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ECE 4820 Senior Design

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Real-Time Testbed for Transmission Line Protection

04/25/2024

Abstract

Hardware in the loop (HIL) testing is crucial for designing and managing electric power grids. These grids are becoming larger and more complex. The importance for students to have safe and intuitive ways to interact with the devices associated with the power grids has never been more crucial. Since most of these tests involve high voltages, this can be a deterrent for instructors and students in undergraduate programs. HIL testing is a solution to these common issues. This method has become one of the most popular methods for testing these power systems. With the use of Western Michigan University's (WMU) Real-Time Digital Simulator (RTDS) and SEL-421-7 protection relay, a HIL testbed has been created. These devices were interconnected using the communication protocol known as Generic Object-Oriented Substation Event (GOOSE). A simulated transmission line system was modeled in an RTDS software RSCAD as the basis for this testbed. This model simulated different types of faults that could occur in a transmission line while in operation. The SEL-421-7 relay is connected to the RSCAD simulation via GOOSE to protect our simulated transmission line. This testbed was set up to give students a clear understanding of how distance protection works as well as how the SEL-421-7 will react to various kinds of faults, in addition to how useful the RTDS can be when testing different power systems.

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Acknowledgements

We would like to express our sincere gratitude to all those who have contributed to the completion of this project. First, we would like to thank Dr. Pablo Gomez for giving us the opportunity to work with the equipment provided through the WMU InterEnergy Center. Dr. Gomez was also the professor that oversaw ECE 4810 or Senior design I which prepared us very well for the road ahead. Without the support from the research center there would have been no research for us to complete on the RTDS or the SEL-421-7. We would also like to thank Dr. Dinesh Maddipatla, who oversaw ECE 4820 or Senior Design II, who kept us on track during the final semester of this project. With the clear instructions and goals laid out for us at the beginning of the semester, it was useful for us to stay on track and complete our project.

Special thanks to the representatives from Schweitzer Engineering Laboratories (SEL) and RTDS Technologies who provided their time to help us troubleshoot challenges that we encountered over the project. The representatives from SEL, Tim Lewis & Nicholas Jones, were exceptional and offered help understanding the SEL-421-7 and all programs that corresponded to the function of the device. The representative from RTDS Technologies, Chris Dyck, was very timely with his answers to our challenges. We could not have asked for better representatives from either company to help us through these turbulent months.

TABLE OF CONTENTS

1. Introduction

The importance for students to have a safe and intuitive way to understand how power grids and distance protection relays react to multiple types of faults is growing as careers in the power industry increase. Most labs or demonstrations either involve high voltage or are purely simulation. The issue with the high voltage route is that it is dangerous, complicated, and consumes a large amount of power. The other option is hardware-in-the-loop (HIL) testing, which has become one of the most common methods for testing these large power systems. HIL methods are rare in undergraduate programs; therefore, this project focuses on creating a testbed that would utilize HIL techniques for educational purposes.

1.1 Purpose & Scope

With the aging transmission infrastructure in the United States, transmission line protection has never been so important to the flow of power across the country. A significant portion of the transmission equipment in the U.S. has passed its life expectancy and therefore has become outdated for society's current needs or lacks the ability to continue supplying power in a reliable manner [1]. It is happening more often that these lines and towers are subject to extreme weather events that can damage them. A tree branch falling on a transmission line may cause a fault, which could be detrimental to equipment or even deadly to workers or the general population. Considering these new challenges, protection devices have become more necessary to prevent detrimental effects and keep the flow of power to critical loads. As the demand for power grows and power grids become more complex, there is a need for automated protection of these lines. The SEL-421-7 is the most common protection relay for transmission line protection, so a testbed that incorporates this device would be a great asset for educational and training purposes.

The goals of this testbed are to spark the interest of the next generation of Western Michigan University (WMU) students and encourage them to seek careers in the power industry. HIL testing provides a safe and realistic environment for students to interact with these devices and learn about power grids. Students may use this testbed in an undergraduate or graduate lab to expand their understanding of HIL testing and distance protection.

2. Discussion

Hardware in the loop test methods are safer than the other lab-based alternative and provides a way to more induvial to work with devices they normally would not have access to, the alternative seen by S.P. Carullo [8]. An opportunity to use unique and rare equipment was presented to create a testbed to further advance the WMU InterEnergy center's mission. This initial design will be the basis for more work and publicity through this center. It is explained below the specifications we wanted to comply with, the design process, resulting product, and how the testbed will affect the world over power systems.

2.1 Overview

There are many components involved to make this testbed a useful training tool for external devices. The design specifications lay the groundwork for the design to be improved upon. All the hardware and software tools are defined below and can be improved to create a more complex learning and training experience. The testbed is meant to be recreated by companies and universities that have the required equipment.

2.1.1 Background & Need Statement

This testbed is comprised of WMU's Real-Time Digital Simulator (RTDS) and an SEL-421-7 protection relay. Both devices are top of the line in their respective fields. These devices are connected via Generic Object-Oriented Substation Event (GOOSE) communication protocol and sampled values. The RTDS simulates the transmission line model in RSCAD, which is a power systems simulation software developed for the RTDS [4]. The transmission line simulation is basic in terms of what could be found in the field since it is only comprised of one transmission line with Thevenin equivalents on both the sending and receiving node of the line to represent the rest of the system. There is integrated logic that allows six distinct types of faults to be simulated at any location along the transmission line. The sending node of the transmission line is where the external (physical) protection relay is measuring data through sampled values. At the receiving node there is a virtual protection relay block that has the same protection elements and settings as the external counterpart. Multiple data points are monitored while the simulator is operational, such as the trip and breaker status of the internal and external protection relays, as well as the voltage and current at each node.

The Real-Time Digital Simulator (RTDS) is a state-of-the-art device that is used to simulate complex power systems models in real time. The RTDS, made by RTDS Technologies, can simulate multiple types of grid configurations including forms of renewable power generation [9]. It also has the capabilities to implement diverse types of logic, such as faults into the system. The RSCAD software also shows the data produced by the simulated model in real-time through graphs and digital displays. This device is widely used amongst power companies and research groups to configure proposed grids or to test new devices through hardware-in-the-loop test methods. For the proposed testbed using an SEL-421-7, the capabilities of the RTDS just barely scratched the surface of what can be completed. The model used was simple and can be developed to create a model that emulates a transmission system found in the field, containing several SEL-421-7 protection relays [7]. The RTDS, seen below in Figure 1, shows the device used to complete the HIL testbed.

Figure 1: Real Time Digital Simulator

The SEL-421-7 protection relay was connected to the RTDS which can be seen in Figure 1. The SEL-421-7 protection relay was created by Schweitzer Engineering Laboratories. This was connected to the RTDS creating a HIL testbed for testing the capabilities of the SEL-421-7, and to see how the protection relay would react to multiple types of faults. The SEL-421-7 is the most popular device used for fault protection. The protection relay can use multiple types of protection schemes such as distance protection, over current/voltage, and frequency fluctuation [9]. However, for time and proof of concept, this testbed was designed to only include distance protection. This device was connected to the RTDS using ethernet cables and communicates using the IEC 61850 standard or the GOOSE Communication standard. The SEL-421-7 has LEDs that in the event of a fault will light up to display the characteristics of the faults such as the type of fault (phase/line) and will display whether it occurred in zone 1 or 2 of the protection [7]. There are also many buttons that can be configured to do a multitude of actions, but for our project we only used the two buttons in the right column on the bottom, which were responsible for manually opening and closing the internal breaker. In Figure 2, we can see the SEL-421-7 Distance Protection Relay that was used in the testbed.

Figure 2: SEL-421-7 Distance Protection Relay

The testbed created is a great opportunity for Western Michigan University, because it will create an educational benchmark for HIL testing in undergraduate programs. WMU’s students will work with equipment that is sought out by prominent power companies that hire electrical and computer engineers. All the equipment needed to complete this project is provided by the WMU InterEnergy Center, so there is no financial commitment needed for these programs.

It has become evident in recent years that the world of power is changing more frequently and rapidly than ever before. This includes legislation worldwide to eliminate carbon emissions from electric power generation and invest more into renewable energy. The increase of students into the field means that safer and more efficient ways of testing these innovative technologies are needed. The testbed can also create a more focused learning experience, specifically about transmission systems to encourage students to engage with this power revolution.

2.1.2 High-Level System Diagram

In Figure 3, we can see a block diagram depicting our testbed and all the connections between the devices. The blue box shows all the devices that are within the RTDS cubicle, the green box shows the SEL-421-7, and the yellow box denotes the External PC. The NovaCor is a multi-processor device that runs a simulated model built in RSCAD. The NovaCor communicates with the RSCAD simulation on the External PC. The RSCAD model communicates the sampled values and GOOSE data through their respective blocks in the model to the GTNET card to the SEL-421-7 [7]. The SEL-421-7 then interprets this data then sends the trip signal back to the GTNET card using GOOSE commutations. The results from the SEL-421-7 through GOOSE messages and the GOOSE block, which are sent to the RSCAD model by the GTNET card to be viewed in graphical form. The GTSYNC card is a device that keeps the RSCAD simulation running in real-time. All the devices exchange data through the ethernet switch, which is in the RTDS cubicle. All the gray arrows in Figure 3 represent ethernet cables, while the orange arrows represent fiber optic cables. The ports where these cables are connected are labeled on each device. This block diagram is one of the several pieces of information that was created to make this testbed repeatable.

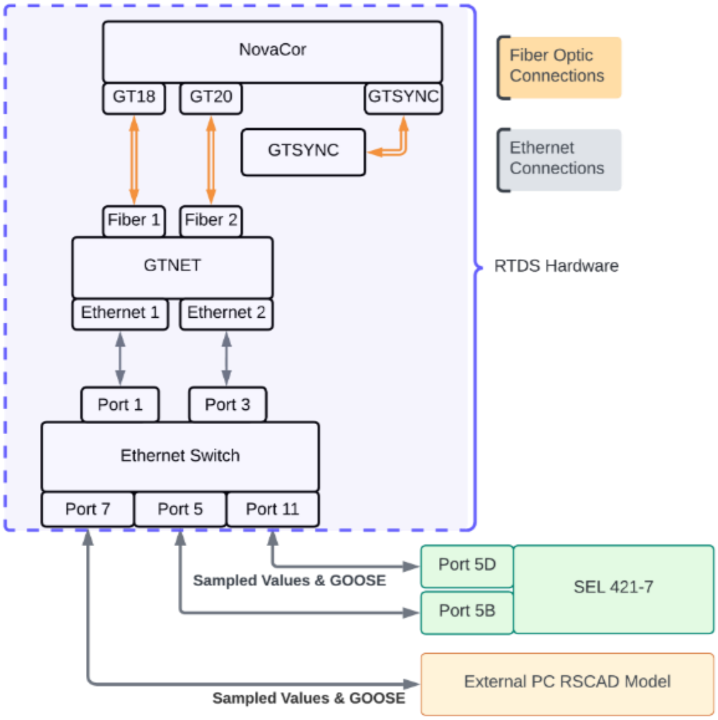


Figure 3: Overall Block Diagram of Testbed

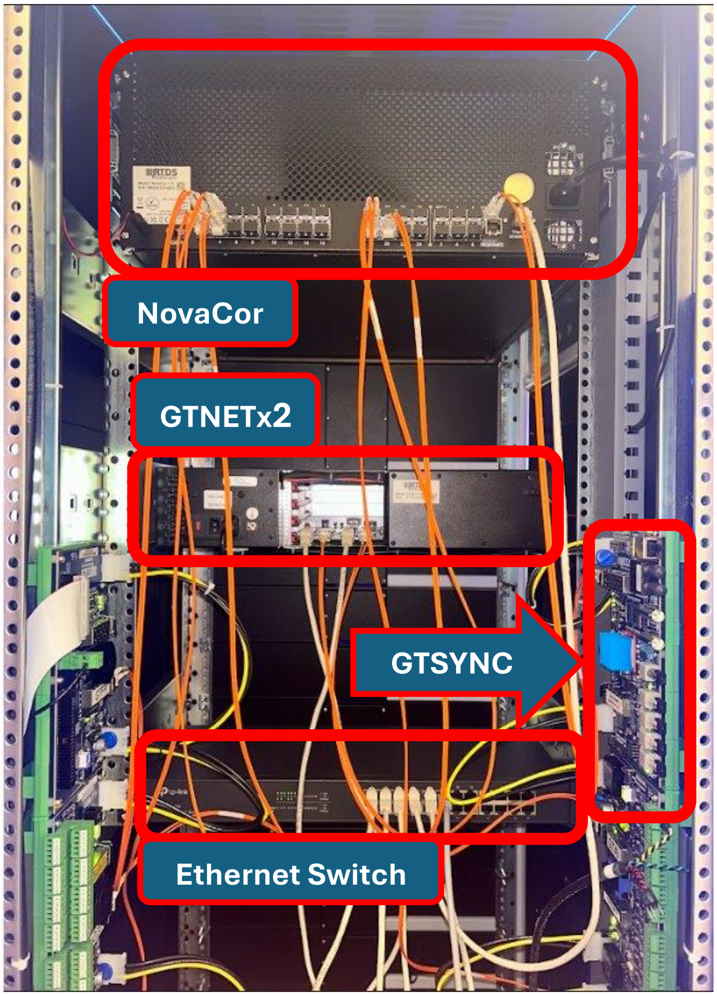


Figure 4: Inside the RTDS Cubicle

In Figure 4, we can see the different devices inside of the RTDS cubicle.

2.1.3 Specifications

This project aims to create a safe, educational, and informative HIL testbed to monitor faults of a transmission line and test the user's knowledge of distance protection. The initial goal was to design a compact system consisting of the RTDS, an SEL-421-7 Distance Protection Relay, and GOOSE communication protocol through fiber optic and ethernet cabling. The secondary motive of this project is to create a basis for future WMU projects testing with the RTDS and its HIL capabilities. The specifications also reflect the desire for other senior design or research groups to continue experimenting with the RTDS using our project as a baseline. The future work should also carry on experimenting with the RTDS and SEL-421-7 or other external devices to broaden the horizon for safe testing methods and encourage future students to work within the power systems industry.

2.1.3.1 Physical Characteristics

The hardware and equipment used was already assembled and ready to use, so there were minimal physical specifications to comply with. The specifications that relate to physical characteristics are wired connections between devices and using embedded LCD and LED screens. Below are the physical specifications that were created to design the testbed.

1. - All devices must be connected using IEC 61850 communication standards.
2. - RTDS will be connected to an external workstation for RSCAD simulation.
3. - Devices will be connected via an internal ethernet switch or fiber optic cables.
4. - SEL-421-7 must use LED and LCD to display the status of the relay itself.
5. - SEL-421-7 must be powered with an alternative method if not using an SEL approved rack.

2.1.3.2 Functionality

The functionality specifications of this testbed are much more important to complete than the physical ones. The specifications are divided into multiple sections for the different components used to make the testbed function. The sections include the RTDS apparatus, the RSCAD simulation model, and the setup of the SEL-421-7 Distance Protection Relay.

1. RSCAD Model

1.1 The RSCAD model must emulate a realistic transmission system.

1.2 RSCAD model must use built in libraries to interpret logic before exporting data to SEL-421-7.

1.3 RSCAD model must simulate all relevant types of faults, which are:

- Line-Line-Line-Ground
- Line-Line-Line
- Line-Line-Ground
- Line-Line
- Line-Ground

1.4 Documentation must be provided on how the RSCAD simulation functions including

- Which components were used in the power systems model.
- How to configure all block logic.
- A brief explanation of what each block represents in the field.

2. RTDS Apparatus

2.1 GTSYNC must synchronize the RSCAD Simulation with a time reference.

2.2 GSE or GOOSE block must read the trip signal from SEL-421-7.

2.3 GTNETx2 board must communicate with RSCAD simulation.

2.3.1 GTNET-GSE firmware found on GTNETx2 to be used to interpret IEC 61850 communication.

2.3.2 GTNET-SV firmware found on GTNETx2 to be used to connect SEL-421-7 with the RTDS.

2.4 Documentation must be provided, which describes how the RTDS will be used for our project, which will include:

- The components used within the RTDS.
- A diagram of all internal components and their connections.
- Description of signals sent to internal & external devices.
- List of input/outputs and which port they correspond to.

3. SEL-421-7 Relay

3.1 The SEL-421-7 shall interpret logic exported from RTDS to accurately protect the simulated transmission system.

3.2 The SEL-421-7 must use imbedded software (acSELerator Quickset) to interpret inputs produced by the RTDS.

3.3 Documentation must be provided, which describes how the SEL-421-7 was used over the course of this project and will include:

- All the connections between devices including port numbers
- How to install and use acSELerator to configure the SEL-421-7.
- Results expected from models of different complexity.

2.1.3.3 Specification Validation

This section describes which specifications the testbed complies with and shows proof of completion for each specification. Many of the specifications were completed, with the outliers incomplete due to plans that were not finished when the original specifications were made. These challenges emerged because of overestimating the complexity of the work that needed to be completed. All the validation figures are shown in the Appendix and a select few are in-text to indicate the completion of important specifications for each section.

The RSCAD model used considers two relays, a virtual relay, and the SEL-421-7. This model was created to send and receive data to an external relay in real time, shown as the

RSCAD "Runtime" model in Figure 5. Although this model comes close to a transmission line setup, it did not fully represent a power system found in the field. In practice, there would be multiple transmission lines at both ends of the line where the protection devices are located. The transmission line model shown in Figure 5 does not extend past the virtual relay node. The model parameters include typical zone reaches, transmission line length, and voltage ratings. The Sampled Values (SV) block and GOOSE block were used from the RSCAD built-in library to interpret the data from the SEL-421-7. The RSCAD "Runtime" tab allows the user to change the fault type and any other fault parameters. Figure 3 validates most of our specifications for the RTDS apparatus. The core of RSCAD's functionality is to use GTSYNC to create an accurate time reference, which is taken in 50 millisecond increments. The GTNETx2 board was loaded with SV and GOOSE values, evident in Figure 6.

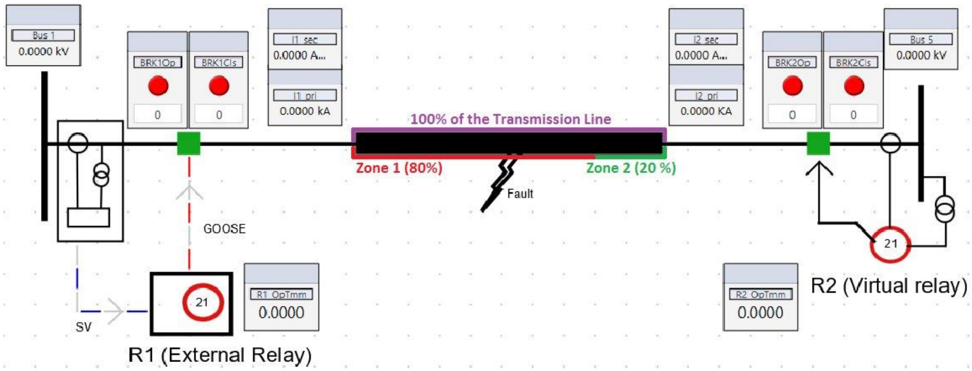
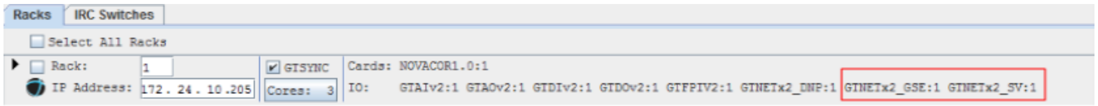


Figure 5: Representation of Transmission Line Model in RSCAD



☐ Select All Racks

☐ Rack: 1

IP Address: 172. 24. 10.205

☑ GTSYNC

Cores: 3

Cards: NOVACOR1.0:1

IO: GTAIv2:1 GTAOv2:1 GTDIv2:1 GTDOv2:1 GTFPIV2:1 GTNETx2_DNP:1 GTNETx2_GSE:1 GTNETx2_SV:1

Figure 6: GTNETx2 loaded programs

The SEL-421-7 receives SV voltage and current measurements as well as GOOSE data for the fault and circuit breakers from the GTNETx2. Furthermore, the SEL-421-7 also sends GOOSE data signifying the trip signal. The goal was to configure the SEL-421-7 to replicate the virtual relay provided in the RSCAD model. This task's completion indicates the SEL-421-7 is receiving and sending the data correctly. In fact, the SEL-421-7 reacts exactly as the RSCAD model's virtual relay. This is evident in Figure 7.a, 7.b, and 7.c, where the SEL-421-7's breaker data is in the left plot and the Virtual Relay's breaker data is in the right plot. Figure 7.a shows when the fault is in the middle of the line, which is zone 1 for both the relays. The trip signal for the SEL-421-7 is the same duration and it happens at the same time. Figure 7.b shows when the fault location is set to 85% from the SEL-421-7, which makes the SEL-421-7 relay delay the trip for 20 cycles. This is to compare with Figure 7.c, which the location of the fault is at 15%, showing that the virtual relay and the SEL-421-7 zone 2 response is the same. The SEL-421-7 was programed with SEL Grid Configurator, a newer version of acSELerator Quickset. This program controls the logic and parameters of the trip signal.

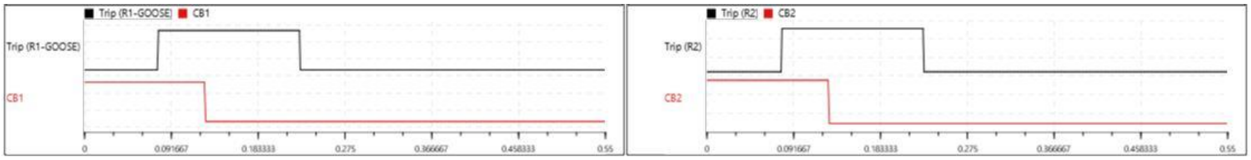


Figure 7.a: Fault Occurred in Zone 1 of Both Relays

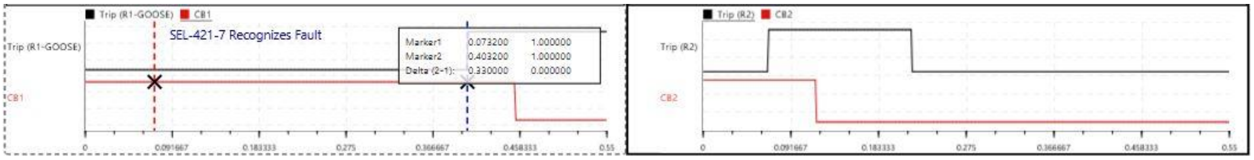


Figure 7.b: Fault Occurred in Zone 1 of Virtual Relay

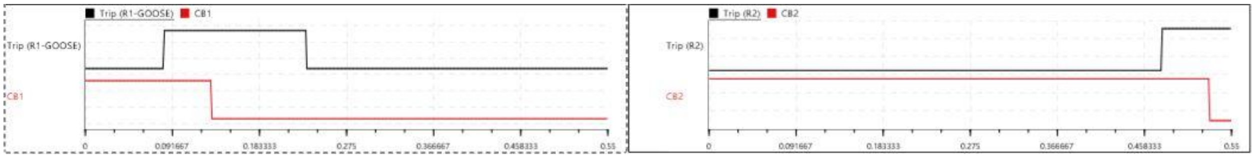
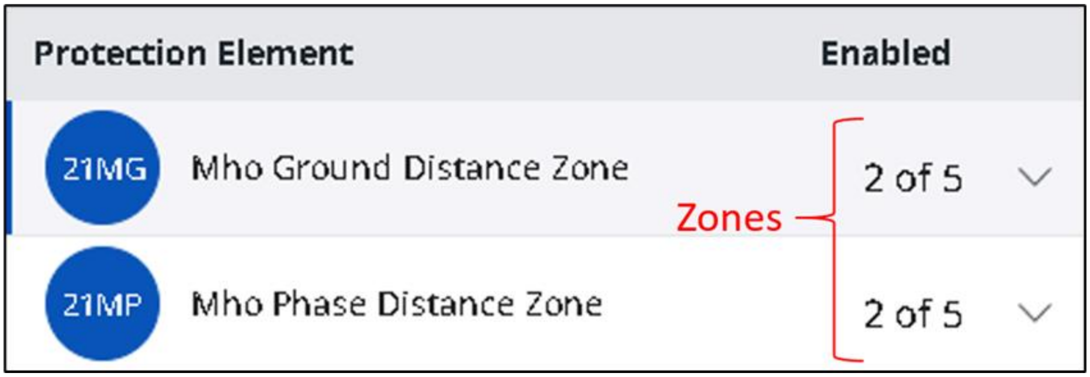


Figure 7.c: Fault Occurred in Zone 1 of SEL-421-7 Realy

Only two sections of the “Protection Element” tab of SEL Grid Configurator were used, which is shown in Figure 8. These 2 elements have the “MG21” settings protect against the line-to-ground fault while the “MP21” settings protect against the line-to-line faults. The two separate sections within these protection elements outline Zone 1 and Zone 2 parameters. In these settings there can be a maximum of 5 zones enabled but for this testbed we only used two. The most effective way to validate the specifications is to show the relay results of the simulation in each of the four cases: AG in Zone 1, AG in Zone 2, AB in Zone 1, and AB in Zone 2. Again, these simulations encompass the four setting sections in SEL Grid Configurator. The idea is that if an AG fault and an AB fault work independently, then an ABG or ABCG fault would work because they use the same protection elements. The Zone 1 fault location for the SEL-421-7 will be set at 15% of the line, since that will display how the virtual relay reacts when it detects a fault within its Zone 2. The fault in Figure 7.a is simulated at the center of the line. This is used to show the similarities between the response of the SEL-421-7 and the virtual relay.



Protection Element		Enabled
21MG	Mho Ground Distance Zone	2 of 5
21MP	Mho Phase Distance Zone	2 of 5

Figure 8: Protection Element in Grid Configurator

Although most of the documentation is completed to the degree of specifications, the structure has changed. Three main documents have been created: two that relate to the lab created for students, and one made for an instructor to understand how to set up the apparatus and communications. The lab documentation consists of a lab workbook that gives students five tasks to better understand distance protection schemes. The other part of the lab documentation is a student manual used to explain how to use RSCAD and SEL Grid Configurator, along with relevant equations students can use to determine the parameters [5].

The final specification that was not met was specification number 1.1. This specification stated that the simulated transmission model used in the testbed would emulate a transmission model found in the field and contains an SEL-421-7. This specification was not met because the model used is a simplified version of a transmission topology found in the field, since it contains two Thevenin equivalents connected at both ends of one transmission line that is faulted. This is too simple of a model to meet this specification. The model would have to include multiple loads, transmission lines, transformers, and relays to meet this final specification.

2.1.4 Project Deliverables

Besides the testbed itself with its hardware and software components and deliverables to include documentation of the findings and procedures so this work can be continued by the WMU InterEnergy Center. The documentation includes the necessary diagrams and instructions for reproduction of the testbed setup consisting of the RTDS and SEL-421-7 devices interconnected using GOOSE communication protocol. The goal is that the testbed can be used as the basis for using the RTDS in a lab setting by undergraduate students. It is the hope that this testbed will bring attention to the WMU InterEnergy Center and better engage students who share the center's goals.

2.1.4.1 Hardware

Since this testbed is a proof-of-concept, the final product does not have many physical deliverables in comparison to the software and instruction deliverables. The main hardware component resulting from this testbed is the testbed itself, which consists of the RTDS and the SEL-421-7, along with connecting cables. The testbed was designed to be as compact and intuitive as possible to avoid human error and to be as safe as possible, which can be seen in Figure 3.

2.1.4.2 Software

This testbed relies heavily on software use, as all of it contributes to our simulated transmission line model. The specific software utilized in this project was RSCAD, Grid Configurator, and acSELerator Architect. RSCAD housed the transmission line model design, along with all the necessary communication blocks such as SV and GOOSE. It also housed the displayed data that allowed us to know the testbed was set correctly and working. Grid Configurator was utilized to set up the SEL-421-7 relay accurately. This included the distance protection settings such as the values and zones. It also gave us access to the tripping logic that interpreted the sampled values from the RSCAD simulation. This allowed the SEL-421-7 to accurately read the voltage and current values to determine if a fault has occurred. AcSELerator Architect was utilized to set up the correct GOOSE trip signals to be utilized by the simulation model in RSCAD. The messages sent from the RTDS would not be interpreted correctly without the file being set up and then uploading onto the SEL-421-7.

