response of the EBP relay monitoring the line B7080-B8070 for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 1, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the line. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated line is reconnected back into the network.

Consequently, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 2, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.

Performance of Estimation-based Protection and Control monitoring XFMR 70L-70H

For Event 5, we can observe that subevent 1 is an A-G fault happening on the transmission line B7080 to B8070 at 12 miles from Substation-70 which is 75% of the transmission line length and subevent 2 is a B-G fault happening on the high side of the transformer XFMR70L to XFMR70H. In this case the correct action of the protection and control system is that **only the protective relay for protection zone 2 acts to isolate the transformer XFMR70H to XFMR70L for subevent 2**.

Subevents-1 and 2:



Figure B-2.2E5.2 EBP relay response monitoring XFMR 70L-70H for subevents 1 and 2.

Figure B-2.2E5.2 shows the response of the EBP relay monitoring the XFMR 70L-70H for subevents 1 and 2. We can observe that the confidence level generated by the state estimator of the EBP relay is now zero for subevent 2, this indicates that there is a fault on the equipment monitored by the EBP relay; In turn the EBP relay generates a trip signal after a delay (inhibit time). Therefore, this relay will act to disconnect the transformer. This is the correct action for this relay.

It can be observed that the trip signal stays on for a few cycles after the fault is cleared; this is to ensure that the fault is completely cleared, and the isolated XFMR is reconnected back into the network.

However, the confidence level generated by the state estimator of the EBP relay is at 100% for subevent 1, this indicates that there is no fault on the equipment monitored by the EBP relay; In turn the EBP relay does not generate a trip signal. When there is a fault the confidence level drops from 100%. The trip signal in the EBP relay is based on the confidence level; lower the confidence level (less than 10%), higher the probability that the EBP generates a trip signal. Therefore, the relay will not act to disconnect the line in this instance. This is the correct action for this relay.