2.1.4.2.1 RSCAD

RSCAD is a circuit simulation software used by the RTDS NovaCor. The RSCAD model of the transmission line was the base of the testbed. The model was premade as a tutorial case named “Relay_Interfacing_with_IEC61850”. This information included the primary line impedance, the Current Transformer (CT) and Potential Transformer (PT) settings, and the Virtual Relay (VR) settings. This information was all that was needed to calculate the parameters used in the SEL-421-7. The model was also created to incorporate SV and GOOSE communication protocols, which must be specified and uploaded to the RTDS. Figure 9 shows the CT and PT devices that were in RSCAD.

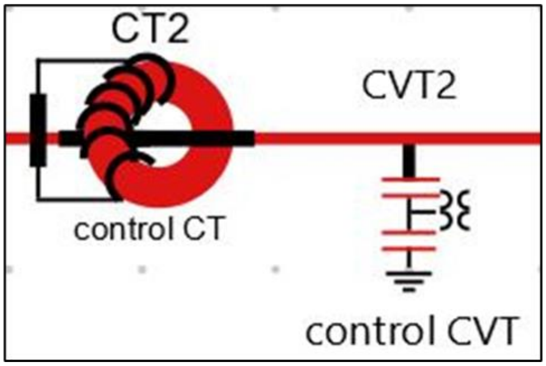


Figure 9: CT & PT Blocks in RSCAD

The RSCAD model also incorporated logic into the simulations, which is used in many ways. The first way RSCAD uses logic blocks is so that the user can change the settings within the user interface labeled “Runtime.” This helped when creating a distance protection testbed for laboratory use because many students do not know their way around RSCAD when different faults and settings will need to be employed. The second reason logic is useful in the model is because of how the VR operates. Like the SEL-421-7, The VR is a block shown in Figure 10 which uses specified trip outputs describing information in the form of bits and words. The complex web of logic controls fault settings, Runtime displays, and breaker statuses from the VR outputs.

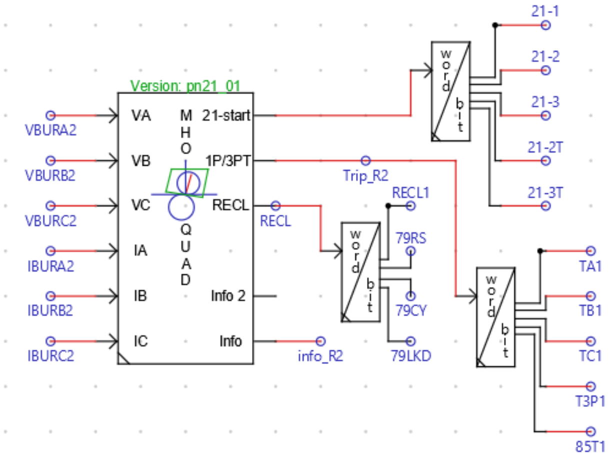


Figure 10: Virtual Relay Output Scheme

Another reason RSCAD is best suited for a learning environment is because of the “Runtime” tab. This tab can be seen in Figure 11, which shows a graphical representation of the transmission line setup. The right-hand side of this representation shows switches, buttons, and sliders to change settings related to the simulation. Some buttons operate each breaker status independently, which coincides with the SEL-421-7 Relay. The two buttons at the top generate a fault or reset the simulation, clearing the fault, and closing the breakers. Most of the switches indicate the type of fault that will be generated. The last input is the sliders, which adjust the parameters of the fault, such as location, resistance, and time. All these inputs are important to the functionality of the RSCAD model and essential for troubleshooting the simulation.

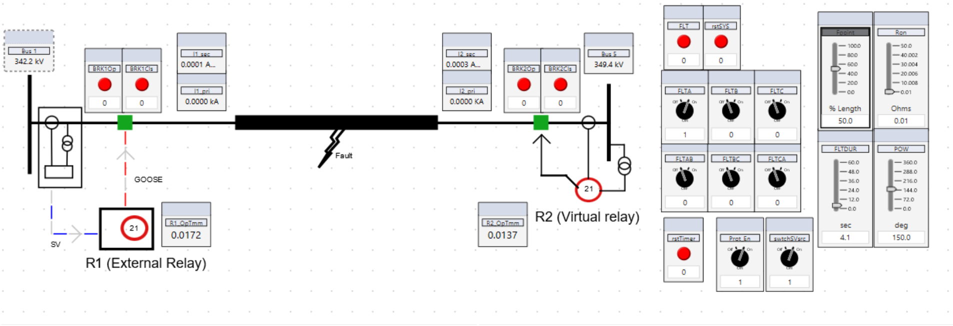

Bus 1 342.2 kV
BRK1Op 0
BRK1Cls 0
I1_sec 0.0001 A...
I1_pri 0.0000 kA
R1_OpTmm 0.0172
I2_sec 0.0003 A...
I2_pri 0.0000 KA
BRK2Op 0
BRK2Cls 0
Bus 5 349.4 kV
R2_OpTmm 0.0137
FLT 0
rstSYS 0
FLTA 1
FLTB 0
FLTC 0
FLTAB 0
FLTBC 0
FLTCA 0
rstTimer 0
Prot_En 1
swtchSVsrc 1
Fpoint % Length 50.0
Ron Ohms 0.01
FLTDUR sec 4.1
POW deg 150.0

Figure 11: Virtual Relay Output Scheme

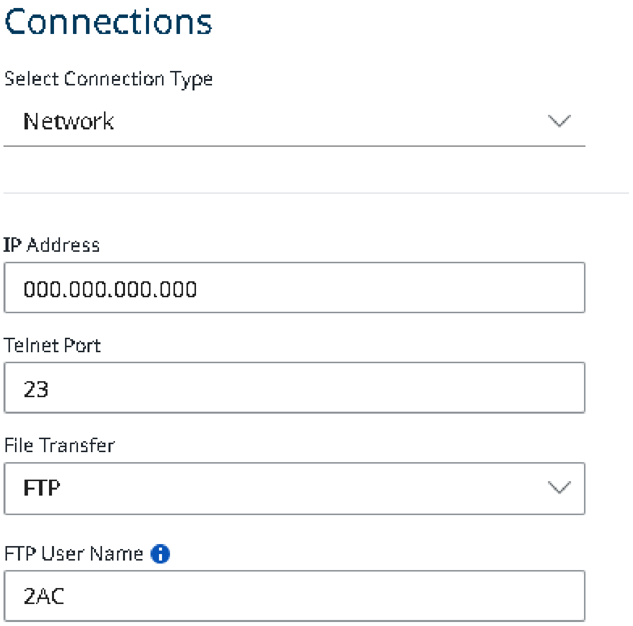
The reason this model is different from a distance protection model found in another program is because it can send and receive communication signals. These blocks deal with the SV and GOOSE communication protocols. The PT and CT blocks are connected to the SV block using the RSCAD’s built in logic scheme. This SV block’s settings are used to target the SEL-421-7 using its MAC address to guarantee a successful transmission of voltage and current measurements. The GOOSE block connects to the circuit breaker using a different logic scheme. This is a two-way communication scheme which sends breaker status information one way, and the trip signal the other way.

2.1.4.2.2 Grid Configurator

Grid Configurator is a new software tool that is used to program the SEL-421-7 and all the protection elements that can be used. Grid Configurator has many uses and features when setting up a complex grid, many of which are not used except to troubleshoot any inconsistencies. A troubleshooting technique that was often employed was to check the individual bits of each setting from the terminal window. All settings are given a bit, either a 1 or

0, representing enabled or disabled. This was used to understand how the SEL-421-7 was functioning. All the parameters are entered under Group 5, which is the only group enabled, seen by using the troubleshooting technique mentioned prior. The main settings changed can be found in the protection elements and the grid settings.

Primarily, The SEL-421-7 must be connected to the network. The SEL-421-7 operates at various levels of access. Once the SEL-421-7 is unlocked with the correct password using the user interface, it can be connected to the network using FTP file transfer. These settings are shown in Figure 12.a. FTP has a much faster file transfer, which is why it is being used instead of Telnet; however, Telnet will suffice when setting up the SEL-421-7 as shown in Figure 12.b. The username and password for this access level is 2AC and TAIL, respectively.



Connections

Select Connection Type: Network

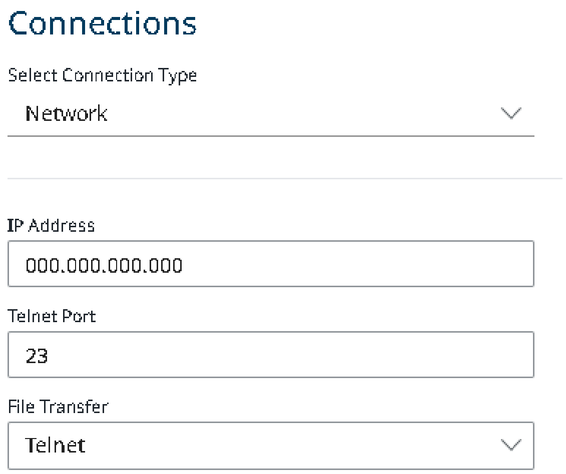
IP Address: 000.000.000.000

Telnet Port: 23

File Transfer: FTP

FTP User Name: 2AC

Figure 12.a: FTP SEL-421-7 Connection Port



Connections

Select Connection Type: Network

IP Address: 000.000.000.000

Telnet Port: 23

File Transfer: Telnet

Figure 12.b: IP Address & Telnet Connection Port

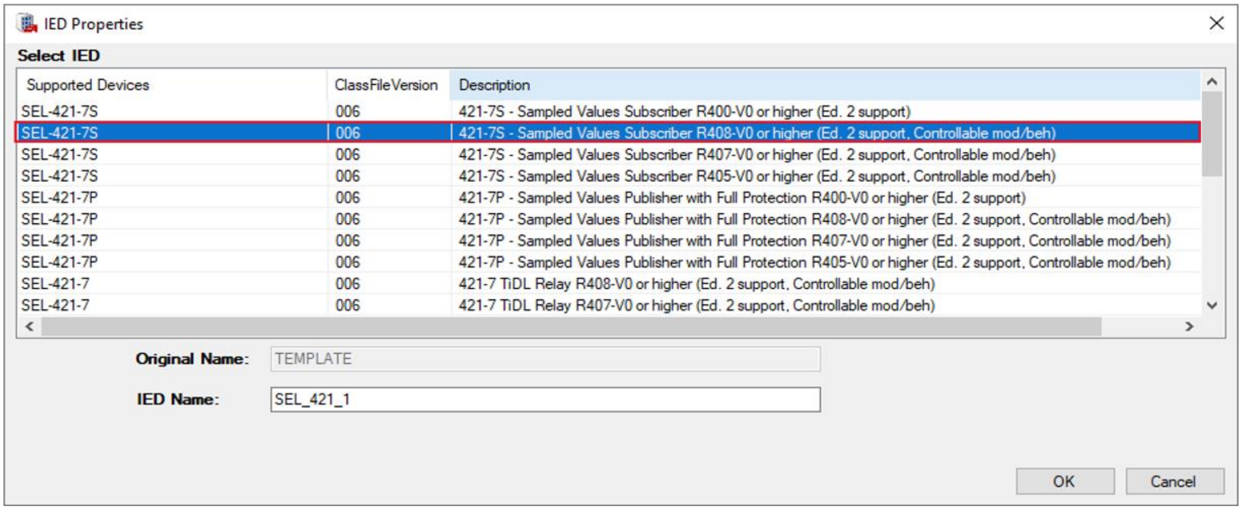
The line and zone parameters were found using basic distance protection and zone equations, found in the Appendix. The reach used was 80% of the secondary line impedance for zone 1 and 120% for zone 2. These values were determined by the response of the virtual relay, which is related to the industry standard practices [6]. Although zone 2’s reach is 20% beyond the simulated lines length, the grid configurator data is still valuable for two reasons. The first reason is because the testbed is supposed to be as accurate as possible, to give students a deeper understanding of fault protection practices. The second reason is to allow the user to input settings for when the fault does not fall into zone 1’s reach. The SEL-421-7's response must replicate the virtual relays response as close as possible with the same fault parameters relative to the relay. This meant that the SEL-421-7 must trip instantly when the fault is seen in zone 1 and must wait 20 cycles when the fault is seen in zone 2.

The line settings are in “Settings Grid” under “Group 5”. The name of the settings can be found in section 5.6 in the Appendix on Table 2. These include the potential and current transformer ratios, secondary line impedance, and the length of the line. Group 5 is arbitrary, and any group will work if the group is selected in the settings.

Another valuable tool when troubleshooting the code on the SEL-421-7 is by displaying parameters on the rolling screen display. This was done by utilizing “Bay Control” settings, specifically the setting labeled “MDELE#.” There is a whole library of codes to display specific parameter values.

2.1.4.2.3 acSELerator Architect

AcSELerator Architect is a unique and useful tool when having to set up communication on an SEL-421-7. It allows for the configuration of inputs for GOOSE communication from the SEL-421-7, which is responsible for tripping the relay's breaker. These logic inputs come from a separate IED file, specific to the current relay setup, which can be downloaded from SEL's website with their ICD package. AcSELerator Architect allows for specific inputs to be placed into a dataset and configured into a GOOSE message, then exported to the SEL-421-7 to update the functionality of those inputs and prepares them for communication. Figure 13 shows the IED selection screen that can also be found when setting up the acSELerator Architect. This can also be found in Appendix section 5.1.



Supported Devices	ClassFileVersion	Description
SEL-421-7S	006	421-7S - Sampled Values Subscriber R400-V0 or higher (Ed. 2 support)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R407-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R405-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R400-V0 or higher (Ed. 2 support)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R407-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R405-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7	006	421-7 TiDL Relay R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7	006	421-7 TiDL Relay R407-V0 or higher (Ed. 2 support, Controllable mod/beh)

Original Name: TEMPLATE

IED Name: SEL_421_1

Figure 13: IED Chosen for Testbed

2.1.4.3 Lab Manuals & Device Documentation

Three documents were created each for a different purpose. The first document is used to aid other professors or institutions, given that they have the required equipment. This document explains each relevant step, using AcSELerator architect, SEL Grid Configurator, and RSCAD. This process was partially explained in the documentation within the RSCAD's model folder [6], but the initial document left out many details required for the testbed to run correctly. The latest version includes all settings not explained in the initial document.

The next two documents pertain to the student lab; one is the lab workbook, and the other one is the student manual. The lab workbook familiarizes students with industry standards, important calculations, and fault parameters. The students work with RSCAD and SEL Grid Configurator to find line parameters and program the relay to trip appropriately. These programs are complex, but the student has the manual to help familiarize themselves with these programs. RSCAD is not expected to be used when designing and automating a transmission line relay, so the RSCAD instructions are very direct. The SEL Grid Configurator instructions are less direct, since it is likely for an engineer to use this software, or others like it, in the future. Students are expected to take some time before and during the lab to familiarize themselves with the lab.

These three documents have all the information for a distance protection lab. They help everyone involved, from the professor troubleshooting an issue with the software to the student learning how to use the testbed. These documents call be found in the appendix.

2.2 Design & Implementation

The design of the transmission line, virtual relay, and RSCAD simulation were made by RTDS Technologies for HIL testbeds using the external devices, specifically the SEL-421-7. This simulation file was accompanied by a document that detailed the setup of the testbed using the SEL-421-7. This includes SEL Grid Configurator connection and settings, AcSELerator Architect setup, and the configuration of the GOOSE and SV blocks in RSCAD. Although this document explains how to set up everything for working conditions, it falls short in several areas, bringing challenges to the user.

The RTDS enclosure includes the NovaCor, GTNETx2, GTSYNC, and an ethernet switch. The NovaCor is connected to the GTSYNC card, so that the simulation can be made in real time. The NovaCor is also connected to the GTNETx2 which handles the communication protocols GOOSE and SV. The GTNETx2, SEL-421-7, and external computer were plugged into the ethernet switch. The whole connection scheme can be seen in Figure 3.

SEL Grid Configurator used Telnet and FTP, but FTP is faster due to the higher priority level. Since SEL creates most of the programs used in this project, much of the setup requires downloading separate configurations such as SEL Compass, which is the IED library for our specific device. The library gives Architect fault conditions for each phase line, which needs to be introduced into the dataset. Once the Architect file is sent to the SEL-421-7 a trip signal can be sent through Port 5D of the SEL-421-7, using GOOSE, when the trip activates.

The Zone parameters were given in the RTDS document, that thankfully were already up to industry standard values. Still, the calculations were redone to prepare the lab documentation, with “Zone 1 Reach” being 80% of the line and “Zone 2 Reach” going from 80% to 120%. The calculations stem from the value of the primary line impedance, the Current Transformer (CT) Ratio and the Potential Transformer (PT) Ratio given on RSCAD. The SEL-421-7 Although the RSCAD simulation only shows one transmission line, being 100%, using 120% of the line impedance for Zone 2 is imperative to the testbed being as realistic as possible. The calculations needed for the protection elements in SEL Grid Configurator consist of 80% and 120% of the secondary line impedance. These will be shown in Equations 1 and 2 which can be seen below. Other parameters that need to be uploaded are CT and PT values, line length, and secondary line impedance. Logic that needed to be included was breaker control codes and trip control. The X denotes how large or small you want your zone to be. For this testbed Zone 1 was 80 percent and Zone 2 was 120 percent so we would multiply this by the result of equation 1.

$$\text{Equation 1: } Z_{sec} = Z_1\left(\frac{CT}{PT}\right)$$

$$\text{Equation 2: } Zone\ Impedances = X\% * Z_{sec}$$

Three documents were written. The first document was a detailed outline of the testbed setup. This includes the connection of the SEL-421-7 to the RTDS, SEL Grid Configurator, RSCAD, and AcSELerator Architect. This document is useful for any institution that would like to create a lab based on a HIL design, provided they have the required hardware. The Student Lab Workbook document provides the student with five tasks to strengthen their understanding of distance protection. The first couple tasks guide the student through calculations, such as secondary line impedance and zone values. The next tasks require the student to upload the parameters to the SEL-421-7 to finally display different faults on the RSCAD runtime. These faults directions are so the student must choose the right parameters so that the SEL-421-7 and virtual relay react accordingly. More explanation can be found in the Student Lab Workbook found in the appendix. The last documentation is the Student Lab Manual used to support the student during the lab. This explains how to use the programs SEL Grid Configurator and RSCAD.

2.2.1 Performance Testing & Analysis

The testing was partially discussed in the previous section 2.1.3.3 Specification Validation. There are four simulations to validate that all protection elements are working. These simulations comprise of two ground faults and phase faults, each with Zones 1 and Zones 2. Although these are the only required faults, many more were done including a ground fault of each line, multiple line to line faults, and many combinations. Furthermore, the accuracy of the zone limits was tested by simulating a fault at 79% and the other at 81%. Both cases, the SEL-421-7, reacted as expected with one triggering in Zone 1 and the other with Zone 2. The SEL-421-7 was also tested within Zone 2, to be sure that it will only send a trip signal if the fault lasts for more than 20 cycles or 333 milliseconds. The last test was a visual analysis making sure that the SEL-421-7 reacted the same as the virtual relay, down to the duration of the trip signal which was 150 milliseconds. The similarities, including the response time, can be found in section 5.5 of the Appendix due to the quantity of information. A lab was made to test the training capabilities of the testbed, electrical engineering students were asked to take this lab to see if it contained enough information to be informative. Students were also given an evaluation form to fill out after this lab's completion. The evaluation contained questions about the clarity of questions and if the material it contained would be a useful training tool. These questions and the results are detailed in the Appendix section 5.4 Lab Workbook Evaluation.

2.2.2 Design Consideration

There were many different routes that could have been taken when designing this testbed, and some presented themselves at various levels of completion. The original plan was to create a simulated transmission model emulating a power system found in the field. There was a lot of extra research that had to be done on RSCAD to build a more complex model. The RSCAD model used in the testbed is a modified version of an example model created by RTDS technologies. The model was modified to best reflect the specifications. This was the best avenue that could have been taken as a lot of time was spent researching the SEL-421-7 and related programs [7]. The example model met most of the specifications such as using a virtual relay in conjunction with an external protection relay and could simulate several types of faults.

Another edit made to the original work path was creating a lab exercise to display the testbed's training capabilities. The lab was taken by students who had little to no experience with distance protection, and no experience with the RTDS. A student lab manual was also made which helps students specifically with the lab tasks and gives a general overview of how to use RSCAD and Grid Configurator. It was decided to split these up to prove that the testbed could be a useful training tool. These were separate documents from the professor documentation which was an original specification

2.2.2.1 Public Health

non-applicable

2.2.2.2 Safety & Welfare

This testbed will be used in a lab setting, so the safety of the equipment, connection, and operators involved would be one of the most important considerations when this testbed was being designed. We diligently labeled all the port connections to ensure minimal mistakes when the testbed is being recreated. The testbed takes some of the danger of testing these devices in the field since there are no high voltages or currents, but sampled values. The safety and welfare of everyone involved is unavoidable and should be considered at every point of the testbed, from setup of the testbed to running the simulation.

2.2.2.3 Global Impact

The RTDS and RSCAD can be used to simulate complex power systems, which limits the danger and cost of testing these high-voltage systems. The testbed using these devices will help WMU InterEnergy Center to propel the world forward to a brighter future in the world of power generation, transmission, and storage. Since the world is working to move away from carbon producing forms of power generation this testbed can be the first steppingstone to make that goal fully realizable.

2.2.2.4 Cultural Impact

non-applicable

2.2.2.5 Social Impact

The impact that this testbed will have on the WMU Electrical & Computer engineering department will be substantial. Since this will bring more attention to the department and the school regarding power systems. The testbed was one of the first experiments done using the RTDS which was provided by the WMU InterEnergy Center. This was just a fraction of the experiments that can be completed using this device and brings substantial attention to this newly founded research center [18].

2.2.2.6 Environmental & Sustainability

The testbed that was created is an extremely specific transmission line setup and tests only one device, however the RTDS can be setup to be substantially more complex and encompass multiple different devices and or schemes [9]. If the RTDS can test multiple types of power grid configurations through real time simulations, this removes the need to set up full size tests, which consumes time and resources. The world is beginning to move away from fossil fuels and with that the need to test new versions of renewable-based power systems is also growing in importance, which can also be tested with the RTDS. Finally, the RTDS can be used to lay out proposed power grids to test their capacity or incorporate proposed devices without physically installing them into the grid, which saves money, time, and resources.

2.2.2.7 Economic

For WMU, the initial investment for the RTDS and the SEL-421-7 were already made before plans for the testbed were created. So, the power consumption needed for the RTDS, and the SEL-421-7 were the only costs while creating this testbed. The financial commitment for this equipment is steep but if used by power companies and or research centers the devices pay for themselves through research conducted with the equipment. With the initial upfront cost, there can be limitless experiences and cases tested to better engage students, or if used for research can cut the cost of traditional testing methods.

2.2.3 Design Impact

Since the RTDS is unique, the possibilities are not fully realized or documented [6]. The documentation included with the testbed serves as the basis for HIL testing with the RTDS, as there has not been detailed documentation released for connecting the RTDS and SEL-421-7 that is readily available. With this current information now available it opens the doors for WMU to begin more complex work and research with the RTDS. The WMU InterEnergy Center will investigate a multitude of challenges currently facing the world of power systems now using the RTDS. This will bring more attention to the university through the work being done by the center to combat these challenges.

Another major impact comes from the distance protection lab that was created. Since WMU does not have a transmission line protection class, the testbed and accompanied documentation could make the class a realistic goal in the future. This in turn could strengthen the Electrical and Computer Engineering department's status as a potential university to transfer and incoming students.

2.2.3.1 Global

Currently the world thrives on access to reliable power. The activities involved with the testbed can lead to limitless experiences and revelations within the power industry. The RTDS and RSCAD models can limit the chance of exposure to high voltage systems and make testing of power equipment safer and more reliable. This paves the way for new experiments that were not feasible or too expensive before this device was available. The documentation included in the appendix will bring attention to what is possible with these devices. The documentation's goal is to encourage students worldwide to seek out classes and careers in power systems.

2.2.3.2 Economic

The economic benefits of this testbed are unquantifiable because this equipment is extremely expensive to obtain, so many companies and research groups will have no training or experience for how to use these devices. Since one of the deliverables for this testbed is a lab workbook, a class can be created around the idea of faults and transmission systems. This will further entice students looking for careers in power systems to choose WMU for an education.

2.2.3.3 Environmental

The testbed displays the capabilities of the RTDS, which can also help the power industry to narrow down power alternatives in contention for the future of power generation. As countless countries have now set a timeline to be carbon neutral, the days of using fossil fuels to generate society's power have been numbered. With the increased efficiency of testing these power systems, we can reduce the time spent on testing different methods. The dream of achieving net-zero carbon emissions can be realized even sooner.

2.2.3.4 Societal

The full potential of this testbed will be achieved when it is evolved to encompass more complex power systems. This will in turn make power systems easier to work with and test. When the way we work on the power grid is changed and becomes more available, society will benefit. When the testing methods become more streamline and easy to complete this will open the door to endless advancements for the world of power. The hope of this testbed was to start this improvement process so society can benefit from the results.

3. Conclusions

The real-time testbed for transmission line protection project has successfully demonstrated an educational tool that integrates Western Michigan University's RTDS and SEL-421-7 protection relay. This testbed, utilizing the GOOSE communication protocol, offers a safe and comprehensive environment for students to explore and understand the behavior of protection relays in response to various fault conditions in power transmission lines. The project highlights the accessibility and safety of high-voltage power system testing through hardware-in-the-loop methodologies. By doing so, it prepares future engineers for the complexities of modern power systems and contributes significantly to the academic and professional development of students in electrical engineering fields of study. The documentation and testbed setup serve as a robust foundation for further educational and research activities, potentially leading to more advanced studies and innovations in power system protection.

4. Recommendations

The SEL-421-7 has many more settings to automate a distance protection scheme. The protection settings can monitor many aspects of a transmission line including the following: breaker failures, underpower, overpower, recloser and manual closing, and switch on to fault. The SEL logic scheme allows engineers to automate the protection to respond correctly in complex situations. Some of these protection options are unable to be implemented using the original RSCAD model. Fortunately, The RTDS can simulate a more complicated system. RSCAD has many other examples and tutorials, meaning the external relays can simulate anything from low-voltage grids to transmission grids, giving students a well-rounded understanding of power grids. It is also possible to simulate a distance protection scheme with multiple external relays. This would require purchasing more relays, different from a SEL-421-7, so students can understand how field relays transmit data and work together to protect a grid or system. This is possible because the GTNETx2 card can use many types of communication protocols to communicate with other types of relays. Although the newer and faster communication protocol is IEC 61850, older communications such as DNP3, MODBUS, and proprietary can be used as well [2][3].

5. APPENDIX –Project Documentation, Results, & Standards

5.1 Professor Documentation

Western Michigan University
College of Engineering and Applied Sciences

ECE 4820 Senior Design

Mark Booge

Kyle Taiariol
Nolan Ulp

Dr. Pablo Gomez

Real-Time Testbed for Transmission Line Protection

Professor Master Configuration Manual

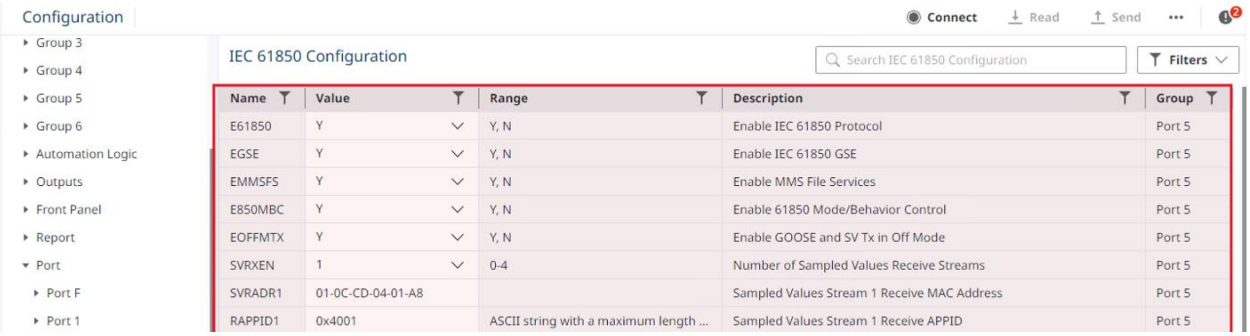
04/25/2024

Table of Contents

Disclaimer: *This manual describes the setup between the RTDS simulator and the SEL-421-7. However, these steps can be generally applied to any IEC 61850 Intelligent Electronic Device (IED) with the RTDS simulator. Different steps may be required to set up another IED.*

Grid Configurator

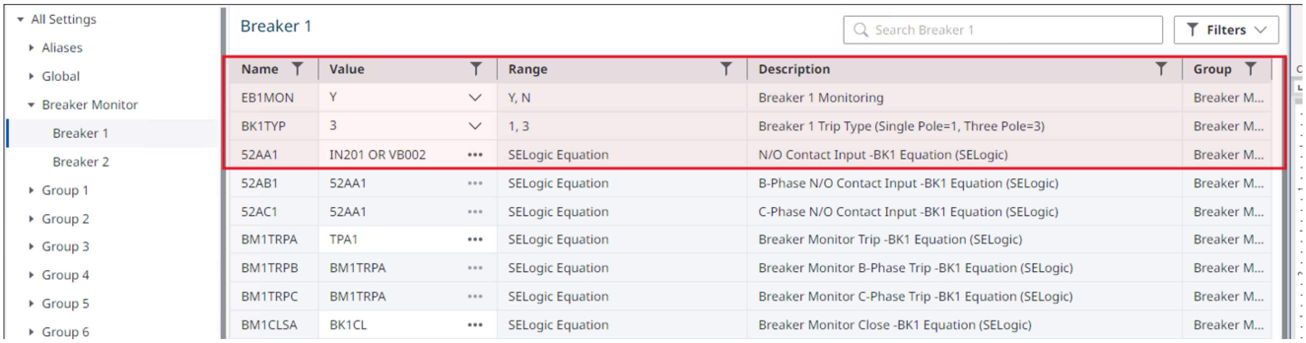
1. To ensure that sampled values, GOOSE Messaging, and Trip Logic are set up correctly for the SEL-421-7, open Grid Configurator and connect to the relay. Make sure to follow the connect to relay steps first in the Other Helpful Information section.
2. Once connected, navigate to "Settings Grid => All Settings => Port => Port 5 => IEC 61850 Configuration => Sampled Values Receive"
3. The first three settings in the list are all that should be focused on, set them up according to these guidelines:



Name	Value	Range	Description	Group
E61850	Y	Y, N	Enable IEC 61850 Protocol	Port 5
EGSE	Y	Y, N	Enable IEC 61850 GSE	Port 5
EMMSFS	Y	Y, N	Enable MMS File Services	Port 5
E850MBC	Y	Y, N	Enable 61850 Mode/Behavior Control	Port 5
EOFFMTX	Y	Y, N	Enable GOOSE and SV Tx in Off Mode	Port 5
SVRXEN	1	0-4	Number of Sampled Values Receive Streams	Port 5
SVRADR1	01-0C-CD-04-01-A8		Sampled Values Stream 1 Receive MAC Address	Port 5
RAPPID1	0x4001	ASCII string with a maximum length ...	Sampled Values Stream 1 Receive APPID	Port 5

   a. Enable All Y/N settings in the highlighted section to Y
   b. SVRXEN: 1
   c. SVRADR1: 01-0C-CD-04-01-A8 (this should match the MAC address in SV block)
   d. RAPPID1: 0x4001 (this should match the APPID in SV block)

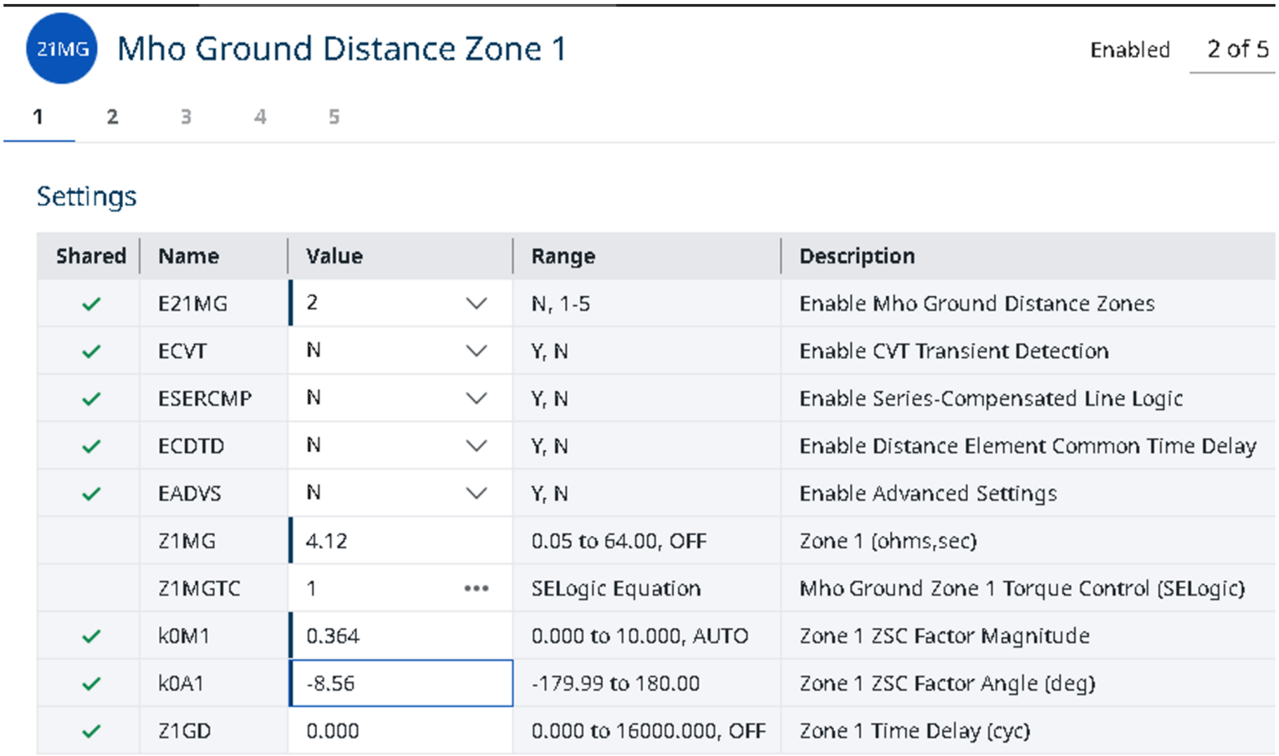
4. Scroll down to find "Settings Grid => All Settings => Breaker Monitor => Breaker 1, and set up these settings as follows:



Name	Value	Range	Description	Group
EB1MON	Y	Y, N	Breaker 1 Monitoring	Breaker M...
BK1TYP	3	1, 3	Breaker 1 Trip Type (Single Pole=1, Three Pole=3)	Breaker M...
52AA1	IN201 OR VB002	SELogic Equation	N/O Contact Input -BK1 Equation (SELogic)	Breaker M...
52AB1	52AA1	SELogic Equation	B-Phase N/O Contact Input -BK1 Equation (SELogic)	Breaker M...
52AC1	52AA1	SELogic Equation	C-Phase N/O Contact Input -BK1 Equation (SELogic)	Breaker M...
BM1TRPA	TPA1	SELogic Equation	Breaker Monitor Trip -BK1 Equation (SELogic)	Breaker M...
BM1TRPB	BM1TRPA	SELogic Equation	Breaker Monitor B-Phase Trip -BK1 Equation (SELogic)	Breaker M...
BM1TRPC	BM1TRPA	SELogic Equation	Breaker Monitor C-Phase Trip -BK1 Equation (SELogic)	Breaker M...
BM1CLSA	BK1CL	SELogic Equation	Breaker Monitor Close -BK1 Equation (SELogic)	Breaker M...

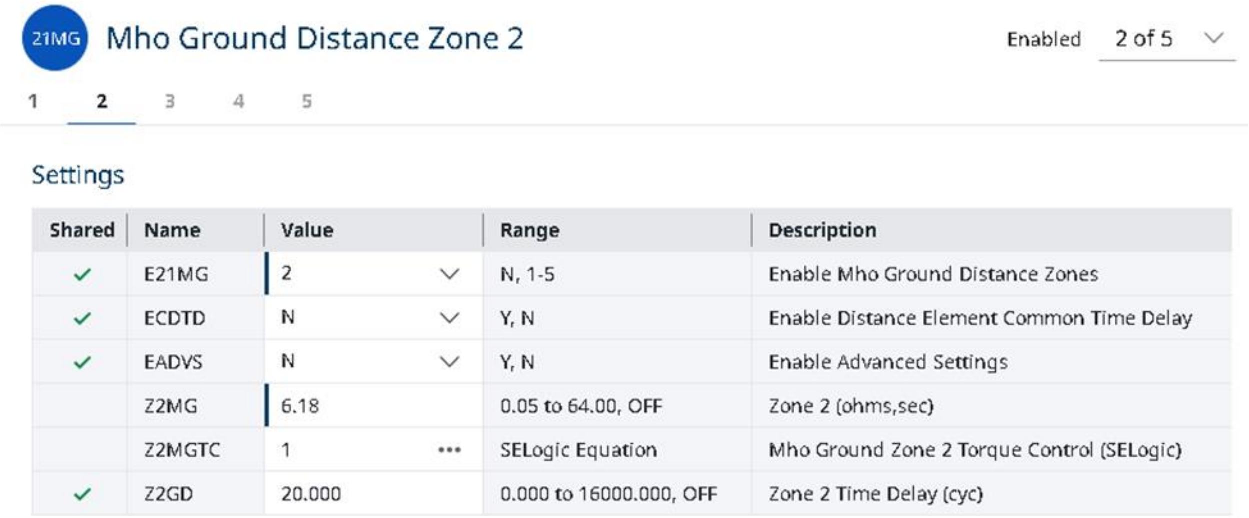
   a. EB1MON: Y
   b. BK1TYP: 3
   c. 52AA1: IN201 OR VB002

5. Find the “Protection” then Click “Protection Elements.” Set up these settings as follows:
    a. Mho Ground Distance Zone 1:



Shared	Name	Value	Range	Description
✓	E21MG	2	N, 1-5	Enable Mho Ground Distance Zones
✓	ECVT	N	Y, N	Enable CVT Transient Detection
✓	ESERCMP	N	Y, N	Enable Series-Compensated Line Logic
✓	ECDTD	N	Y, N	Enable Distance Element Common Time Delay
✓	EADVS	N	Y, N	Enable Advanced Settings
	Z1MG	4.12	0.05 to 64.00, OFF	Zone 1 (ohms,sec)
	Z1MGTC	1	SELogic Equation	Mho Ground Zone 1 Torque Control (SELogic)
✓	k0M1	0.364	0.000 to 10.000, AUTO	Zone 1 ZSC Factor Magnitude
✓	k0A1	-8.56	-179.99 to 180.00	Zone 1 ZSC Factor Angle (deg)
✓	Z1GD	0.000	0.000 to 16000.000, OFF	Zone 1 Time Delay (cyc)

b. Mho Ground Distance Zone 2:



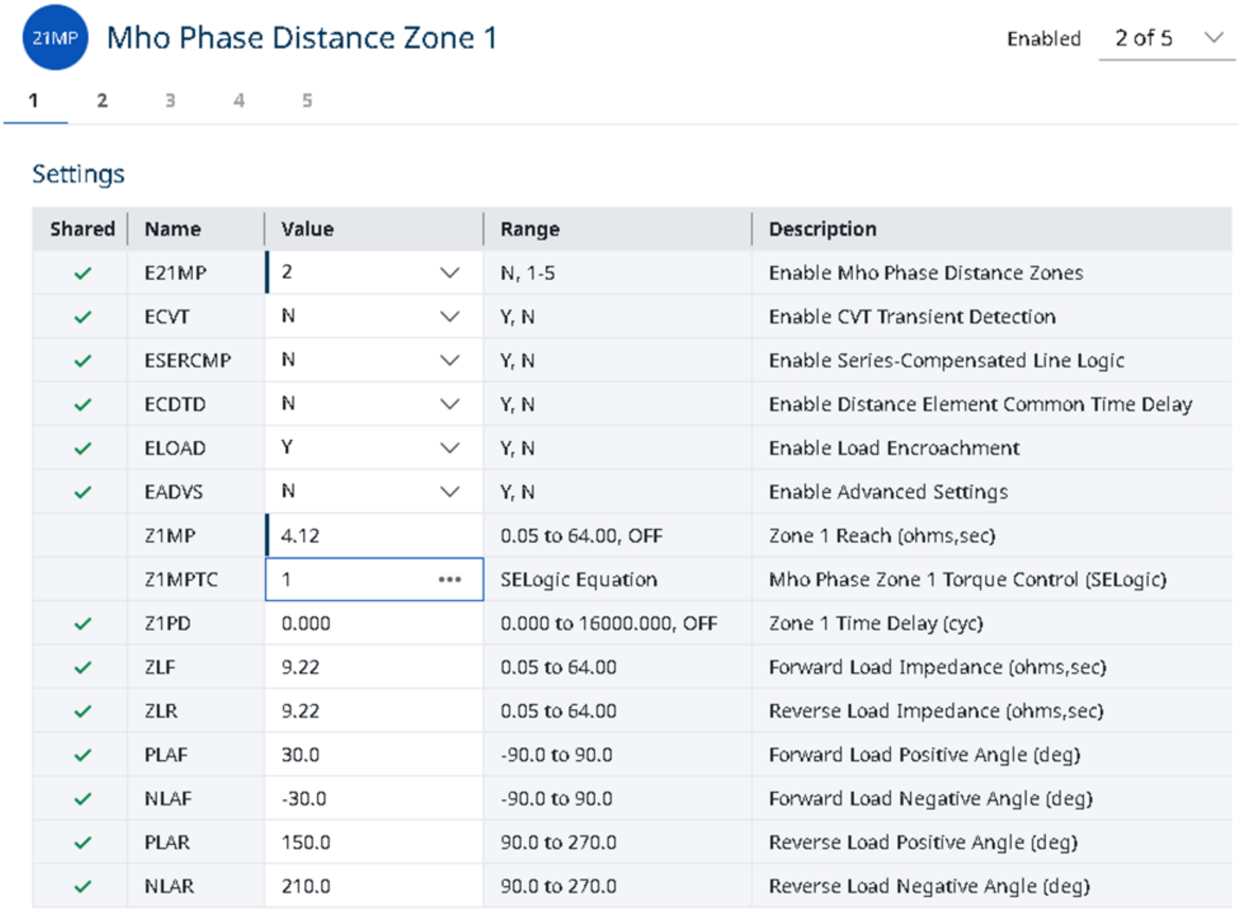
Mho Ground Distance Zone 2

Enabled 2 of 5

Settings

Shared	Name	Value	Range	Description
✓	E21MG	2	N, 1-5	Enable Mho Ground Distance Zones
✓	ECDTD	N	Y, N	Enable Distance Element Common Time Delay
✓	EADVS	N	Y, N	Enable Advanced Settings
	Z2MG	6.18	0.05 to 64.00, OFF	Zone 2 (ohms,sec)
	Z2MGTC	1	SELogic Equation	Mho Ground Zone 2 Torque Control (SELogic)
✓	Z2GD	20.000	0.000 to 16000.000, OFF	Zone 2 Time Delay (cyc)

c. Mho Phase Distance Zone 1:



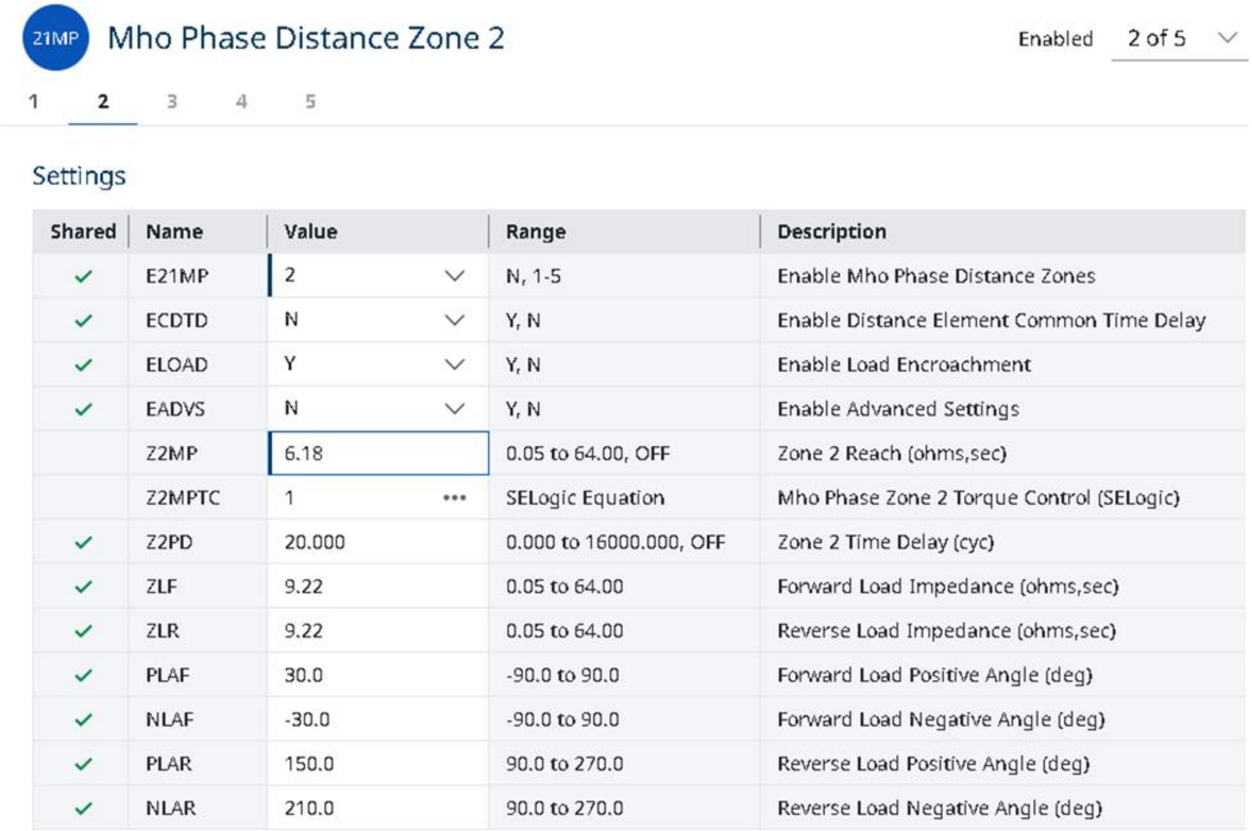
Mho Phase Distance Zone 1

Enabled 2 of 5

Settings

Shared	Name	Value	Range	Description
✓	E21MP	2	N, 1-5	Enable Mho Phase Distance Zones
✓	ECVT	N	Y, N	Enable CVT Transient Detection
✓	ESERCMP	N	Y, N	Enable Series-Compensated Line Logic
✓	ECDTD	N	Y, N	Enable Distance Element Common Time Delay
✓	ELOAD	Y	Y, N	Enable Load Encroachment
✓	EADVS	N	Y, N	Enable Advanced Settings
	Z1MP	4.12	0.05 to 64.00, OFF	Zone 1 Reach (ohms,sec)
	Z1MPTC	1	SELogic Equation	Mho Phase Zone 1 Torque Control (SELogic)
✓	Z1PD	0.000	0.000 to 16000.000, OFF	Zone 1 Time Delay (cyc)
✓	ZLF	9.22	0.05 to 64.00	Forward Load Impedance (ohms,sec)
✓	ZLR	9.22	0.05 to 64.00	Reverse Load Impedance (ohms,sec)
✓	PLAF	30.0	-90.0 to 90.0	Forward Load Positive Angle (deg)
✓	NLAF	-30.0	-90.0 to 90.0	Forward Load Negative Angle (deg)
✓	PLAR	150.0	90.0 to 270.0	Reverse Load Positive Angle (deg)
✓	NLAR	210.0	90.0 to 270.0	Reverse Load Negative Angle (deg)

d. Mho Phase Distance Zone 2:



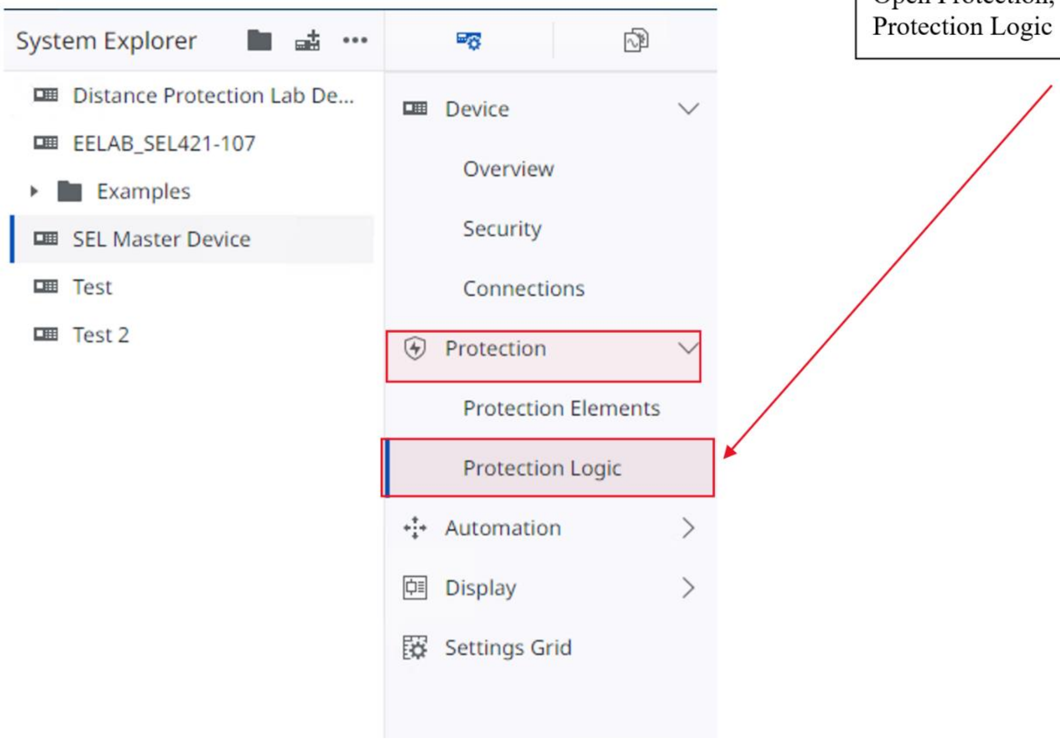
Mho Phase Distance Zone 2

Enabled 2 of 5

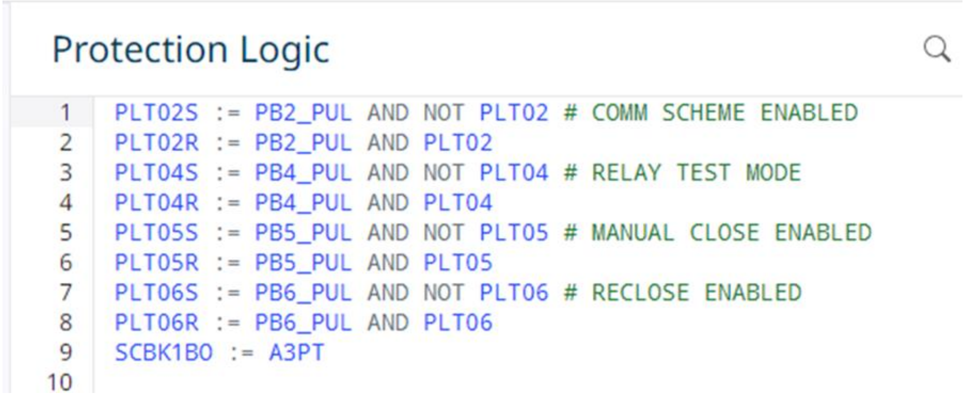
Settings

Shared	Name	Value	Range	Description
✓	E21MP	2	N, 1-5	Enable Mho Phase Distance Zones
✓	ECDTD	N	Y, N	Enable Distance Element Common Time Delay
✓	ELOAD	Y	Y, N	Enable Load Encroachment
✓	EADVS	N	Y, N	Enable Advanced Settings
	Z2MP	6.18	0.05 to 64.00, OFF	Zone 2 Reach (ohms,sec)
	Z2MPTC	1	SELogic Equation	Mho Phase Zone 2 Torque Control (SELogic)
✓	Z2PD	20.000	0.000 to 16000.000, OFF	Zone 2 Time Delay (cyc)
✓	ZLF	9.22	0.05 to 64.00	Forward Load Impedance (ohms,sec)
✓	ZLR	9.22	0.05 to 64.00	Reverse Load Impedance (ohms,sec)
✓	PLAF	30.0	-90.0 to 90.0	Forward Load Positive Angle (deg)
✓	NLAF	-30.0	-90.0 to 90.0	Forward Load Negative Angle (deg)
✓	PLAR	150.0	90.0 to 270.0	Reverse Load Positive Angle (deg)
✓	NLAR	210.0	90.0 to 270.0	Reverse Load Negative Angle (deg)

6. Navigate to the Protection Tab => Protection Logic, then enter in the logic as shown below:



Open Protection, Then Protection Logic



Protection Logic

```
PLT02S  := PB2_PUL  AND  NOT  PLT02  #  COMM  SCHEME  ENABLED
PLT02R  := PB2_PUL  AND  PLT02
PLT04S  := PB4_PUL  AND  NOT  PLT04  #  RELAY  TEST  MODE
PLT04R  := PB4_PUL  AND  PLT04
PLT05S  := PB5_PUL  AND  NOT  PLT05  #  MANUAL  CLOSE  ENABLED
PLT05R  := PB5_PUL  AND  PLT05
PLT06S  := PB6_PUL  AND  NOT  PLT06  #  RECLOSE  ENABLED
PLT06R  := PB6_PUL  AND  PLT06
SCBK1BO  := A3PT

```

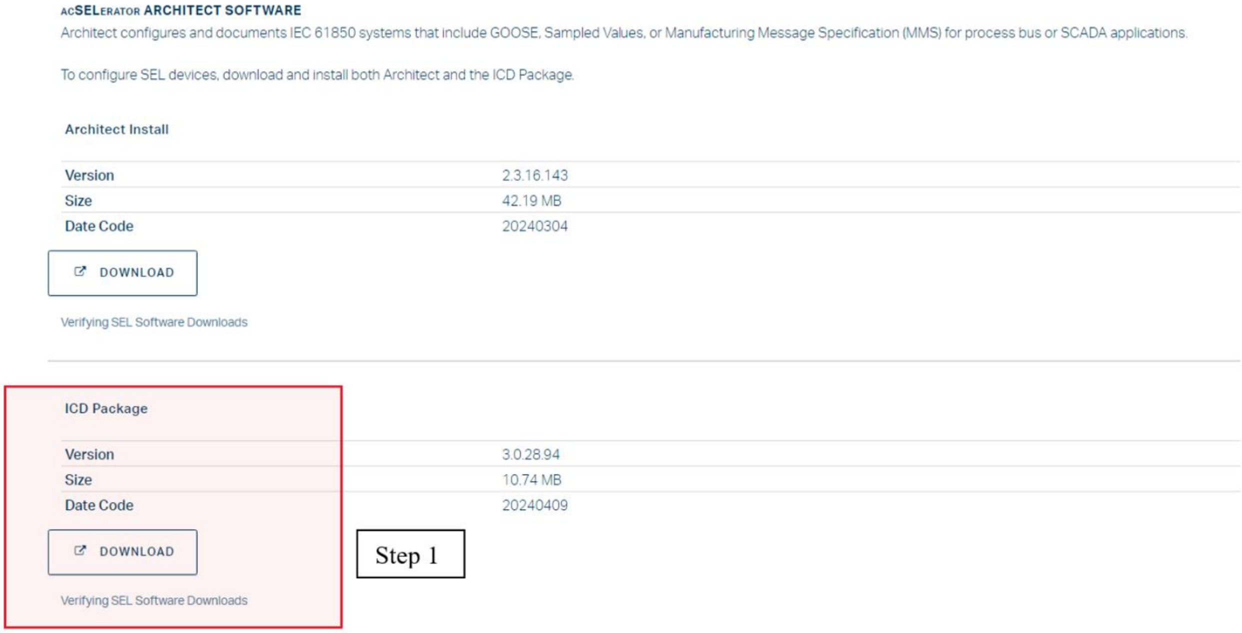
7. Press the Send button to send the updated settings to the SEL. Confirm that Sampled Values are showing up on SEL-421-7 display.

```
RMS LINE METER
VOLTAGE (kV)
  VA =   199.0
  VB =   198.9
  VC =   199.0
CURRENT (A)
  IA =   350.7
  IB =   350.6
  IC =   350.9
FREQ = 59.98 Hz
```

8. After you have completed the Sampled Values Setup, Architect Setup, and GOOSE Block setup, the testbench should be ready to use.

acSELerator Architect

1. Select the correct ‘SEL_421’ IED from the ‘IED palette’ in acSELerator Architect. If no IEDs are loaded, download, and run the .exe ICD package from: ‘https://selinc.com/products/5032/support/#tab-downloads’ to populate the IED palette with different IEDs.



acSELerator ARCHITECT SOFTWARE

Architect configures and documents IEC 61850 systems that include GOOSE, Sampled Values, or Manufacturing Message Specification (MMS) for process bus or SCADA applications.

To configure SEL devices, download and install both Architect and the ICD Package.

Architect Install

Version	2.3.16.143
Size	42.19 MB
Date Code	20240304

Verifying SEL Software Downloads

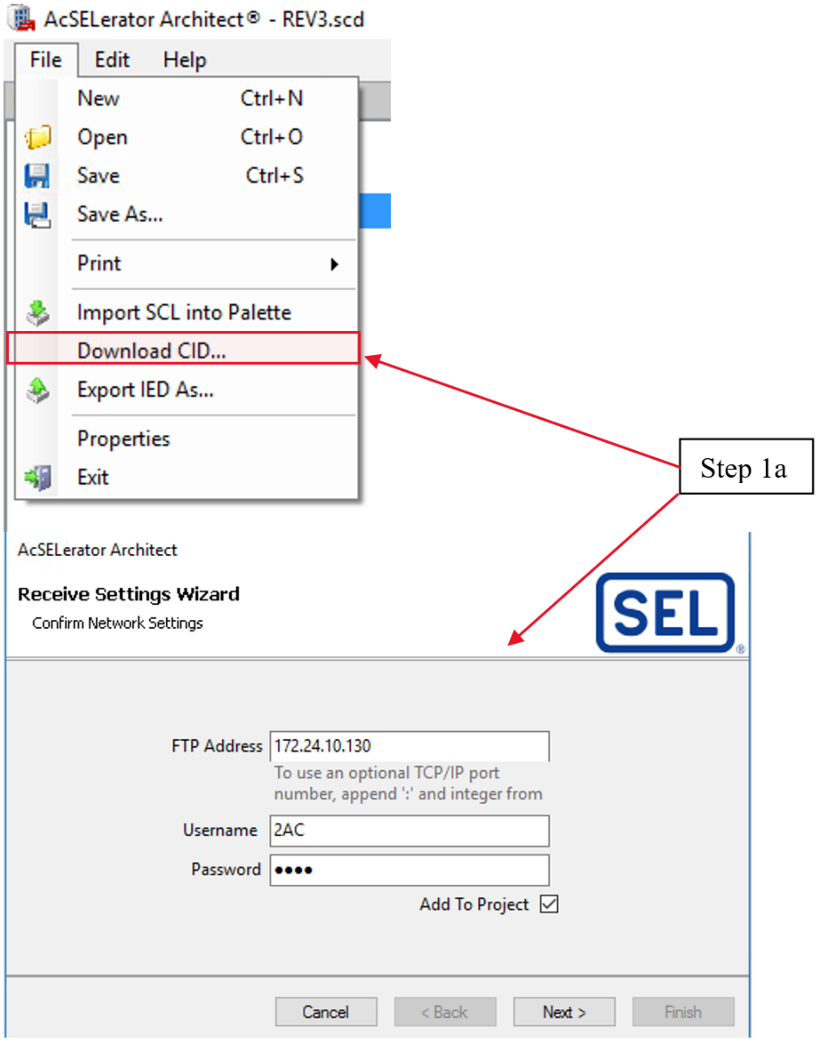
ICD Package

Version	3.0.28.94
Size	10.74 MB
Date Code	20240409

Verifying SEL Software Downloads

Step 1

a. Or, if you have already completed the connection process to the SEL-421-7 through Grid Configurator, you can download the CID file, which will import the IED from the SEL-421-7 into Architect for you to edit. Enter the FTP address 172.24.10.130. The username is 2AC and password is TAIL.



AcSELerator Architect

Receive Settings Wizard

Confirm Network Settings

FTP Address: 172.24.10.130

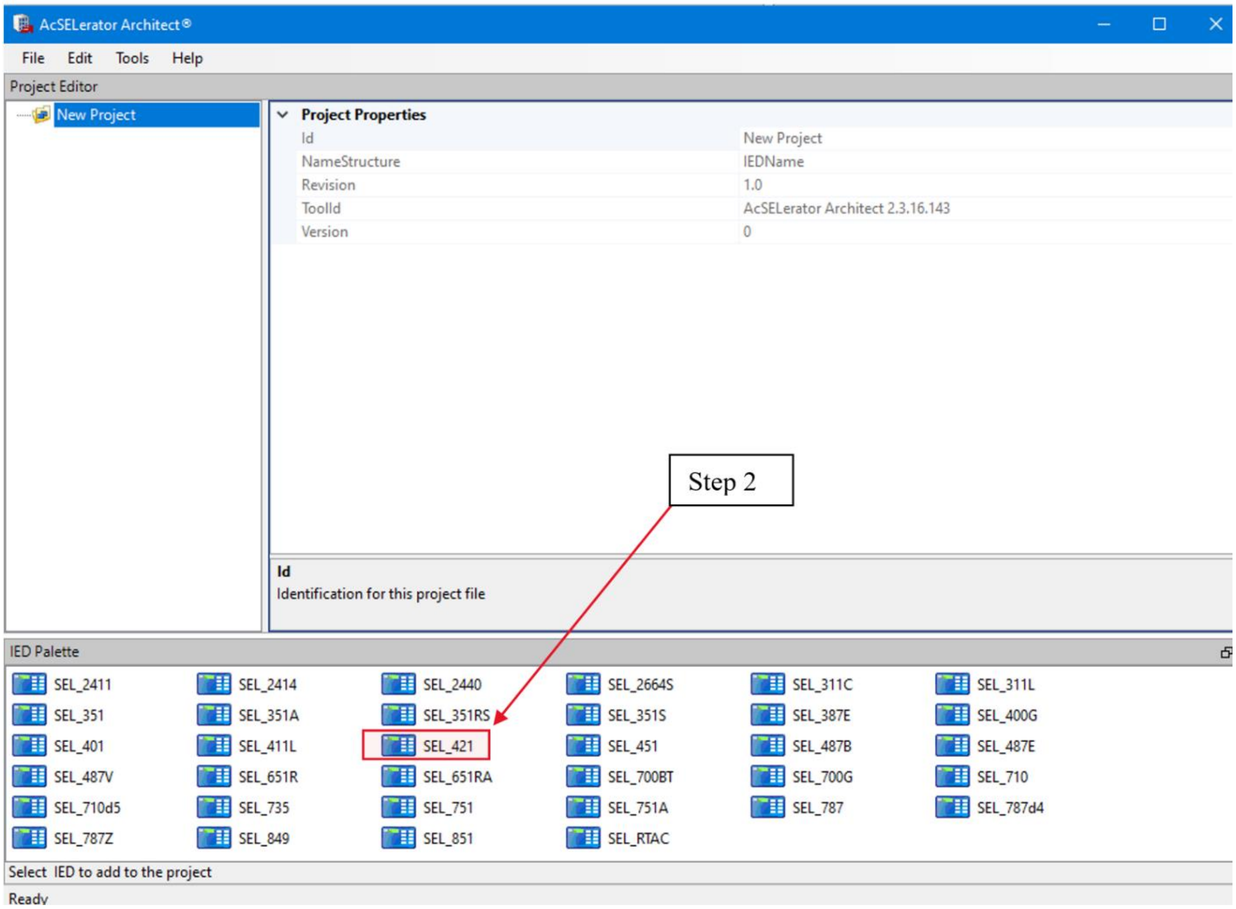
To use an optional TCP/IP port number, append ':' and integer from

Username: 2AC

Password: ••••

Add To Project ☑

2. Once either the ICD Package was downloaded from the website or the CID was downloaded from the relay, the IEDs should show up like in Architect like the image below, make sure to double click ‘SEL-421’ from the IED palette.



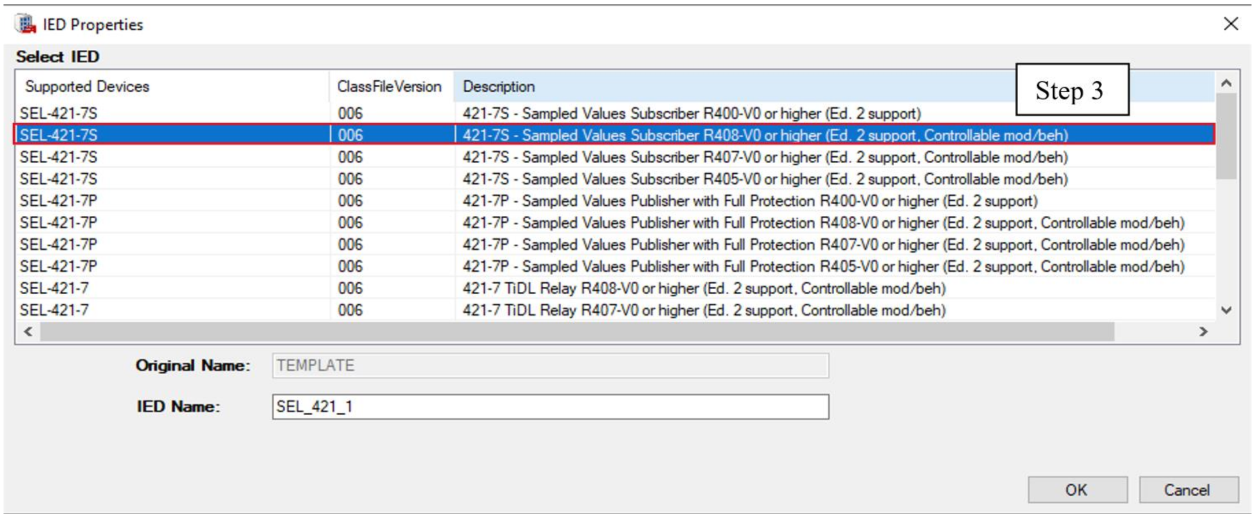
Project Properties

Id	New Project
NameStructure	IEDName
Revision	1.0
ToolId	AcSELerator Architect 2.3.16.143
Version	0

Id
Identification for this project file

Step 2

3. Select SEL-421-7S Class File Version 006 with the same description as highlighted in the image below and press OK, you can name the IED SEL_421_1.



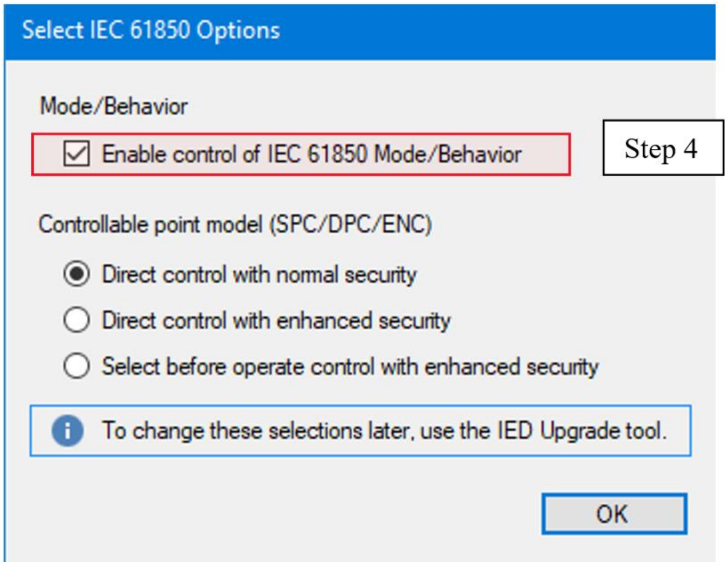
Step 3

Supported Devices	ClassFileVersion	Description
SEL-421-7S	006	421-7S - Sampled Values Subscriber R400-V0 or higher (Ed. 2 support)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R407-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7S	006	421-7S - Sampled Values Subscriber R405-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R400-V0 or higher (Ed. 2 support)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R407-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7P	006	421-7P - Sampled Values Publisher with Full Protection R405-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7	006	421-7 TiDL Relay R408-V0 or higher (Ed. 2 support, Controllable mod/beh)
SEL-421-7	006	421-7 TiDL Relay R407-V0 or higher (Ed. 2 support, Controllable mod/beh)

Original Name: TEMPLATE

IED Name: SEL_421_1

4. Enable control of IEC 61850 Mode/Behavior on the next screen and press OK.



Select IEC 61850 Options

Mode/Behavior

☑ Enable control of IEC 61850 Mode/Behavior

Controllable point model (SPC/DPC/ENC)

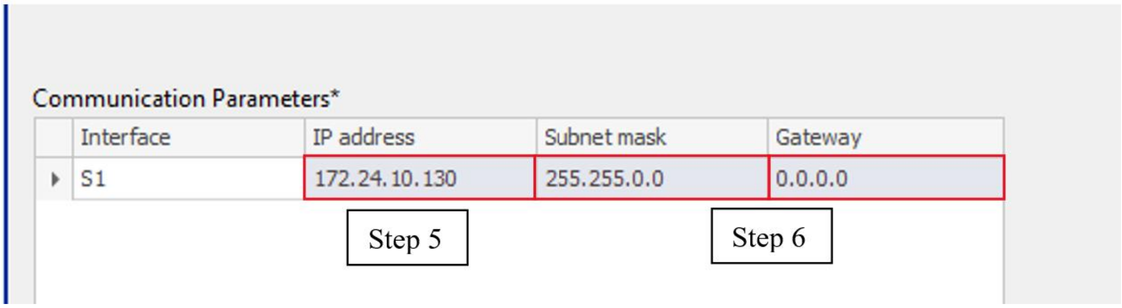
● Direct control with nomal security

○ Direct control with enhanced security

○ Select before operate control with enhanced security

To change these selections later, use the IED Upgrade tool.

5. In the properties tab of SEL_421_1 IED in project editor, set the IP address to 172.24.10.130 to correspond with the IP address of the FTP server needed for communication over to the relay (referenced from Grid Configurator under its FTP Communication settings).

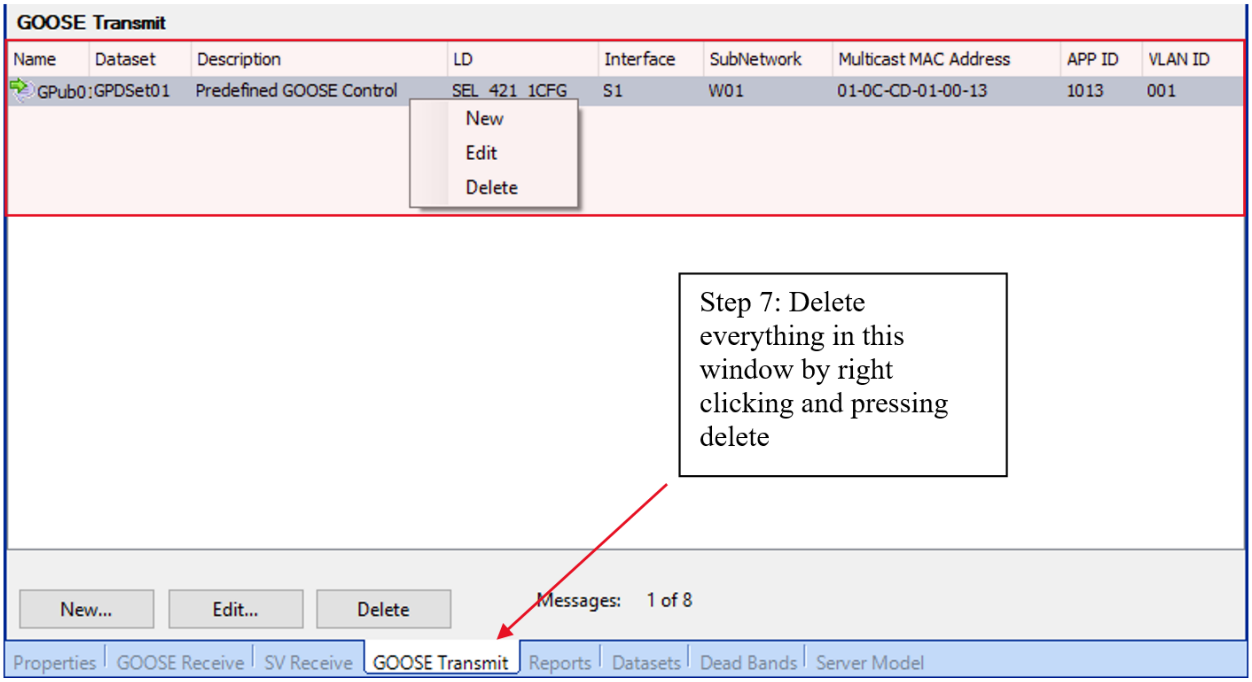


Communication Parameters*

Interface	IP address	Subnet mask	Gateway
S1	172.24.10.130	255.255.0.0	0.0.0.0

6. Set the Subnet Mask to 255.255.0.0 and the Gateway to 0.0.0.0.

7. Open the GOOSE Transmit tab and remove all existing GOOSE control blocks.

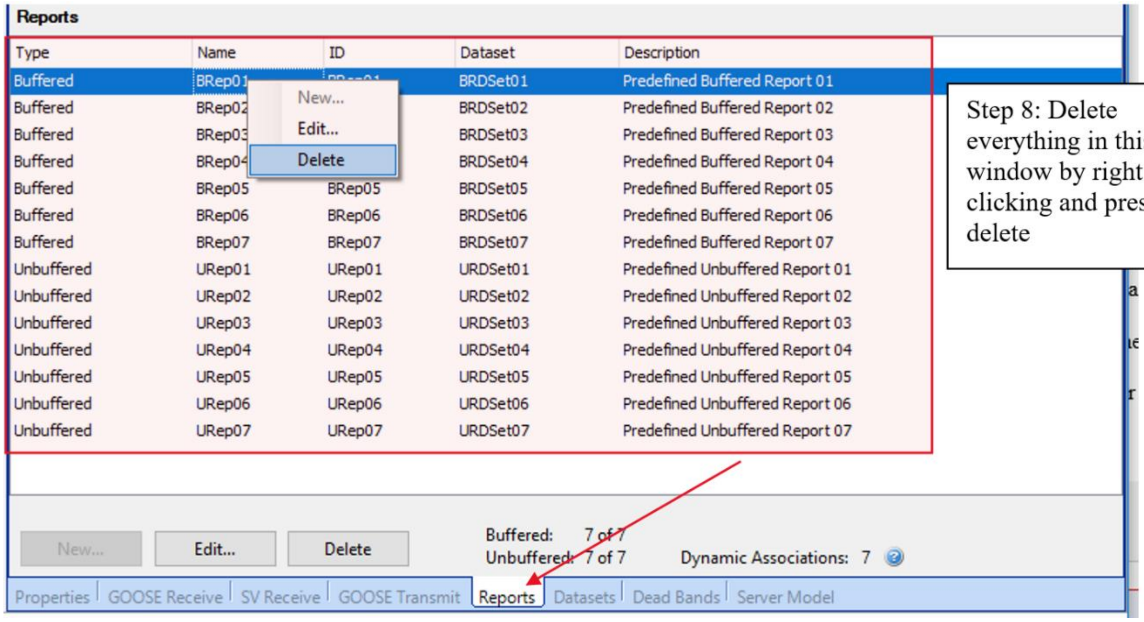


Name	Dataset	Description	LD	Interface	SubNetwork	Multicast MAC Address	APP ID	VLAN ID
GPub0	GPDSet01	Predefined GOOSE Control	SEL_421_1CFG	S1	W01	01-0C-CD-01-00-13	1013	001

Messages: 1 of 8

Step 7: Delete everything in this window by right clicking and pressing delete

8. Open the Reports tab and remove all control blocks.

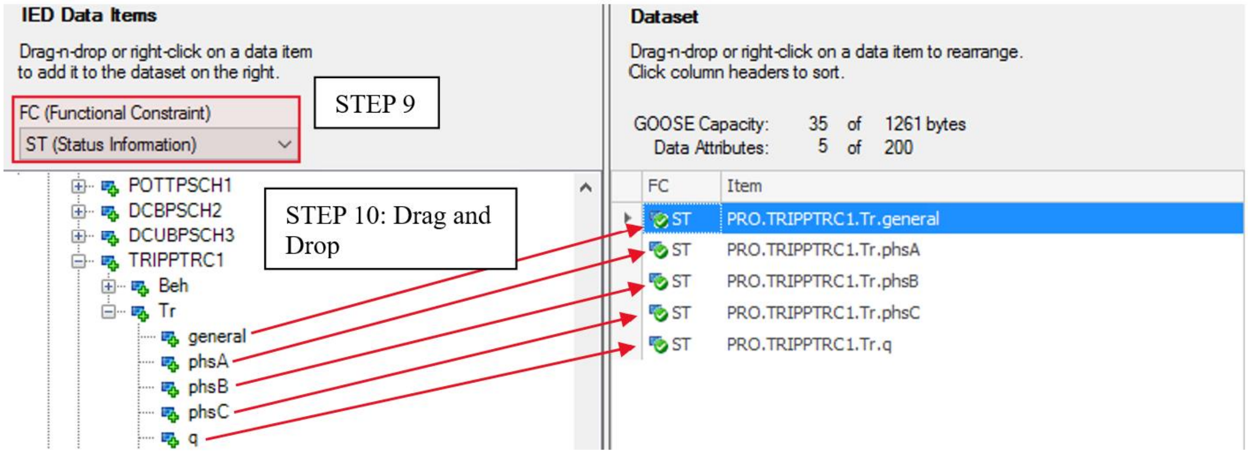


Type	Name	ID	Dataset	Description
Buffered	BRep01		BRDSet01	Predefined Buffered Report 01
Buffered	BRep02		BRDSet02	Predefined Buffered Report 02
Buffered	BRep03		BRDSet03	Predefined Buffered Report 03
Buffered	BRep04		BRDSet04	Predefined Buffered Report 04
Buffered	BRep05	BRep05	BRDSet05	Predefined Buffered Report 05
Buffered	BRep06	BRep06	BRDSet06	Predefined Buffered Report 06
Buffered	BRep07	BRep07	BRDSet07	Predefined Buffered Report 07
Unbuffered	URep01	URep01	URDSet01	Predefined Unbuffered Report 01
Unbuffered	URep02	URep02	URDSet02	Predefined Unbuffered Report 02
Unbuffered	URep03	URep03	URDSet03	Predefined Unbuffered Report 03
Unbuffered	URep04	URep04	URDSet04	Predefined Unbuffered Report 04
Unbuffered	URep05	URep05	URDSet05	Predefined Unbuffered Report 05
Unbuffered	URep06	URep06	URDSet06	Predefined Unbuffered Report 06
Unbuffered	URep07	URep07	URDSet07	Predefined Unbuffered Report 07

Buffered: 7 of 7
Unbuffered: 7 of 7
Dynamic Associations: 7

Step 8: Delete everything in this window by right clicking and pressing delete

9. Create a new data set named CFG.LLN0.REV3DATASET and set the Functional Constraint drop-down menu to ST (status information).
10. Expand the tree to navigate to SEL_421_7_ST Data Items, then to PRO, then TRIPPTRC1, and finally TR. Drag the signals labeled general, phsA, phsB, phsC, and q into the Dataset window.



IED Data Items

Drag-n-drop or right-click on a data item to add it to the dataset on the right.

FC (Functional Constraint): ST (Status Information)

STEP 9

STEP 10: Drag and Drop

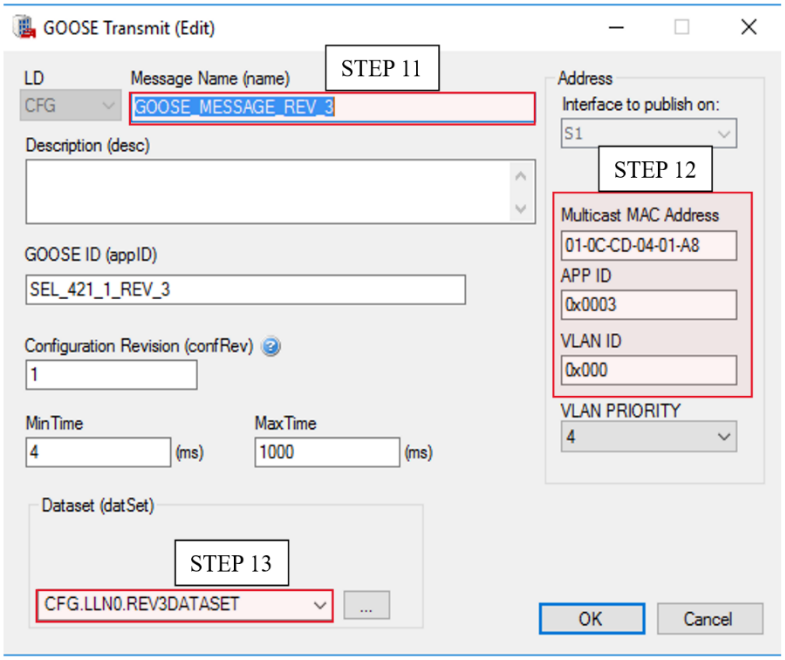
Dataset

Drag-n-drop or right-click on a data item to rearrange.
Click column headers to sort.

GOOSE Capacity: 35 of 1261 bytes
Data Attributes: 5 of 200

FC	Item
ST	PRO.TRIPPTRC1.Tr.general
ST	PRO.TRIPPTRC1.Tr.phsA
ST	PRO.TRIPPTRC1.Tr.phsB
ST	PRO.TRIPPTRC1.Tr.phsC
ST	PRO.TRIPPTRC1.Tr.q

11. Open the GOOSE Transmit tab again and label the message GOOSE_MESSAGE_REV_3.
12. Use the MAC address 01-0C-CD-04-01-A8 and set the APP ID to 0x003. Ensure this MAC address matches with what is referenced in Grid Configurator and RSCAD.



GOOSE Transmit (Edit)

LD: CFG

Message Name (name): GOOSE_MESSAGE_REV_3

STEP 11

Description (desc):

GOOSE ID (appID): SEL_421_1_REV_3

Configuration Revision (confRev): 1

Min Time: 4 (ms)

Max Time: 1000 (ms)

Dataset (datSet): CFG.LLN0.REV3DATASET

STEP 13

Address

Interface to publish on: S1

STEP 12

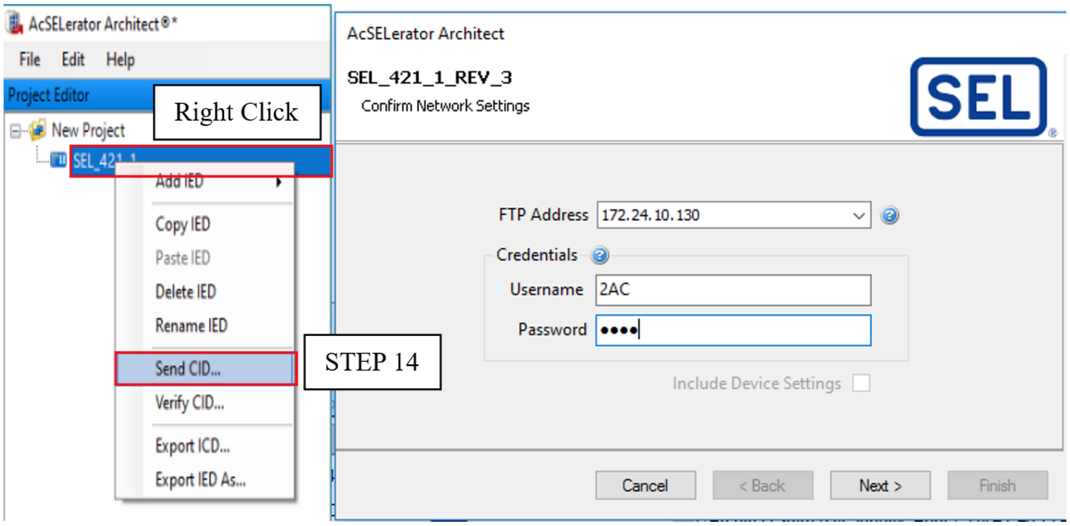
Multicast MAC Address: 01-0C-CD-04-01-A8

APP ID: 0x0003

VLAN ID: 0x000

VLAN PRIORITY: 4

13. Confirm that the dataset at the bottom of the window matches the dataset created previously.
14. Send the CID file containing all configured information to the relay using the FTP IP address, username 2AC, and password TAIL.



AcSELerator Architect

SEL_421_1_REV_3

Confirm Network Settings

FTP Address: 172.24.10.130

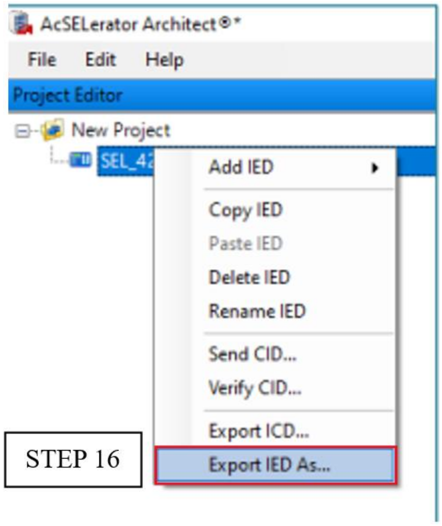
Credentials

Username: 2AC

Password: ••••

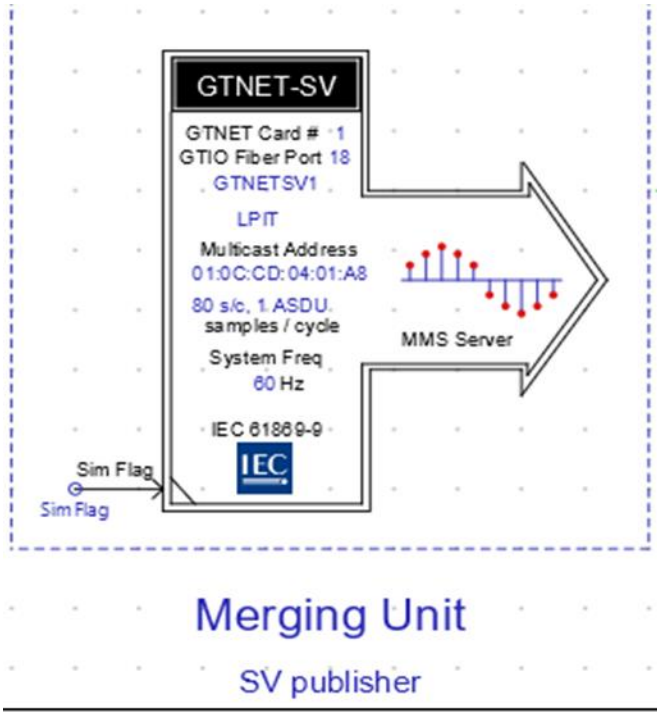
Include Device Settings ☐

15. Wait for a confirmation message from the relay indicating the transfer is completed.
16. Export the CID to a known location on your computer so it can be uploaded to RSCAD later.



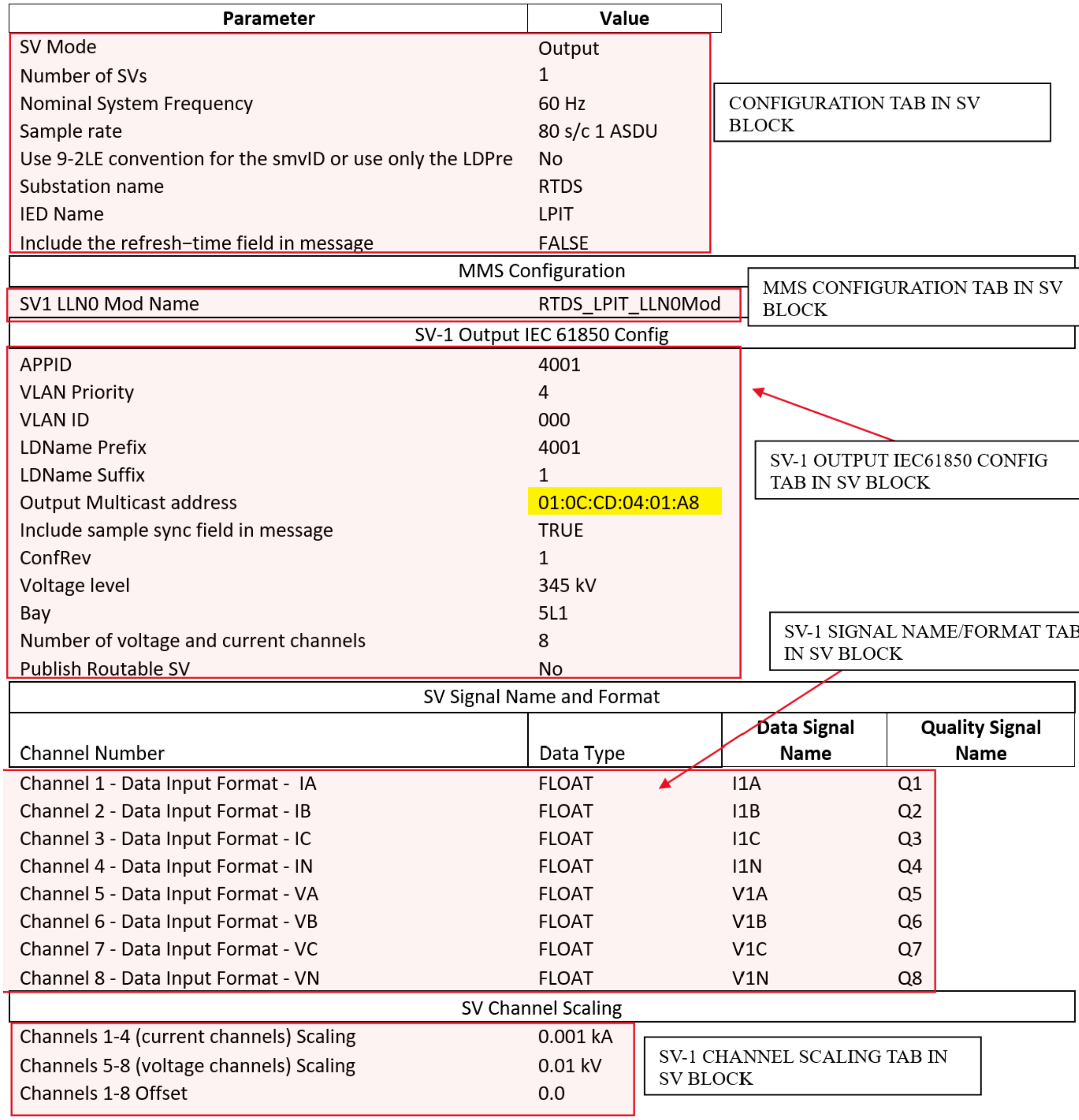
Sampled Values (SV) Block (RSCAD)

1. Grab a block titled GTNET-SV-v6 from the ‘Protection and Automation’ Library, name it GTNETSV1



2. The settings in Table 1 below should guide you in setting up the parameters of the block

Table 1: SV Table of Values



Parameter	Value		
SV Mode	Output		
Number of SVs	1		
Nominal System Frequency	60 Hz		
Sample rate	80 s/c 1 ASDU		
Use 9-2LE convention for the smvID or use only the LDPre	No		
Substation name	RTDS		
IED Name	LPIT		
Include the refresh–time field in message	FALSE		
MMS Configuration			
SV1 LLN0 Mod Name	RTDS_LPIT_LLN0Mod		
SV-1 Output IEC 61850 Config			
APPID	4001		
VLAN Priority	4		
VLAN ID	000		
LDName Prefix	4001		
LDName Suffix	1		
Output Multicast address	01:0C:CD:04:01:A8		
Include sample sync field in message	TRUE		
ConfRev	1		
Voltage level	345 kV		
Bay	5L1		
Number of voltage and current channels	8		
Publish Routable SV	No		
SV Signal Name and Format			
Channel Number	Data Type	**Data Signal Name**	**Quality Signal Name**
Channel 1 - Data Input Format - IA	FLOAT	I1A	Q1
Channel 2 - Data Input Format - IB	FLOAT	I1B	Q2
Channel 3 - Data Input Format - IC	FLOAT	I1C	Q3
Channel 4 - Data Input Format - IN	FLOAT	I1N	Q4
Channel 5 - Data Input Format - VA	FLOAT	V1A	Q5
Channel 6 - Data Input Format - VB	FLOAT	V1B	Q6
Channel 7 - Data Input Format - VC	FLOAT	V1C	Q7
Channel 8 - Data Input Format - VN	FLOAT	V1N	Q8
SV Channel Scaling			
Channels 1-4 (current channels) Scaling	0.001 kA		
Channels 5-8 (voltage channels) Scaling	0.01 kV		
Channels 1-8 Offset	0.0		

CONFIGURATION TAB IN SV BLOCK

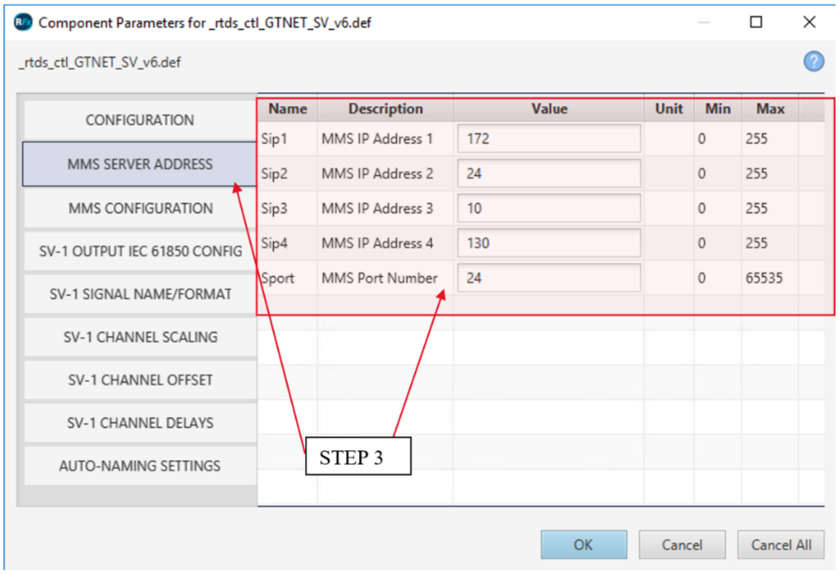
MMS CONFIGURATION TAB IN SV BLOCK

SV-1 OUTPUT IEC61850 CONFIG TAB IN SV BLOCK

SV-1 SIGNAL NAME/FORMAT TAB IN SV BLOCK

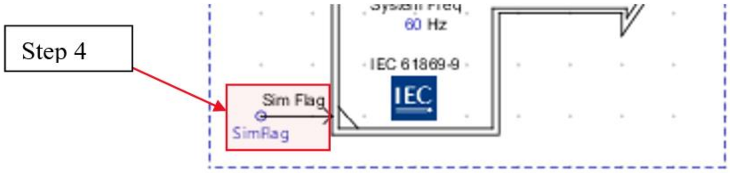
SV-1 CHANNEL SCALING TAB IN SV BLOCK

3. Before exiting the SV block, open the ‘MMS SERVER ADDRESS’ tab. Set the MMS IP Addresses as follows:
    a. MMS IP ADDRESS 1: 172
    b. MMS IP ADDRESS 2: 24
    c. MMS IP ADDRESS 3: 10
    d. MMS IP ADDRESS 4: 130
    e. MMS Port Number: 24

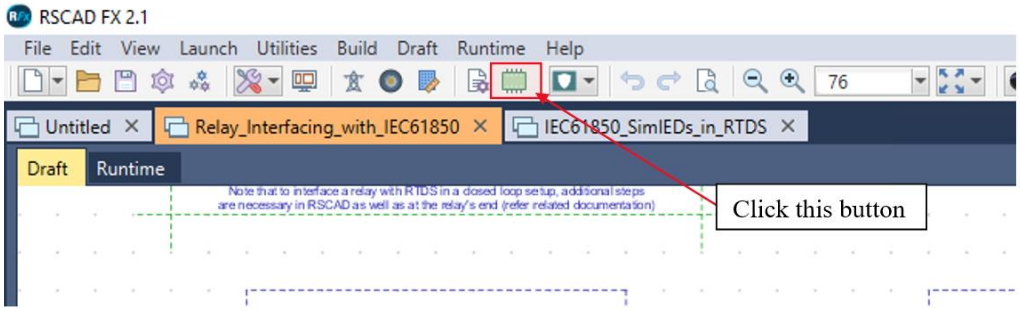


Name	Description	Value	Unit	Min	Max
Sip1	MMS IP Address 1	172		0	255
Sip2	MMS IP Address 2	24		0	255
Sip3	MMS IP Address 3	10		0	255
Sip4	MMS IP Address 4	130		0	255
Sport	MMS Port Number	24		0	65535

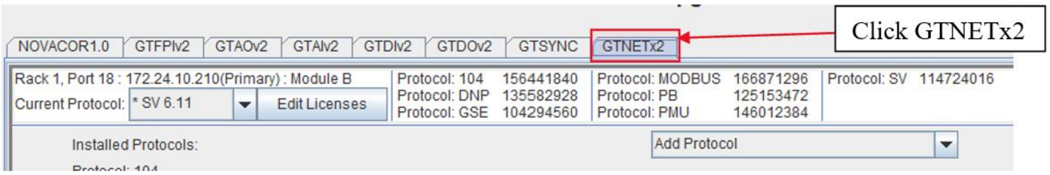
4. Make sure that the SimFlag signal to the Sim Flag input of the SV block is connected. If they are not connected, connect them by dragging the SimFlag bubble to the end of the Sim Flag arrow.



5. In the parameter settings for the block, there should be a port/pin number section. Make sure that number in there is GTNETxx, the “xx” should be whatever port on the GTNET card the SV firmware is loaded to. For our specific RTDS system, that would be either GTNET18 or GTNET20. Please reference the RTDS firmware for specific port configuration. This process to set up the port configuration is the same as for the GSE section, but instead of SV 6.11, it will be GSE 7.23.



Click this button



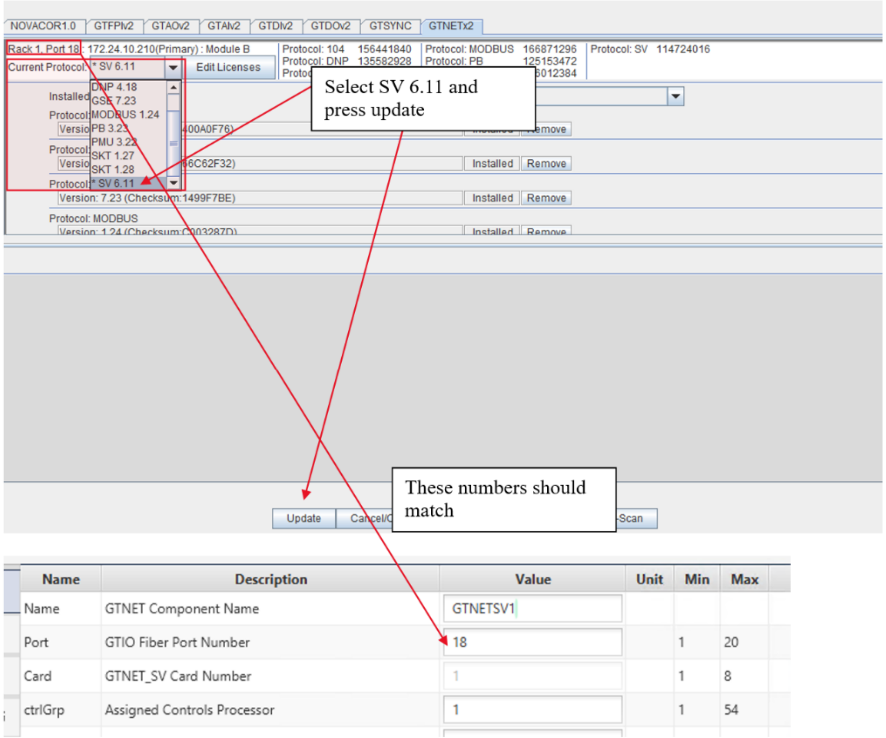
Click GTNETx2

Rack 1, Port 18 : 172.24.10.210(Primary) : Module B

Current Protocol: * SV 6.11

Protocol: 104 156441840
Protocol: DNP 135582928
Protocol: GSE 104294560
Protocol: MODBUS 166871296
Protocol: PB 125153472
Protocol: PMU 146012384
Protocol: SV 114724016

Installed Protocols:



Rack 1, Port 18 : 172.24.10.210(Primary) : Module B

Current Protocol: * SV 6.11

Version: 7.23 (Checksum:1499F7BE)

Protocol: MODBUS

Version: 1.24 (Checksum:C003287D)

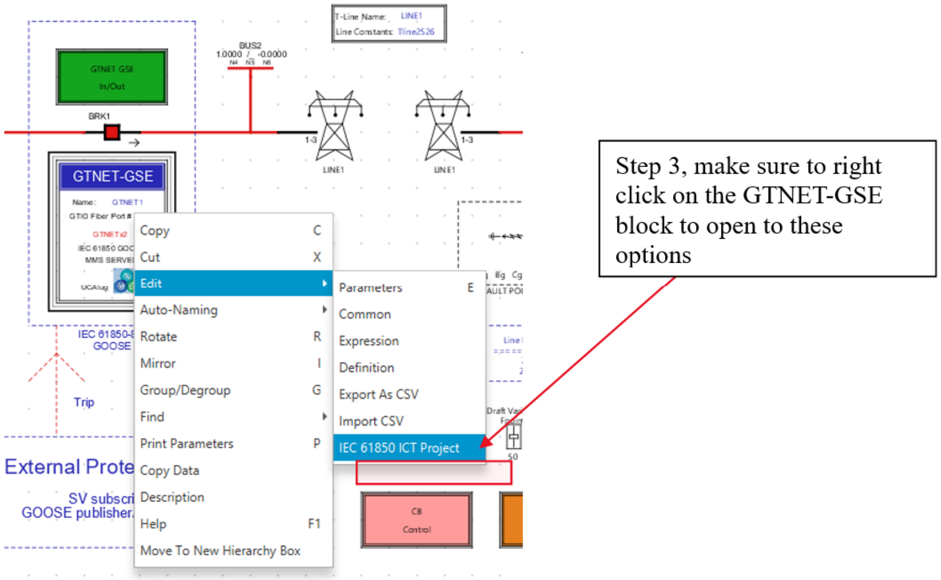
Select SV 6.11 and press update

These numbers should match

Name	Description	Value	Unit	Min	Max
Name	GTNET Component Name	GTNETSV1			
Port	GTIO Fiber Port Number	18		1	20
Card	GTNET_SV Card Number	1		1	8
ctrlGrp	Assigned Controls Processor	1		1	54

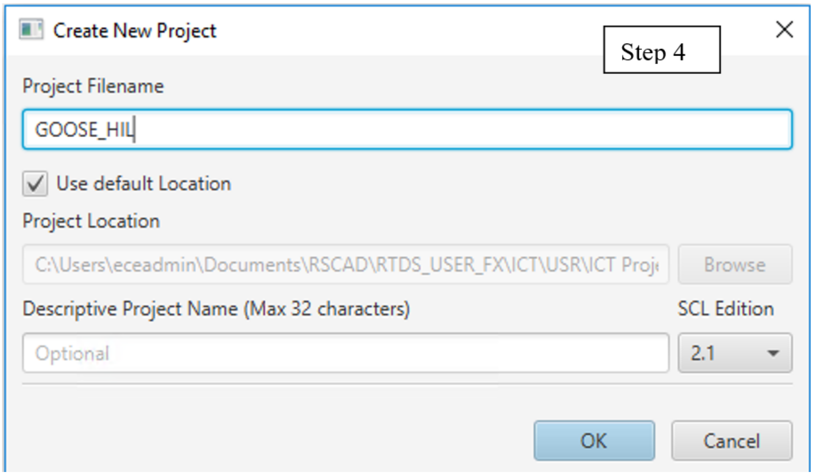
GOOSE Block

1. Once the acSELerator Architect steps have been completed, proceed with these steps
2. Open the RSCAD Relay HIL tutorial case file and navigate to the draft display
3. Locate the GTNET-GSE block on the display, then right click on it, select edit, then click "IEC 61850 ICT Project"



Step 3, make sure to right click on the GTNET-GSE block to open to these options

4. Click file, then New Project, then title the project GOOSE_HIL



Project Filename: GOOSE_HIL

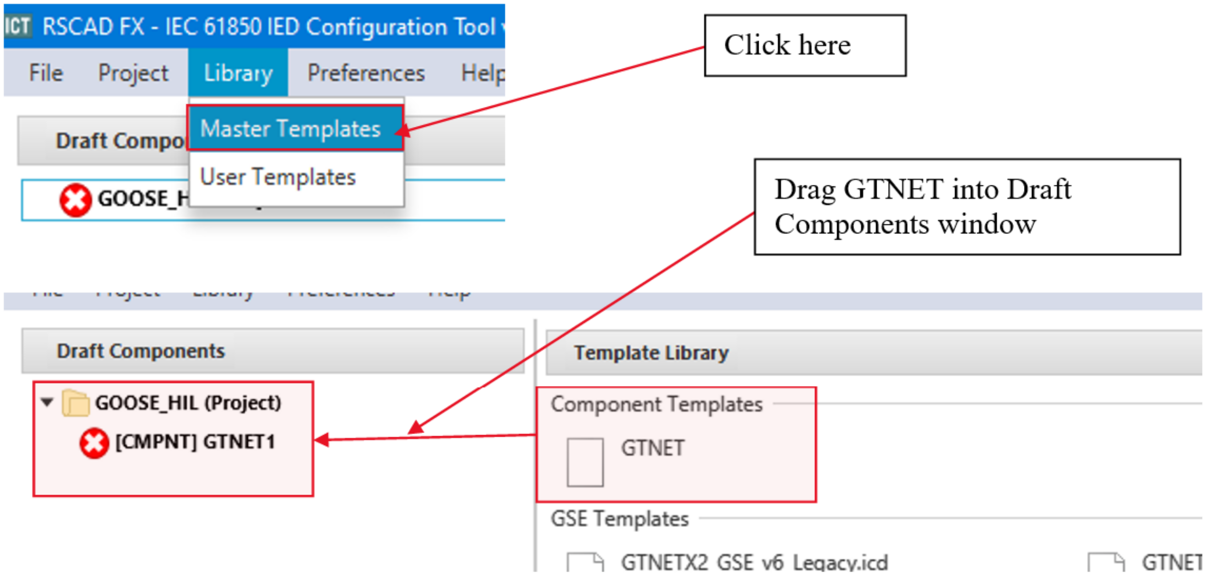
☑ Use default Location

Project Location: C:\Users\eceadmin\Documents\RSCAD\RTDS_USER_FX\ICT\USR\ICT Proj

Descriptive Project Name (Max 32 characters): Optional

SCL Edition: 2.1

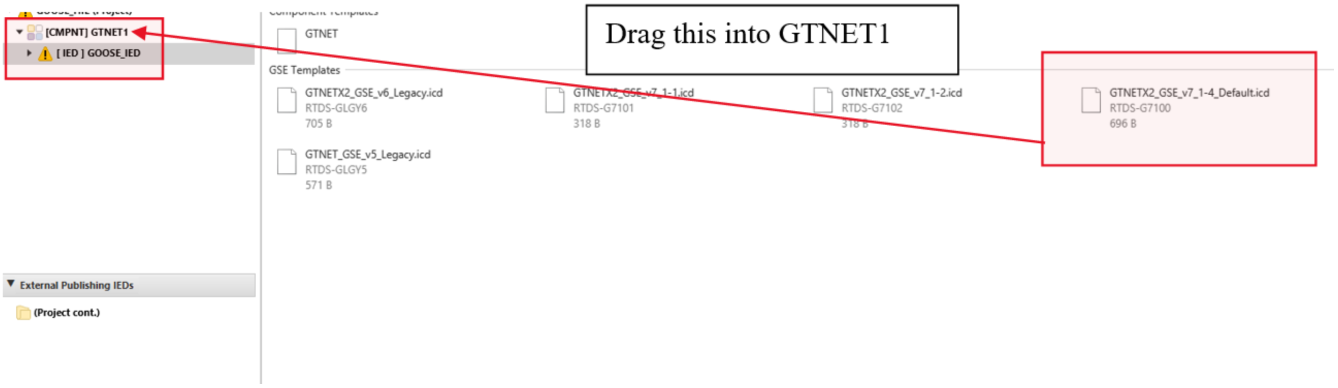
5. Open the library, and then select master templates. Locate the GTNET component, and then drag it into the top of the Project field in the Draft components pane. In the name field, label it Goose_Communication



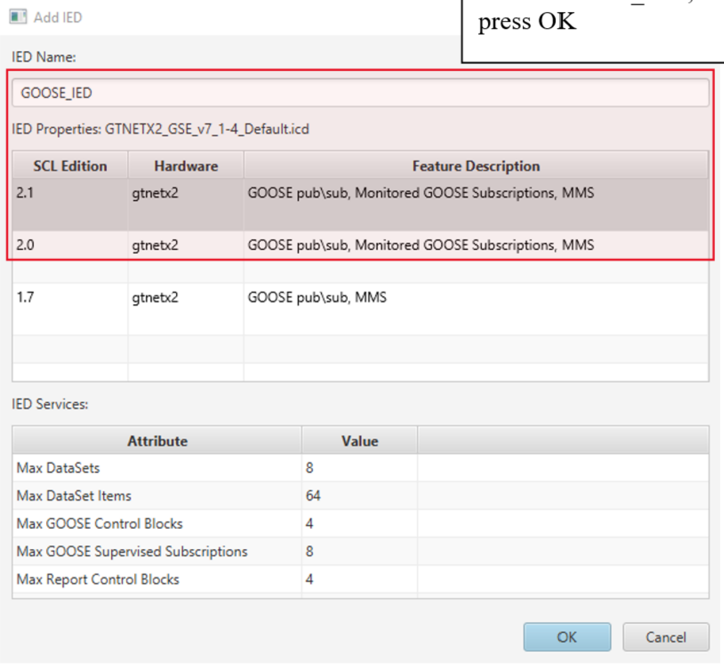
Click here

Drag GTNET into Draft Components window

6. Then locate the GTNETX2GSEv7_1-4Deafult.icd’ IED template and drag it into the GTNET component. Select the SCL edition to be 2.1



Drag this into GTNET1



Label GOOSE_IED, then press OK

IED Name:

GOOSE_IED

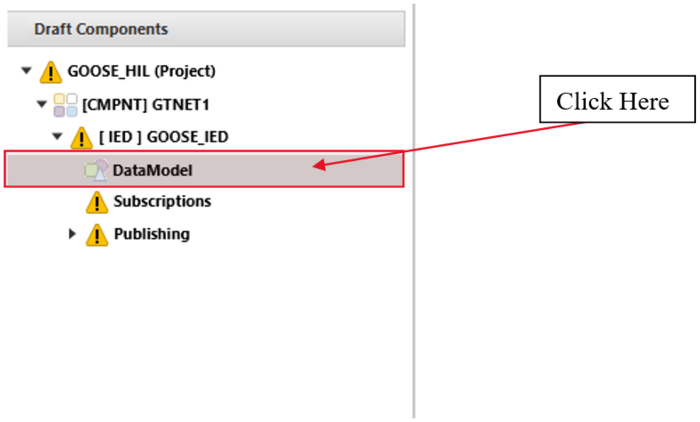
IED Properties: GTNETX2_GSE_v7_1-4_Default.icd

SCL Edition	Hardware	Feature Description
2.1	gtnetx2	GOOSE pub\sub, Monitored GOOSE Subscriptions, MMS
2.0	gtnetx2	GOOSE pub\sub, Monitored GOOSE Subscriptions, MMS
1.7	gtnetx2	GOOSE pub\sub, MMS

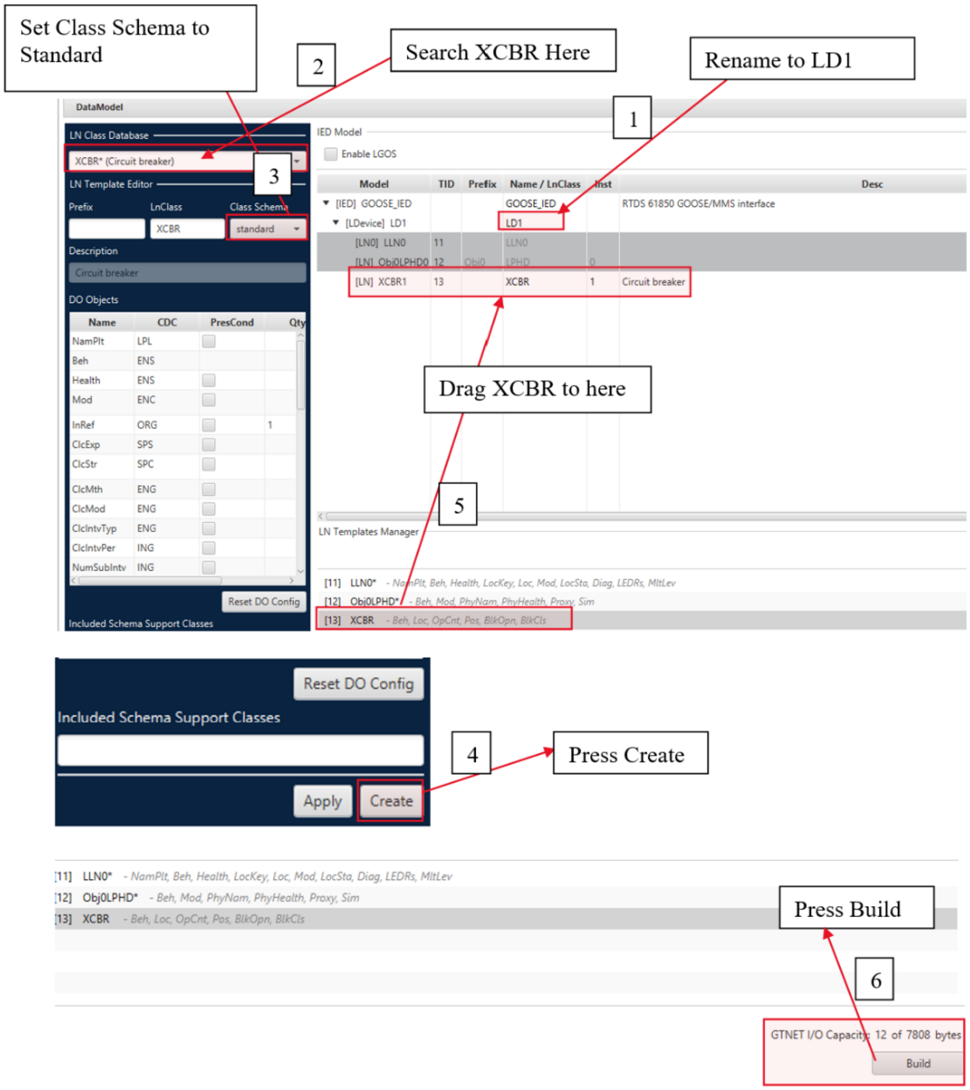
IED Services:

Attribute	Value
Max DataSets	8
Max DataSet Items	64
Max GOOSE Control Blocks	4
Max GOOSE Supervised Subscriptions	8
Max Report Control Blocks	4

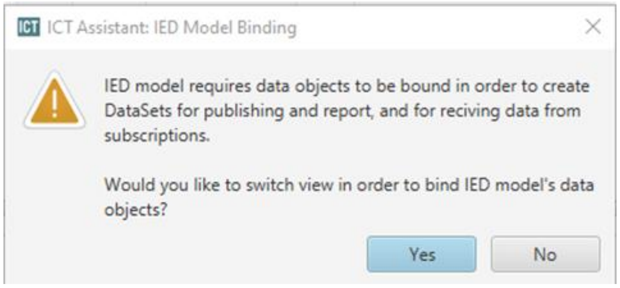
7. Start by modifying the Logical Device (LD) instance name to 'LD1' and then instantiate Logical Nodes (LN) such as 'XCBR' (Circuit Breaker) for required LN classes in the IED’s data model. Ensure to use the standard Data Objects (DOs) available without adding extra ones.



Click Here



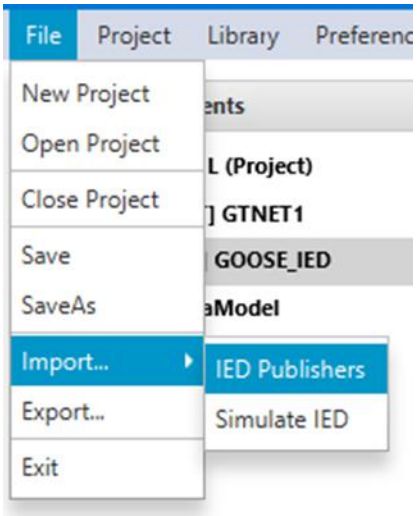
a. When you see this screen below, press no. We will do the data binding later.

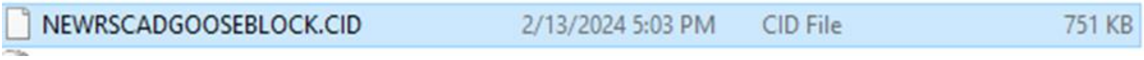


IED model requires data objects to be bound in order to create DataSets for publishing and report, and for reciving data from subscriptions.

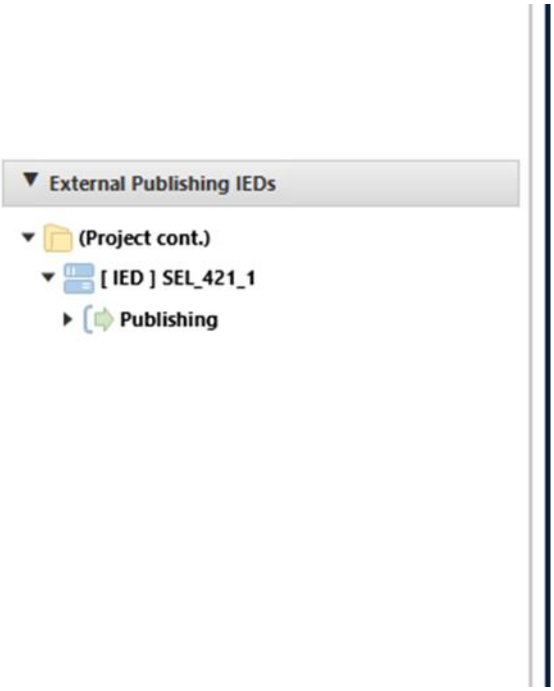
Would you like to switch view in order to bind IED model's data objects?

8. Next, we will Import the IED publishers. This will be the CID file you exported from Architect. Note: Your file name may be different than the one displayed below, just make sure it is a .CID file. If you did it correctly, the External Publishing IEDs tab should be showing your SEL_421_1 IED that you set up in Architect.

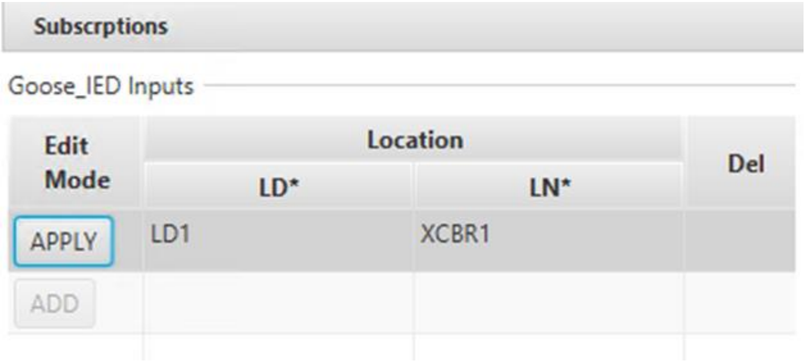




NEWRSCADGOOSEBLOCK.CID 2/13/2024 5:03 PM CID File 751 KB



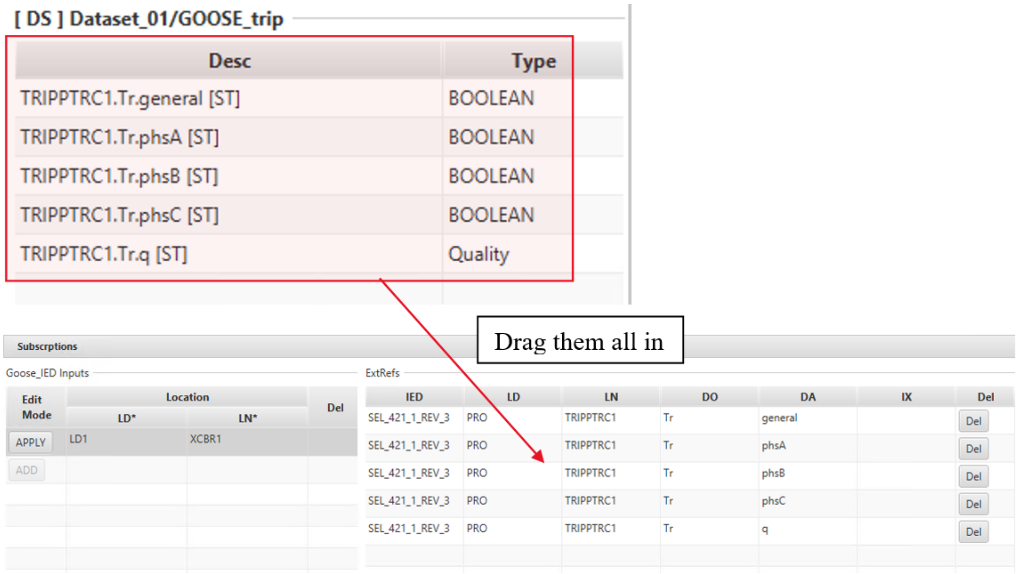
9. In the IED model, under 'Subscriptions', Select edit, then under LD, select LD1, and under LN, select XCBR1.



Edit Mode	Location		Del
	LD*	LN*	
APPLY	LD1	XCBR1	
ADD			

10. Click on CFG, then double click on Dataset_01/xxx. The “xxx” should match what you named your dataset in Architect (e.g., 'Dataset_01/ GOOSE_MESSAGE_REV_3)

11. Select the appropriate dataset from the external relay and drag its attributes to the GOOSE_IED subscriptions.

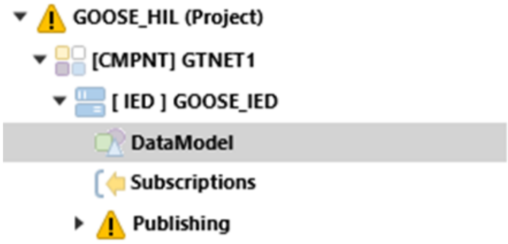


Desc	Type
TRIPPTRC1.Tr.general [ST]	BOOLEAN
TRIPPTRC1.Tr.phsA [ST]	BOOLEAN
TRIPPTRC1.Tr.phsB [ST]	BOOLEAN
TRIPPTRC1.Tr.phsC [ST]	BOOLEAN
TRIPPTRC1.Tr.q [ST]	Quality

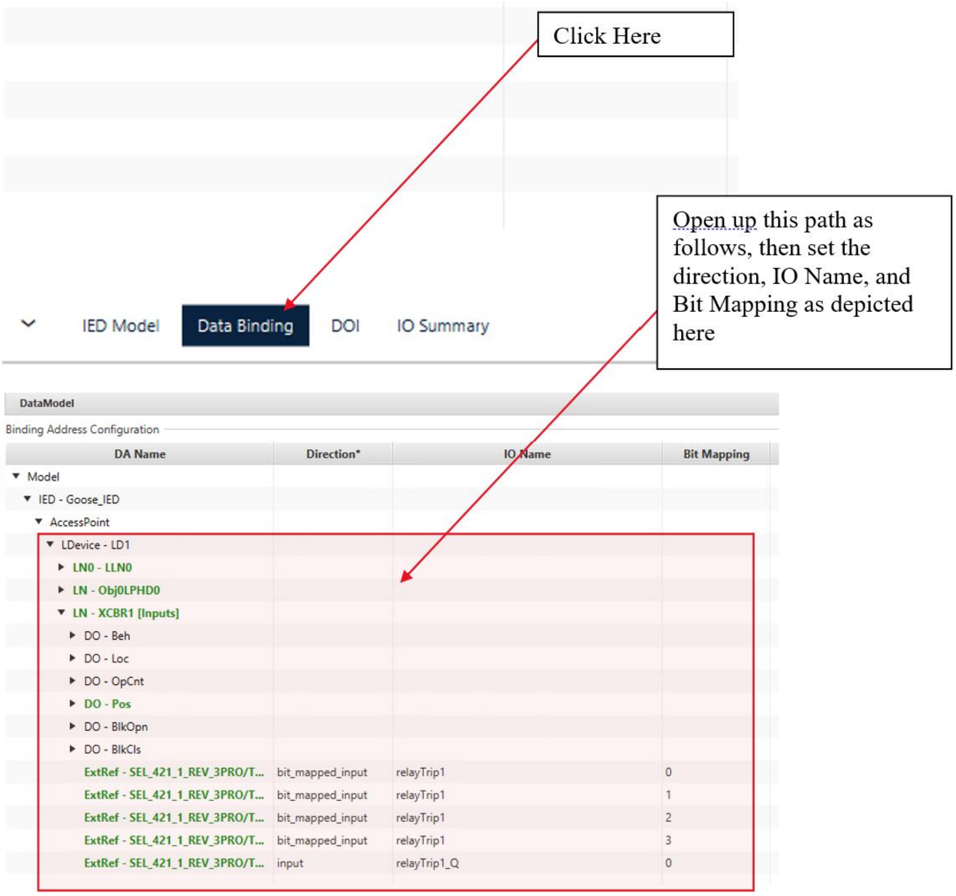
Edit Mode	Location		Del
	LD*	LN*	
APPLY	LD1	XCBR1	
ADD			

IED	LD	LN	DO	DA	IX	Del
SEL_421_1_REV_3	PRO	TRIPPTRC1	Tr	general		Del
SEL_421_1_REV_3	PRO	TRIPPTRC1	Tr	phsA		Del
SEL_421_1_REV_3	PRO	TRIPPTRC1	Tr	phsB		Del
SEL_421_1_REV_3	PRO	TRIPPTRC1	Tr	phsC		Del
SEL_421_1_REV_3	PRO	TRIPPTRC1	Tr	q		Del

12. Click on the ‘Data Model’ Tab again, then click the 'Data Binding' tab in the 'GOOSE_IED' data model to assign signal names to the subscribed inputs for integration into the simulation



GOOSE_HIL (Project)
[CMPNT] GTNET1
[IED] GOOSE_IED
DataModel
Subscriptions
Publishing

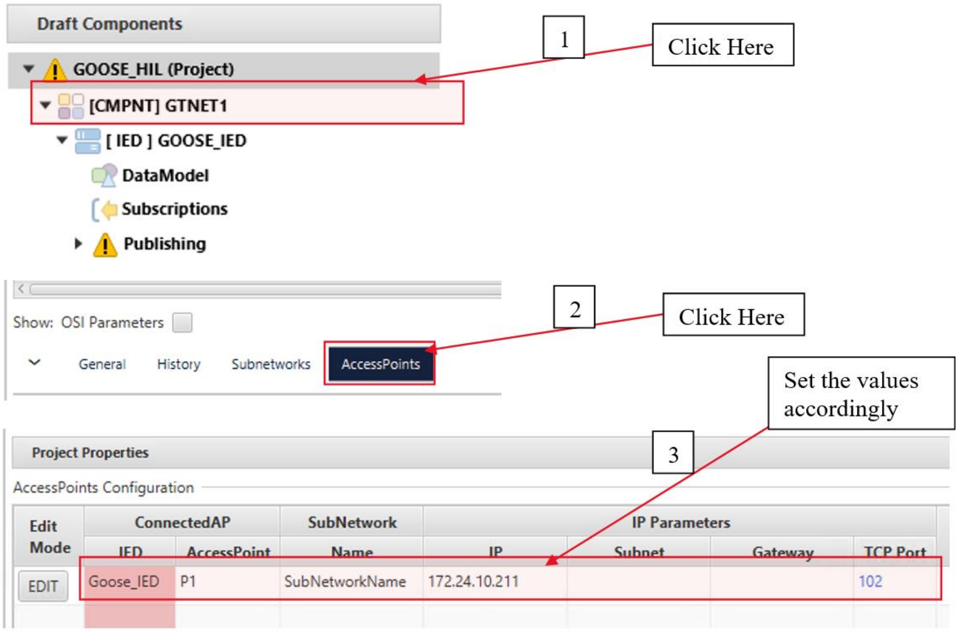


Click Here

Open up this path as follows, then set the direction, IO Name, and Bit Mapping as depicted here

DA Name	Direction*	IO Name	Bit Mapping
Model			
IED - Goose_IED			
AccessPoint			
LDevice - LD1			
LN0 - LLN0			
LN - Obj0LPHD0			
LN - XCBR1 [Inputs]			
DO - Beh			
DO - Loc			
DO - OpCnt			
DO - Pos			
DO - BlkOpn			
DO - BlkCls			
ExtRef - SEL_421_1_REV_3PRO/T...	bit_mapped_input	relayTrip1	0
ExtRef - SEL_421_1_REV_3PRO/T...	bit_mapped_input	relayTrip1	1
ExtRef - SEL_421_1_REV_3PRO/T...	bit_mapped_input	relayTrip1	2
ExtRef - SEL_421_1_REV_3PRO/T...	bit_mapped_input	relayTrip1	3
ExtRef - SEL_421_1_REV_3PRO/T...	input	relayTrip1_Q	0

13. Click on the GOOSE_HIL folder in ‘Draft Components,’ then click the ‘AccessPoint’ Tab. Assign the IP address as 172.24.10.211 to ensure communication between the hardware (GTNETx2 module) and the ICT project. Also, Set the TCP port to 102.



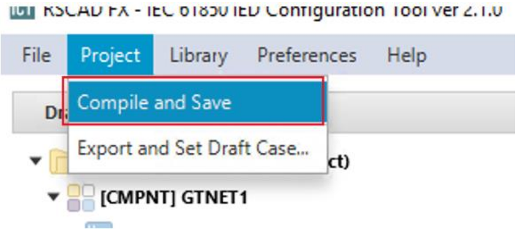
Click Here

Click Here

Set the values accordingly

Edit Mode	ConnectedAP		SubNetwork	IP Parameters			
	IED	AccessPoint	Name	IP	Subnet	Gateway	TCP Port
EDIT	Goose_IED	P1	SubNetworkName	172.24.10.211			102

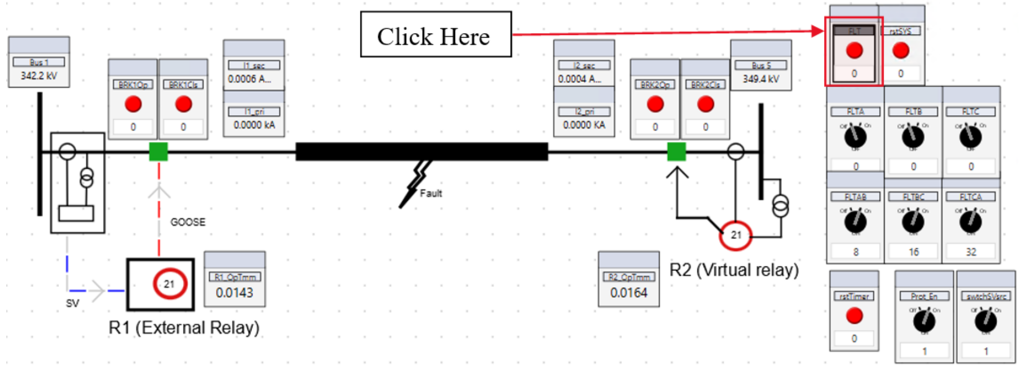
14. Save and compile the ICT project to generate necessary files (CID and IDF) for RSCAD FX draft case compilation. This step prepares the project for simulation.

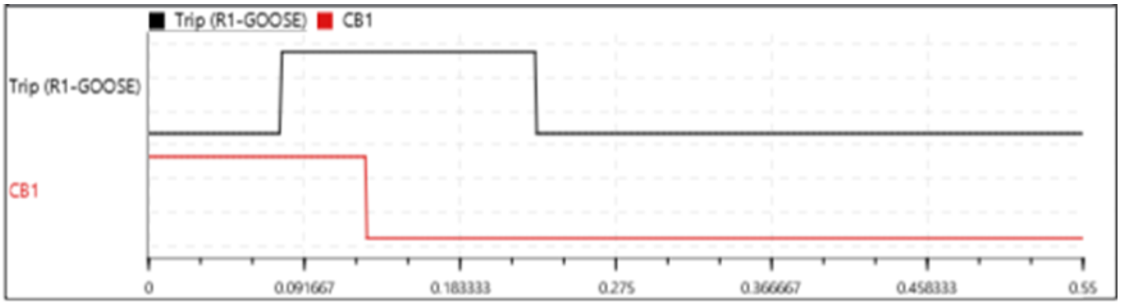


15. You can now close out of the ICT project and go back to the Draft case in RSCAD. Open the GSE block and verify the component name is GTNET1. Verify that the GTIO fiber matches the port selected in Firmware settings. Details on how to get there are described in the Sampled Values Section above.

Name	Description	Value	Unit	Min	Max
sCompName	Component name	GTNET1			
Port	GTIO Fiber Port Number	20		1	20

16. Verify everything was set up correctly by compiling and running the case, navigating to the Runtime tab, Pressing the FLT button to trigger a fault, and confirming that the bottom left graph shown below looks like the graph shown below. This verifies that the trip signals are being sent correctly.





Other Helpful Information

1. If the RTDS ever gets locked, right click rack1 in RSCAD, click unlock rack, use the password ‘rtds’, and run a different case, then stop that case, and the RTDS should be back to normal
2. SEL Username: 2AC
    a. SEL Lower-Level Password: TAIL
    b. SEL Higher Level Password: OTTER
3. IP/MAC Address Info:

Labels	IP Addresses	Port Info	MAC ADDRESS
Novacor	172.24.10.205	N/A	N/A
GTNET 1	172.24.10.210	(PORT 18)	N/A
GTNET 2	172.24.10.211	(PORT 20)	N/A
GTSYNC	172.24.10.212	N/A	N/A
PC	172.24.10.1	N/A	N/A
Remote Desktop	141.218.148.13	N/A	N/A
SEL-421 FTP Server	172.24.10.130	N/A	N/A
SEL-421 TELNET Server	172.24.10.131	N/A	N/A
SEL-421 MAC ADDRESS	N/A	N/A	01:0C:CD:04:01:A8

4. Connecting to the SEL-421-7 for the first time in Grid Configurator:
    a. Make a new Project
    b. Go to “Device Family => SEL-421 => SEL-421-7 => Settings Version 107”
    c. Click next, and make sure all the information matches the following:

Distance Protection Lab Device

Device Model: SEL-421-7
Settings Version Number: 107
Part Number: 04217XXXX600XE8H424XXXXXX
FID: SEL-421-7-R409-V0-Z107003-D20230317
Firmware Version: R409

Serial Number: 1232157421
ID: b4b0ccc1-a2c1-4620-b6aa-a1829955668c
Description:
This device is to be used in a Fault Protection Lab using documentation made by SD Group of Fall 2023 to Spring 2024.

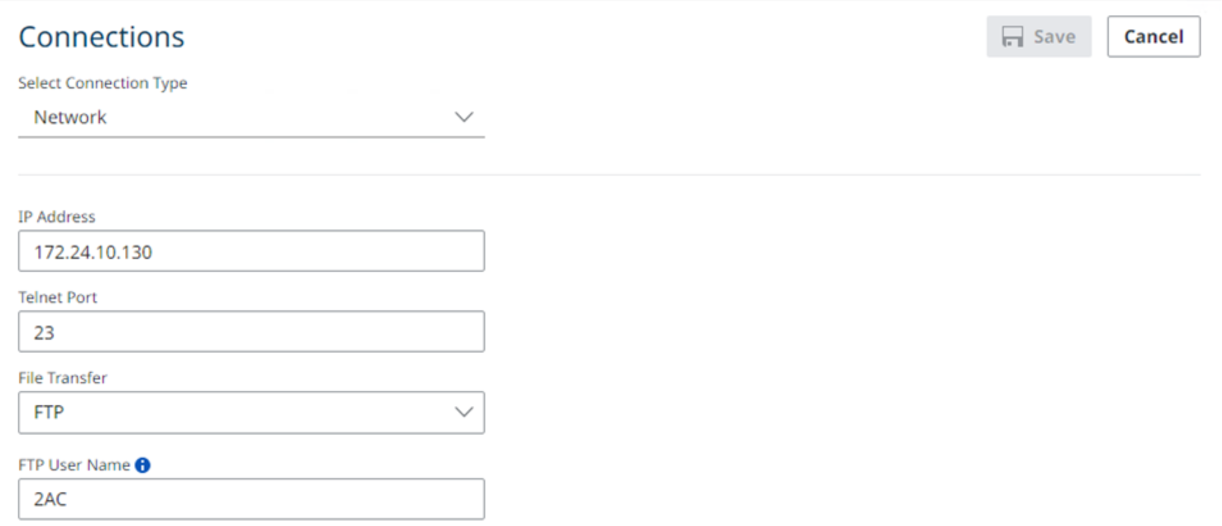
To find this information on the SEL-421-7, follow these steps:

A. When on the rotating display, press enter to navigate to the main menu.
B. Press the down arrows until you are hovering on "View Configuration," then press the enter button.

```
CONFIGURATION INFO
FID=SEL-421-7-R409-
   V0-Z107003-
   D20230317
PART NUMBER: 04217XX
   XX600XE8H424XXXXXX
S/N=1232157421
SELBOOT:
   BFID=SLBT-4XX-
   R302-V0-Z001002-
   D20230317
   CHECKSUM: 5D0E
```

C. This page contains the FID, Part Number, and Serial number to enter Grid Configurator.
D. Make sure the ethernet cord going from the ethernet switch is going into Port 5D on the SEL-421-7
E. Proceed to the "Connections" tab and click edit

    i. Set connection type to Network
    ii. Set IP address to 172.24.10.130
    iii. Set File Transfer to FTP
    iv. Set FTP username to 2AC
    v. Press Save



Select Connection Type: Network

IP Address: 172.24.10.130

Telnet Port: 23

File Transfer: FTP

FTP User Name: 2AC

F. It is important that the SEL-421-7 in on the rotating display

G. Click Connect and wait for connection

5.2 Student Lab Manual

Western Michigan University

College of Engineering and Applied Science

ECE 4820 Senior Design

Mark Booge

Nolan Ulp

Kyle Taiariol

Dr. Pablo Gomez

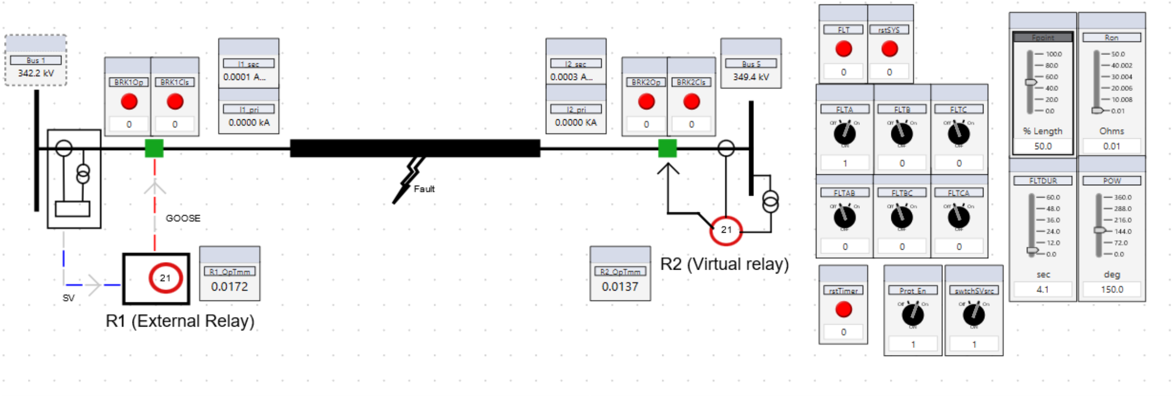
Real-Time Testbed for Transmission Line Protection

Student Lab Manual

04/25/2024

Table of Contents

Runtime User Interface



Bus 1: 342.2 kV
BRK1Op: 0
BRK1Cls: 0
I1_sec: 0.0001 A...
I1_pri: 0.0000 kA
I2_sec: 0.0003 A...
I2_pri: 0.0000 KA
BRK2Op: 0
BRK2Cls: 0
Bus 5: 349.4 kV
R1_OpTmm: 0.0172
R2_OpTmm: 0.0137
FLT: 0
rstSYS: 0
FLTA: 1
FLTB: 0
FLTC: 0
FLTAB: 0
FLTBC: 0
FLTCA: 0
rstTimer: 0
Prot_En: 1
swtchSVsrc: 1
Fpoint: 50.0
Ron: 0.01
FLTDUR: 4.1
POW: 150.0

Figure 1: RSCAD Runtime User Interface

Buttons:

FLT: triggers specified fault

rstSYS: Resets the system. Breakers will be closed and there will be no fault.

BRK1Op & BRK2Op: Opens respective breaker

BRK1Cls & BRK2Cls: Closes respective breaker

rstTimer: Resets the timer for how quickly the breaker closes after the fault trips.

Switches:

FLTA/FLTB/FLTC: Activates the line-to-ground fault for specified line.

FLTAB/FLTBC/FLTCA: Activates the line-to-line fault for specified lines.

Prot_En: Enables the SEL 421-7 Trip signal to open breaker 1.

switchSVsrc: Toggles the values from the PT and CT to MU (Always have on).

Sliders:

Fpoint: Sets the location of where the fault occurs on the transmission line.

FLTDUR: Sets the duration of the fault in seconds.

POW: (Point On Wave) Sets the degree when the fault occurs

Ron: The resistance of the fault

RSCAD Toolbar

Open Config File Editor: This opens a window to show what communication protocols are loaded onto the GTNETx2 card. Figure 2 shows what is to be expected, with a red box around the GTNETx2 Card’s communication Protocols.

☐ Select All Racks

☐ Rack: 1

IP Address: 172. 24. 10 .205

☑ GTSYNC

Cores: 3

Cards: NOVACOR1.0:1

IO: GTAIv2:1 GTAOv2:1 GTDIv2:1 GTDOv2:1 GTFPIV2:1 GTNETx2_DNP:1 GTNETx2_GSE:1 GTNETx2_SV:1

Figure 2: Config File Editor Expectations

Open Firmware: This opens a window which allows you to load different firmware onto the GTNETx2. These should be GOOSE (GSE) and Sampled Values (SV).

Compile: Must Compile the code first if any parameters are changed.

Run Program: Runs the program and resets the simulation.

Stop Program: Stops the Simulation.

Update Plots: Plots are not dynamic, so they will need to be updated.

Plot Information

There are 4 Plots for each relay. The first plot is the line voltage and the second is current, shown in Figure 3.a. These are the most obvious, and the most important. The third plots the burden current. This is the current going through the burden elements of the CT, which can be seen when clicking the help button (?) in the CT settings. The last plot is a digital signal of the trip signal and breaker status. The trip signal is active when the line is high. The breaker is closed when the signal is high and open when the signal is low. A simple function of the breaker opening can be seen in Figure 3.b.

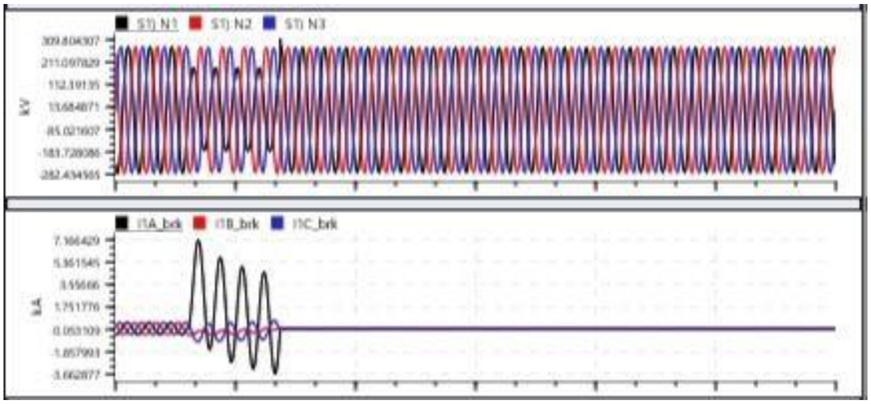


Figure 3.a: Voltage and Current Plot

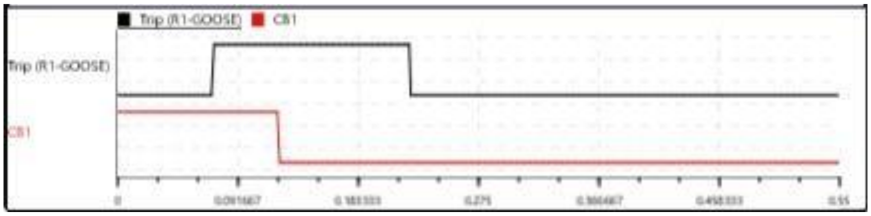


Figure 3.b: Digital Breaker Information Plot

Some plots are analog shown in Figure 3.a and some are digital shown in figure 3.b, but there is another type of data that can be plotted that is more complicated. These are known as word data plots which are plotting multiple digital signals. These are useful to see the overall change in a package of related bits of data but are not particularly useful otherwise. The only place is plot is used in in Figure 4, and this specific plot is plotting multiple words, which is only useful for debugging.

Figure 4: Word Data Plot

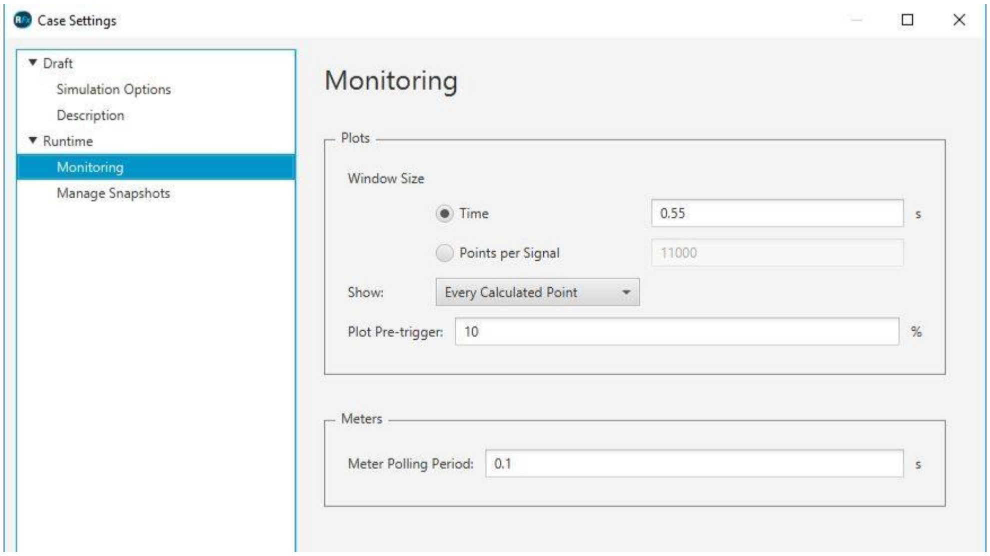
Students will not have to rescale the plots; however, it is useful when troubleshooting a related issue. The steps are as follows:

Step 1: Right click on the background of the Runtime.

Step 2: Click on "Case Settings"

Step 3: Click on "Monitoring" under the "Runtime" tab.

Here you can change the time duration the plot shows, or the data presented before it is triggered with a rising edge or falling edge. This window can be seen in Figure 5



Window Size

● Time 0.55 s

○ Points per Signal 11000

Show: Every Calculated Point

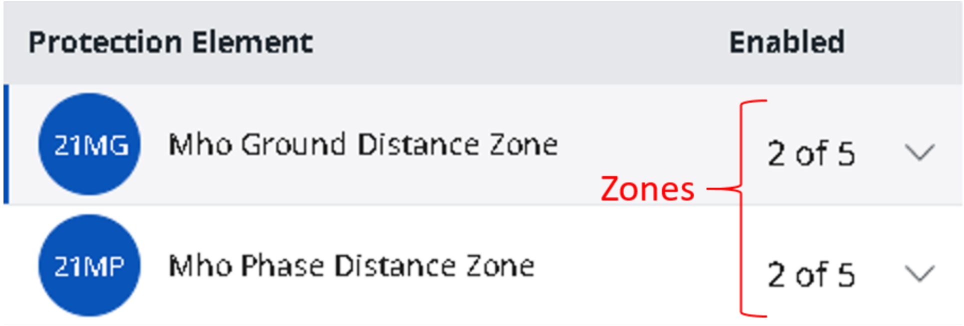
Plot Pre-trigger: 10 %

Meter Polling Period: 0.1 s

Figure 5: Case Settings, Monitoring Window

SEL Grid Configurator

SEL Grid Configurator is the program used to send values to the SEL 421-7 relay. The project students will be using in the lab is “Fault Protection Lab Device.” There are two major parts to this lab. The first part is assigning values to protection elements and the second is to assign values to the grid settings.



Protection Element		Enabled
21MG	Mho Ground Distance Zone	2 of 5
21MP	Mho Phase Distance Zone	2 of 5

Figure 6: SEL Protection Settings

Shown in Figure 6, 21MG and 21MP are the two Protection Elements used for this lab. The 2 of 5 “dropdown” menu indicates the zones enabled, with 5 zones maximum. The settings under these that should be changed are listed below:

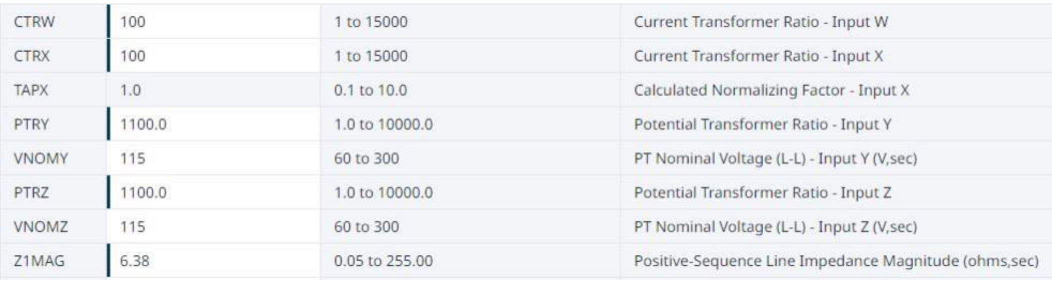
Ground:

- **Z1MG:** Zone 1 Reach (ohms, sec)
- **Z1GD:** Zone 1 Time Delay (cyc)
- **Z2MG:** Zone 2 Reach (ohms, sec)
- **Z2GD:** Zone 2 Time Delay (cyc)

Phase:

- **Z1MP:** Zone 1 Reach (ohms, sec)
- **Z1PD:** Zone 1 Time Delay (cyc)
- **Z2MP:** Zone 2 Reach (ohms, sec)
- **Z2PD:** Zone 2 Time Delay (cyc)

The “Grid Settings” option will direct you towards the CT ratio, PT ratio and the line parameters. **The parameters MUST be in Group 5.** Figure 5 shows the relevant settings in Group 5. The parameters with the black bar next to them show the settings that need to be changed. The Inputs for the CT (W, X) and PT (X, Y) should be equal, as shown in Figure 7.



CTRW	100	1 to 15000	Current Transformer Ratio - Input W
CTRX	100	1 to 15000	Current Transformer Ratio - Input X
TAPX	1.0	0.1 to 10.0	Calculated Normalizing Factor - Input X
PTRY	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Y
VNOMY	115	60 to 300	PT Nominal Voltage (L-L) - Input Y (V,sec)
PTRZ	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Z
VNOMZ	115	60 to 300	PT Nominal Voltage (L-L) - Input Z (V,sec)
Z1MAG	6.38	0.05 to 255.00	Positive-Sequence Line Impedance Magnitude (ohms,sec)

Figure 7: Relevant Grid Settings

Uploading the Settings

Step 1: Unplug the cable from the SEL 421-7 Port 5B

Step 2: Click Connect

Step 3: Once Connected, click “Send”

Step 4: Select “All” and click “Send”

Step 5: Plug the cable back into Port 5B of the SEL 421-7

Useful Equations

Current Transformer Ratio (CT)

Potential Transformer Ratio (PT)

Primary Line Impedance Magnitude (Z_1)

Secondary Line Impedance (Z_{sec})

$$Z_{sec} = Z_1\left(\frac{CT}{PT}\right)$$

The reach of the zones is a percentage of the secondary line impedance magnitude because the angle is consistent since the line’s resistance, capacitance, and inductance is consistent throughout the model of the line. Zone 1’s reach is always less than 100% of the secondary line impedance and Zone 2’s reach is always greater than 100%

5.3 Student Lab Workbook

Real-Time Testbed for Transmission Line Protection Lab Worksheet

Purpose:

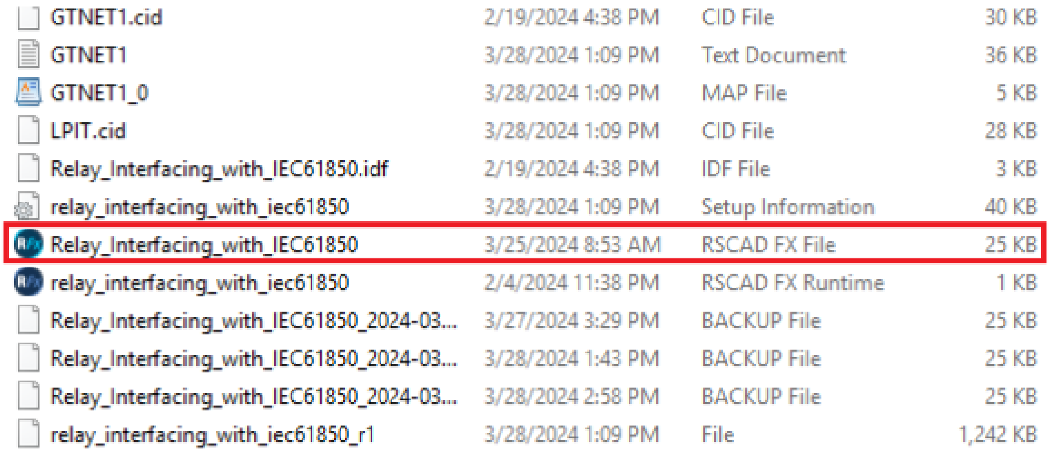
This lab is for the student to gain a deeper understanding of transmission line protection using the SEL 421-7 Relay. Using the specified model on RSCAD, the student must calculate the parameters that define the two zones. These calculations are important because every transmission line is unique, requiring different secondary impedance values. The noted values will then be edited into Grid Configurator and uploaded to the SEL 421-7. The equations needed will be explained in the Lab Manual, along with other useful information about the Grid-Configurator software. The resulting screenshots must show that the SEL-421-7's response matches the virtual relay's response.

Procedure:

Task 1: Open RSCAD

Step 1: Locate the folder named "Fault Protection Lab Test". Here you will find this manual, the lab worksheet and the RSCAD Model. Any extra files are necessary for the function of the program, but no interaction is needed.

Step 2: Open the file named "Relay_Interfacing_with_IEC61850", which is a FX file type shown in Figure 1. This opens the model under the "Draft" tab and the user interface located in the "Runtime" tab.



GTNET1.cid	2/19/2024 4:38 PM	CID File	30 KB
GTNET1	3/28/2024 1:09 PM	Text Document	36 KB
GTNET1_0	3/28/2024 1:09 PM	MAP File	5 KB
LPIT.cid	3/28/2024 1:09 PM	CID File	28 KB
Relay_Interfacing_with_IEC61850.idf	2/19/2024 4:38 PM	IDF File	3 KB
relay_interfacing_with_iec61850	3/28/2024 1:09 PM	Setup Information	40 KB
Relay_Interfacing_with_IEC61850	3/25/2024 8:53 AM	RSCAD FX File	25 KB
relay_interfacing_with_iec61850	2/4/2024 11:38 PM	RSCAD FX Runtime	1 KB
Relay_Interfacing_with_IEC61850_2024-03...	3/27/2024 3:29 PM	BACKUP File	25 KB
Relay_Interfacing_with_IEC61850_2024-03...	3/28/2024 1:43 PM	BACKUP File	25 KB
Relay_Interfacing_with_IEC61850_2024-03...	3/28/2024 2:58 PM	BACKUP File	25 KB
relay_interfacing_with_iec61850_r1	3/28/2024 1:09 PM	File	1,242 KB

Figure 1: RSCAD Model Location

Step 3: Click on the Open Firmware icon, shown in the “RSCAD Toolbar” section of this document.

Step 4: Click GTNETx2 and select the latest versions of the Sampled Value (SV) and GOOSE(GSE) firmware if not already selected, if they are, then go to step 7.

Step 5: Click “Update” then “Confirm” to update the firmware.

Step 6: Click Re-Scan to finish the process

Step 7: The simulation is ready to compile and run.

Task 2: Hand Calculate Zone 1 and Zone 2 Reach

CT Ratio : 400:1
PT Ratio : 3000:1

1. Using the PT Ratio and CT Ratio, Find the magnitude of the secondary impedance of the modeled transmission line. (Primary impedance(Z1) found on RSCAD Model Draft Labed “Line Impedance”)

2. Find the reach of Zone 1 when it is 80% of the modeled transmission line and the reach of Zone 2 when it is120% of the modeled transmission line.

Task 3: Upload Distant Protection Parameters to Relays

Protection Elements

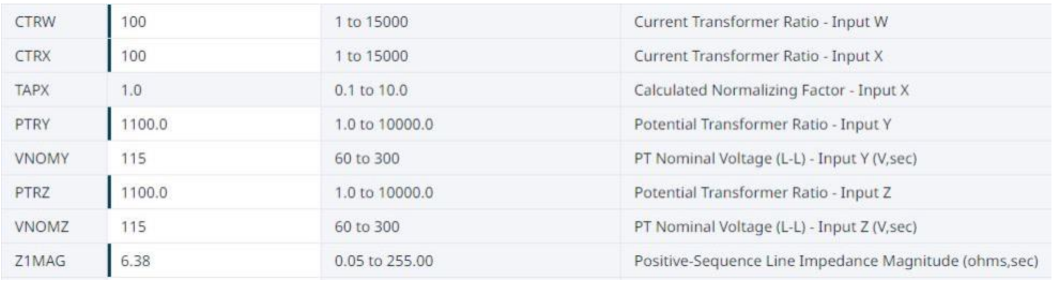
1. Open the “SEL Grid Configurator” program and find the device labeled “Distance Protection Lab Device”
2. Go to Protection>Protection Elements and make sure only two zones are enabled for “Mho Ground Distance Zone” and “Mho Phase Distance Zone.”
   (Be sure this is done in **Group 5** which can be changed at the top of the screen)
3. Input the values you found in task one into these two Protection Elements.
4. The SEL 421-7 should trip instantly when the fault occurs in Zone 1 and should wait 20 cycles before tripping in Zone 2.
5. Screenshot these parameters and include them to your report

CT and PT ratio (Grid Settings)

1. Select Settings Grid>Group 5
2. Input the CT and PT ratios as numerical values and the secondary line impedance (CTRX=CTRW, PTRY=PTRZ, Z1MAG), shown in Figure 2.
3. Screenshot these parameters and include them to your report

Upload the Settings (Must Be on Rolling Screen Display)

1. Unplug the cable from the SEL 421-7 Port 5B
2. Click Connect
3. Once Connected, Click Send
4. Select only “Group 5” and “Protection 5” and then click “Send”
5. Disconnect SEL-421-7 from Grid Configurator and plug the cable back into Port 5B of the SEL 421-7



CTRW	100	1 to 15000	Current Transformer Ratio - Input W
CTRX	100	1 to 15000	Current Transformer Ratio - Input X
TAPX	1.0	0.1 to 10.0	Calculated Normalizing Factor - Input X
PTRY	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Y
VNOMY	115	60 to 300	PT Nominal Voltage (L-L) - Input Y (V,sec)
PTRZ	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Z
VNOMZ	115	60 to 300	PT Nominal Voltage (L-L) - Input Z (V,sec)
Z1MAG	6.38	0.05 to 255.00	Positive-Sequence Line Impedance Magnitude (ohms,sec)

Figure 2: Relevant Grid Settings

Task 4: Test and Show the Runtime Results

Compile and Run the RSCAD model and click “Runtime” to control the fault parameters. After every fault be sure to click “SysReset” on RSCAD and “Target Reset” on the SEL 421-7. Include a screenshot of every instance of RSCAD Runtime and a picture of the SEL 421-7 user interface after every trip. Simulate the following faults:

1. A Line-to-Line fault, where both relays trip instantly.
2. A Line-to-Ground fault where both relays trip instantly.
3. A Line-to-Line-to-Line fault where the SEL 421-7 trips within 20 Cycles.
4. A Line-to-Line-to-Line-to-Ground where the SEL 421-7 trips instantly without the Virtual Relay tripping.

Task 5 (SEL-421-7 ONLY):

1. Redo the lab where the CT Ratio value is 500:1 and the PT Ratio remains the same (3300:1).
2. Zone 1 will reach 75% of the line and trip instantly. Zone 2’s reach is 125% and trip anytime between 450ms and 500ms.
3. Answer the following questions:
    a. What is the Secondary Line Impedance
    b. What is the Reach of Zone 1 and 2
    c. How many cycles should the trip delay be for Zone 2
    d. Now fill out the table 1 for the three instances
    I) A ground fault where both the relays trip instantly
    II) A line-to-line fault where the SEL 421-7 trips within zone 2.
    III) A 3-phase fault were the SEL 421-7 does not trip, but the virtual relay trips.

Instance	Fault Duration(sec,cyc)	Fault Point (%, Km)	Type of Fault
I	(,)	(,)	AG
II	(,)	(,)	
III	(,)	(,)	

Table 1: Task 4 Answers

5.4 Lab Workbook Evaluation Form

We tested our Lab Workbook using students that had no prior knowledge using the RTDS or the SEL-421-7 Protection Relay. Most of the participants had no knowledge of what distance protection was until they completed this lab. After they completed this lab, we asked them to fill out a questionnaire to receive feedback on our skills for developing a lab document that could be used at Western Michigan University. In addition to this we also wanted to see where the lab we created could be improved on. Finally, we also wanted to make sure that this testbed could be used as a training tool for power companies or students who want to go into power systems. The questions and answers to our questionnaire can be seen below in Table 1. The participants' names and WMU emails will not be included in this section for privacy reasons.

Table 1: Questions & Results of Questionnaire

Questions	Answers
1. First Name (Short Answer)	Varies
2. Last Name (Short Answer)	Varies
3. WMU Email (Short Answer)	Varies
4. Undergraduate or Post-Graduate? (Multiple Choice)	100% Undergrad
5. Major? (Short Answer)	100% ECE
6. This Lab Provided Clear Instructions. (1-5)	Avg. = 4/5
7. The lab offered tasks relevant to your major's curriculum. (1-5)	Avg. = 5/5
8. This lab was effective in teaching how to utilize the RTDS and SEL-421-7 relay testbed properly. (1-5)	Avg. = 4.67/5
9. This lab strengthened your knowledge and ability to work with distance-Protection systems/models. (1-5)	Avg. = 5/5
10. All nomenclature referring to ECE Studies (PT ratio, CT ratio, etc.) were understood before starting the lab. (1-5)	Avg. = 4.33/5
11. Do you have any suggestions on how to improve this lab? (Short Answer)	Answers Below
12. Please Upload a copy of your completed lab document. (Add File)	No Responses

Answers for Question 11:

1. One or two words needed to be changed but the whole lab was well explained.
2. Some steps may require a little more detail
3. I would like to see some small picture of the icons to help further know what I'm supposed to be looking for

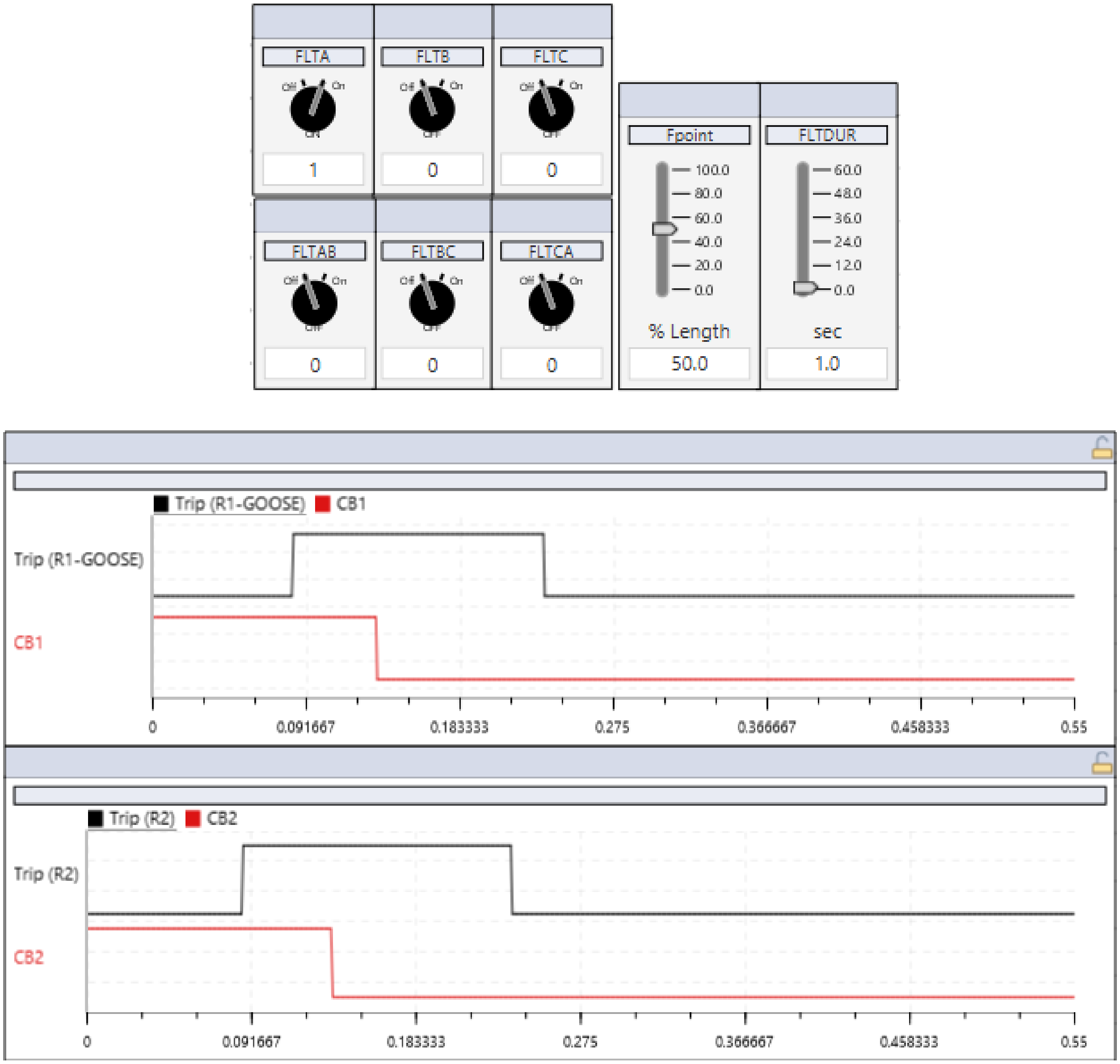
Answers for Question 12:

Since this was a trial run of the lab document the students also wrote notes on their printed-out copies that we kept and made changes between each student taking the lab. The lab also contained questions that required a screenshot to be taken of the results. But for the purpose of time, we allowed the students to skip this step, so the lab did not take longer than needed. These are the reasons no students uploaded their completed labs.

5.5 Evaluation and Results

Definitions

- SEL-421-7 & Virtual Relay Zone 1:
    - Fault Location: 20% to 80%
- Delayed Trip:
    - SEL-421-7 Fault Location: 80% to 100%
    - Virtual Relay Fault Location: 0% to 20%
        - Fault Duration: Greater than 333 milliseconds
- No Trip:
        - Fault Duration: Less than 333 milliseconds
- Ground Fault: Line to Ground
- Phase Fault: Line to Line
- Three Phase Fault: Line to Line to Line



FLTA: 1

FLTB: 0

FLTC: 0

FLTAB: 0

FLTBC: 0

FLTCA: 0

Fpoint: 50.0 % Length

FLTDUR: 1.0 sec

Figure A: Ground (AG) Fault, SEL-421-7 & Virtual Relay Zone 1

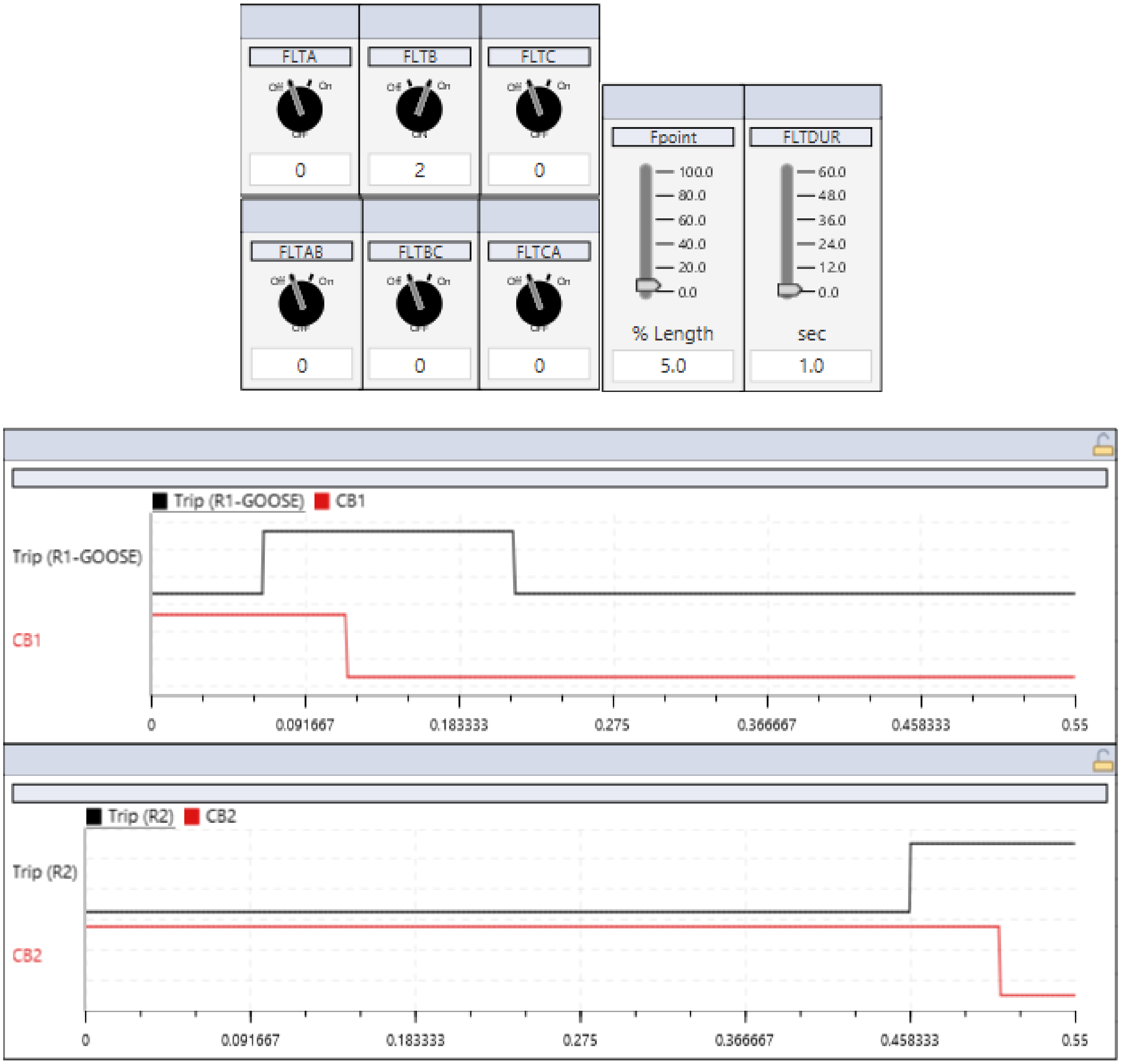
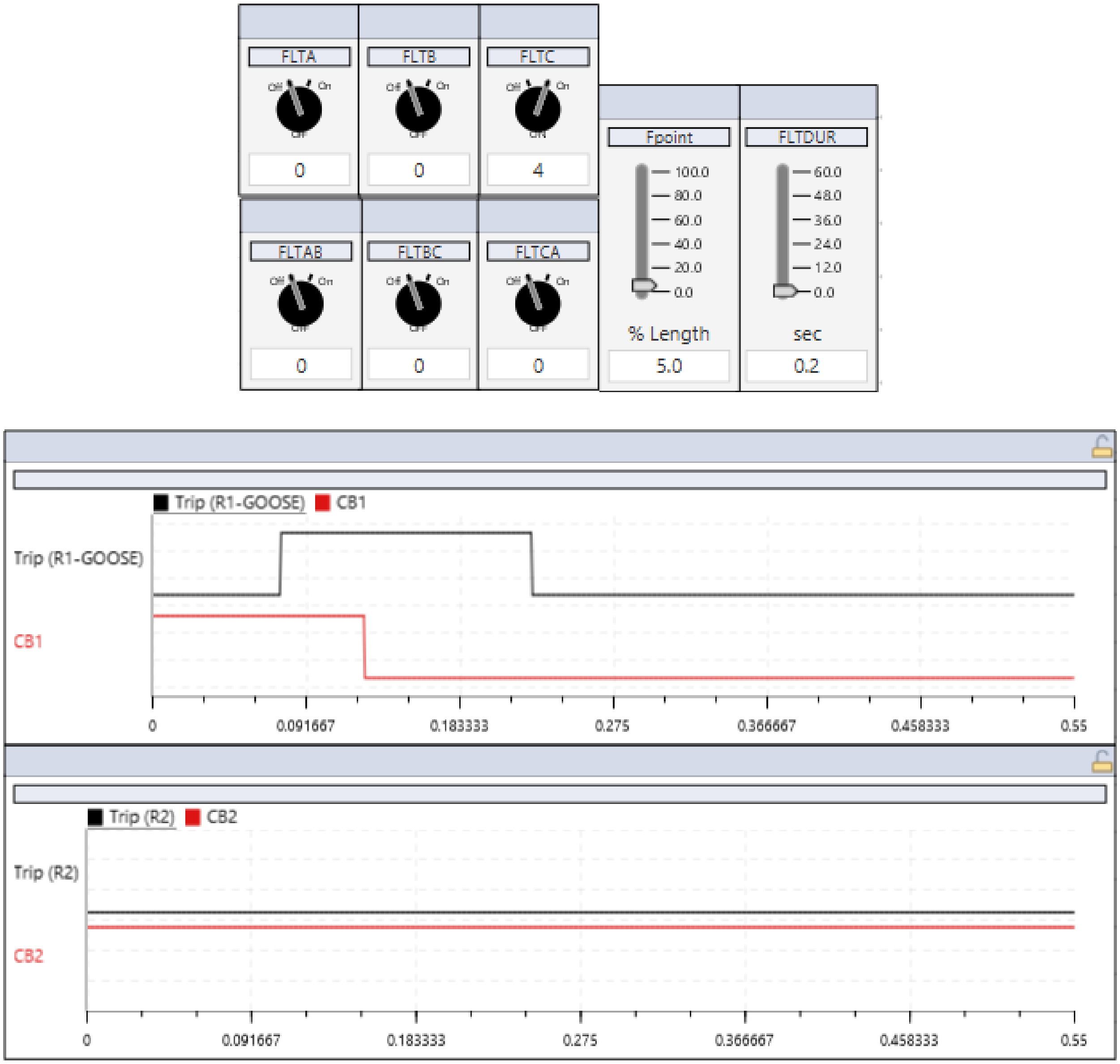


Figure B: Ground (BG) Fault, Virtual Relay Zone 2, Delayed Trip



FLTA 0

FLTB 0

FLTC 4

FLTAB 0

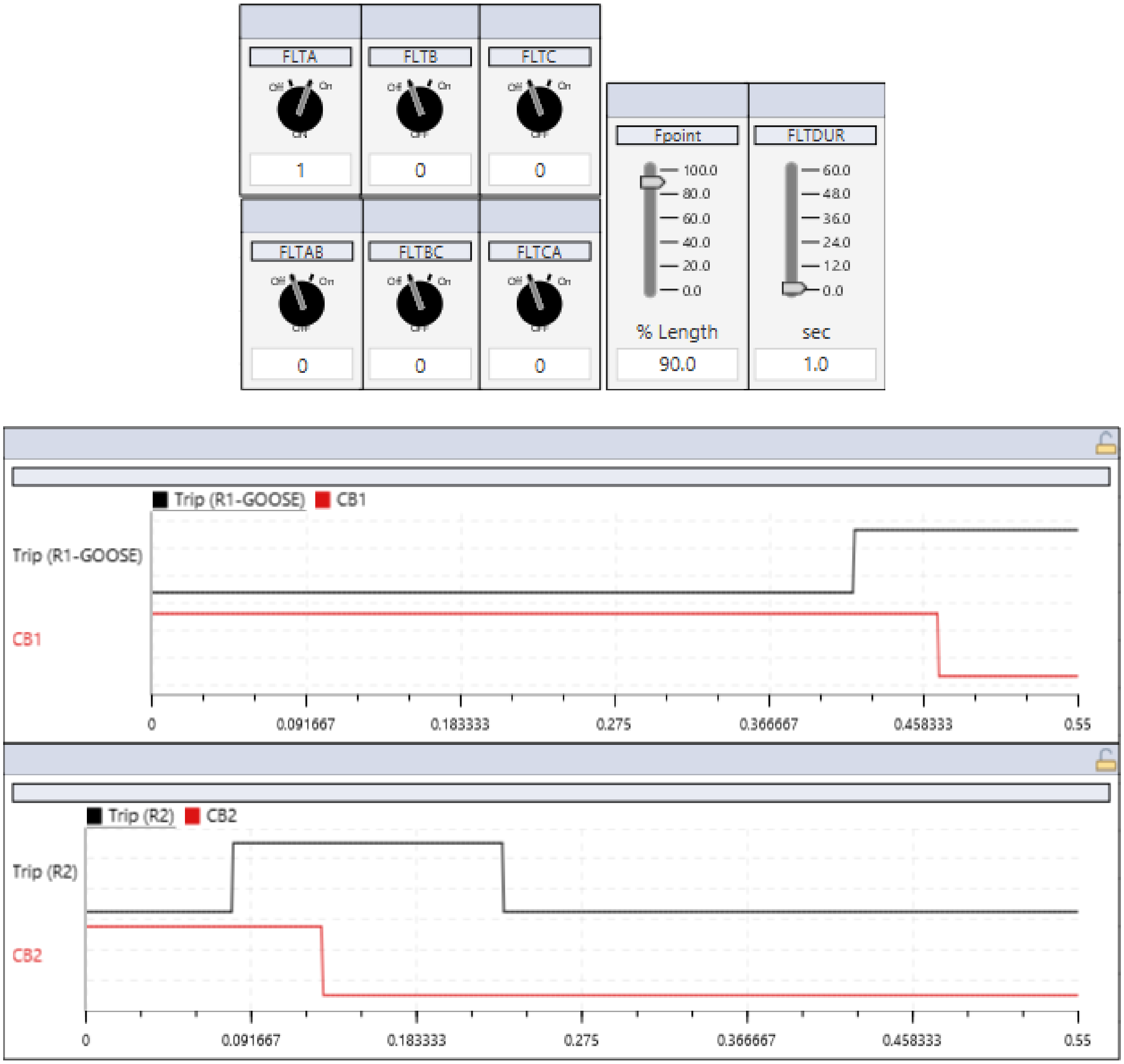
FLTBC 0

FLTCA 0

Fpoint % Length 5.0

FLTDUR sec 0.2

Figure C: Ground (CG) Fault, Virtual Relay Zone 2, No Trip



FLTA 1

FLTB 0

FLTC 0

FLTAB 0

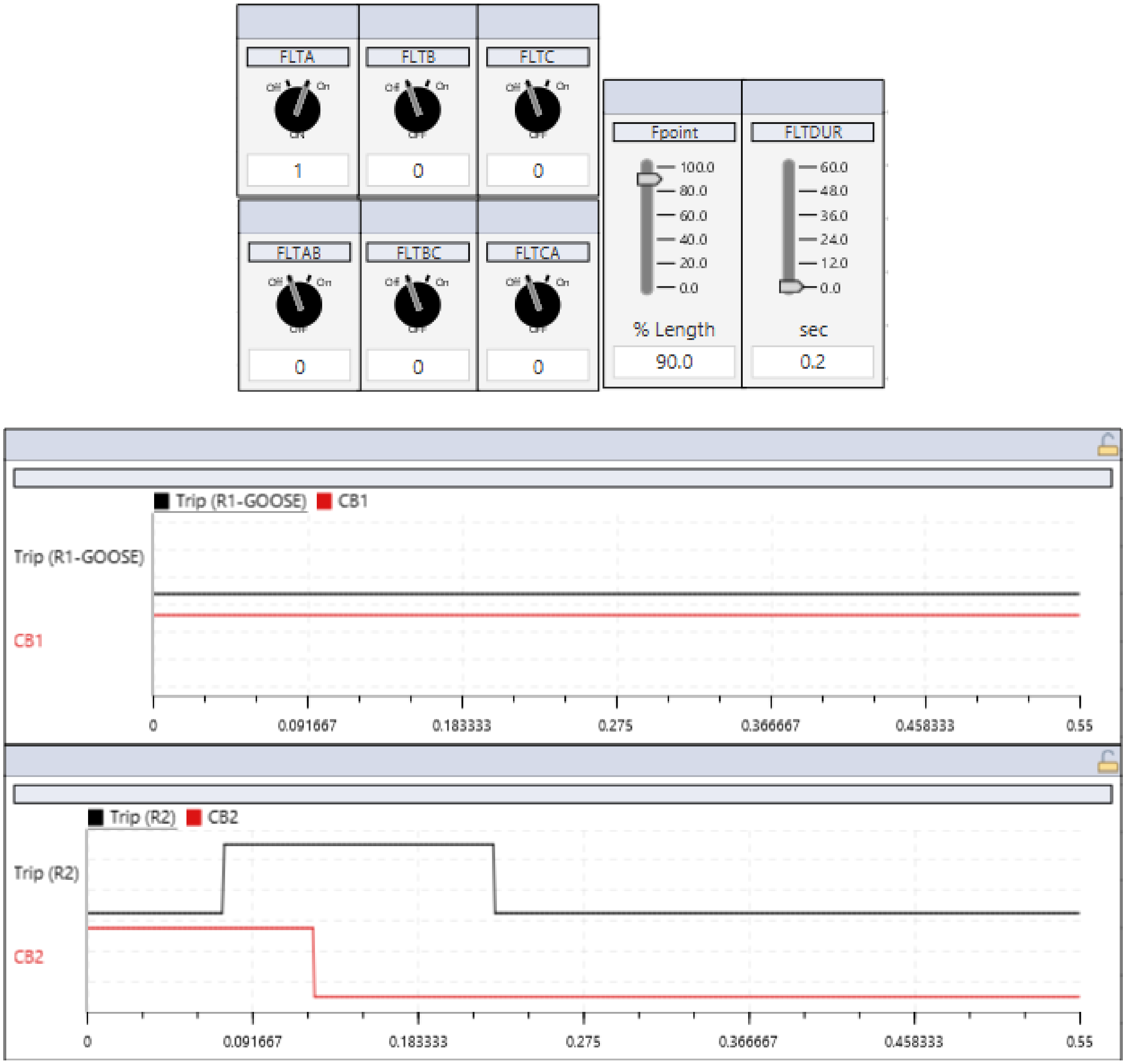
FLTBC 0

FLTCA 0

Fpoint % Length 90.0

FLTDUR sec 1.0

Figure D: Ground (AG) Fault, SEL-421-7 Zone 2, Delayed Trip



FLTA 1

FLTB 0

FLTC 0

FLTAB 0

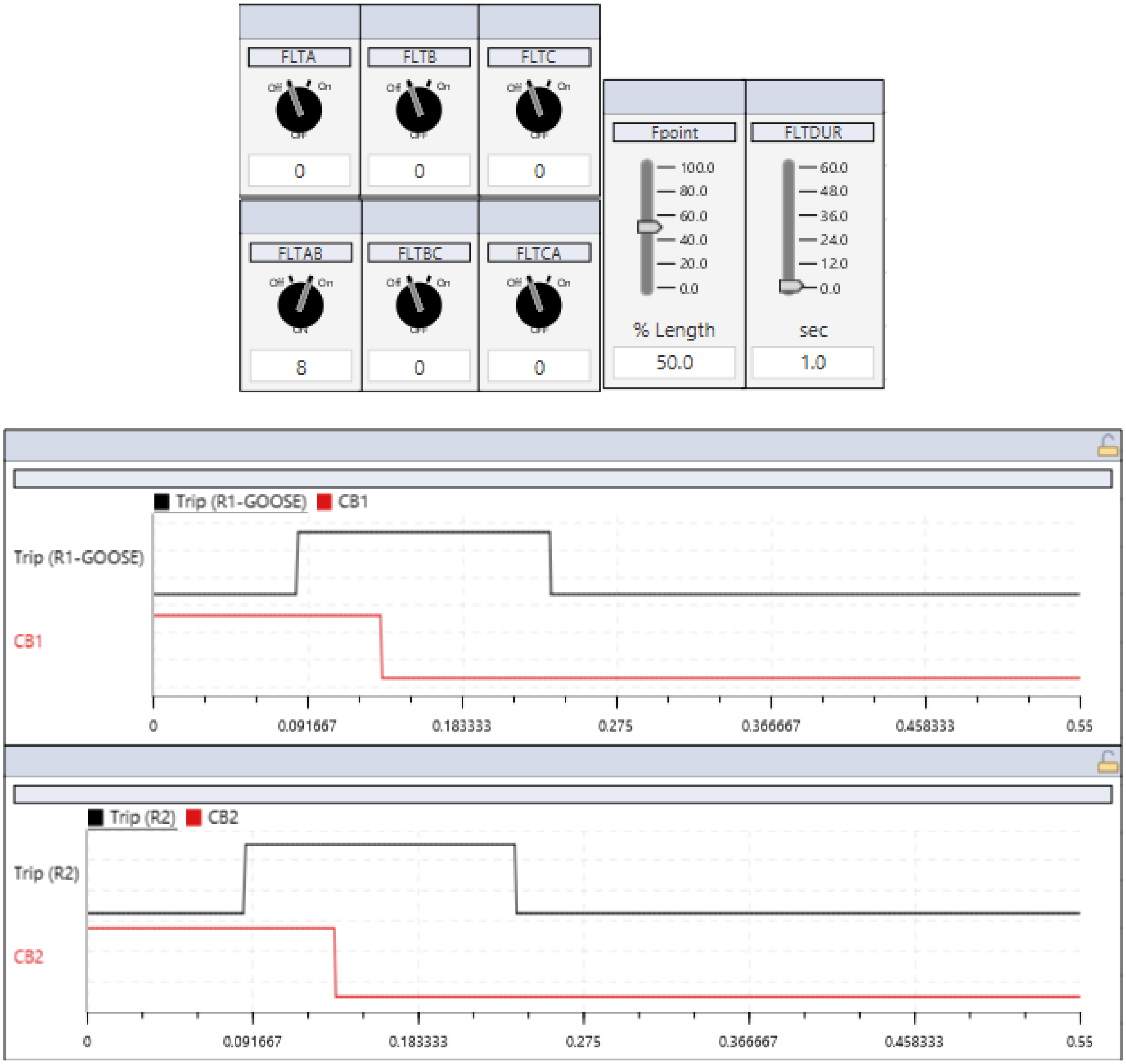
FLTBC 0

FLTCA 0

Fpoint % Length 90.0

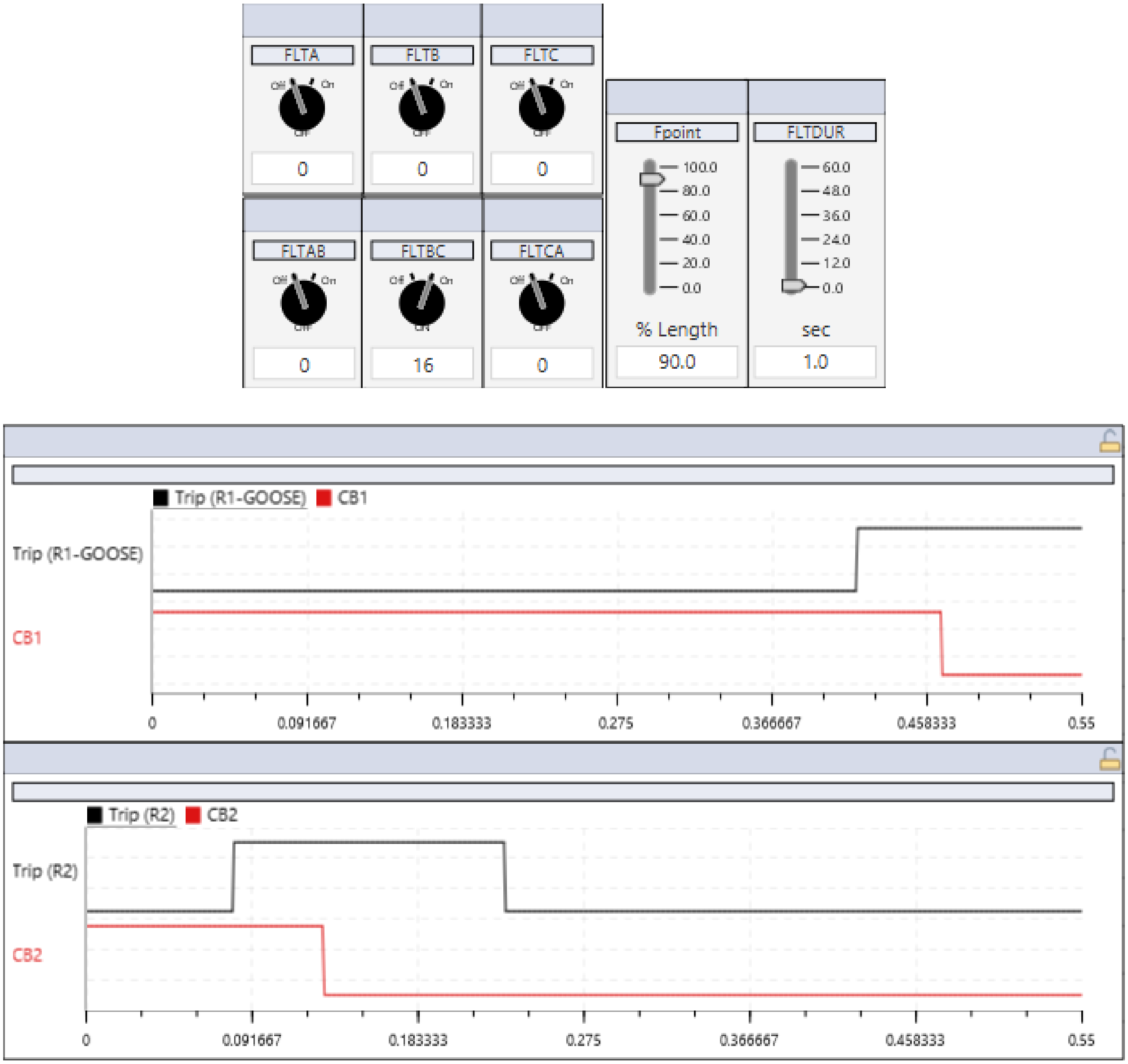
FLTDUR sec 0.2

Figure E: Ground (AG) Fault, SEL-421-7 Zone 2, No Trip



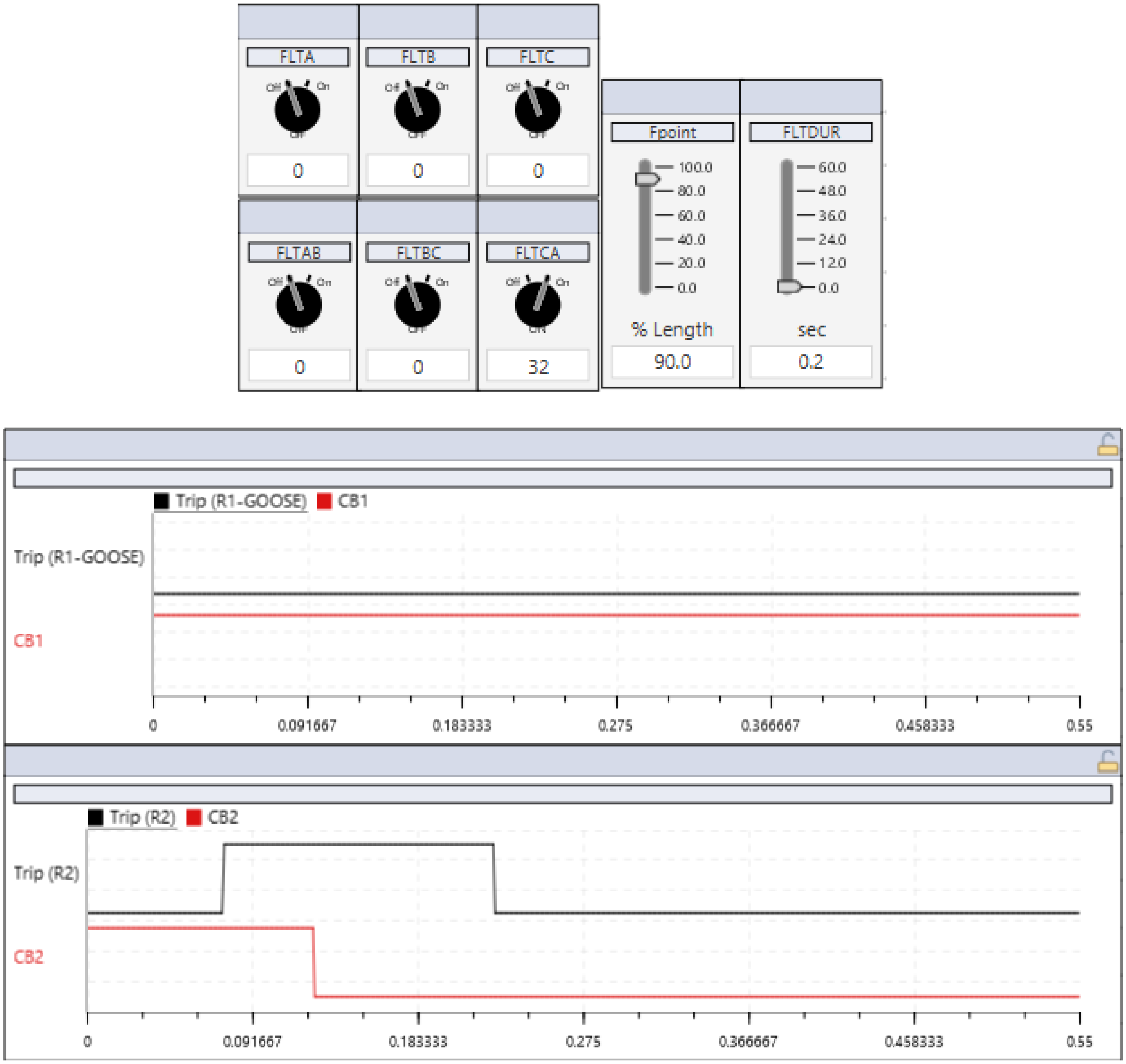
FLTA 0
FLTB 0
FLTC 0
FLTAB 8
FLTBC 0
FLTCA 0
Fpoint % Length 50.0
FLTDUR sec 1.0

Figure F: Phase (AB) Fault, SEL-421-7 & Virtual Relay Zone 1



FLTA 0
FLTB 0
FLTC 0
FLTAB 0
FLTBC 16
FLTCA 0
Fpoint 90.0 % Length
FLTDUR 1.0 sec

Figure G: Phase (BC) Fault, SEL-421-7 Zone 2, Delayed Trip



FLTA 0

FLTB 0

FLTC 0

FLTAB 0

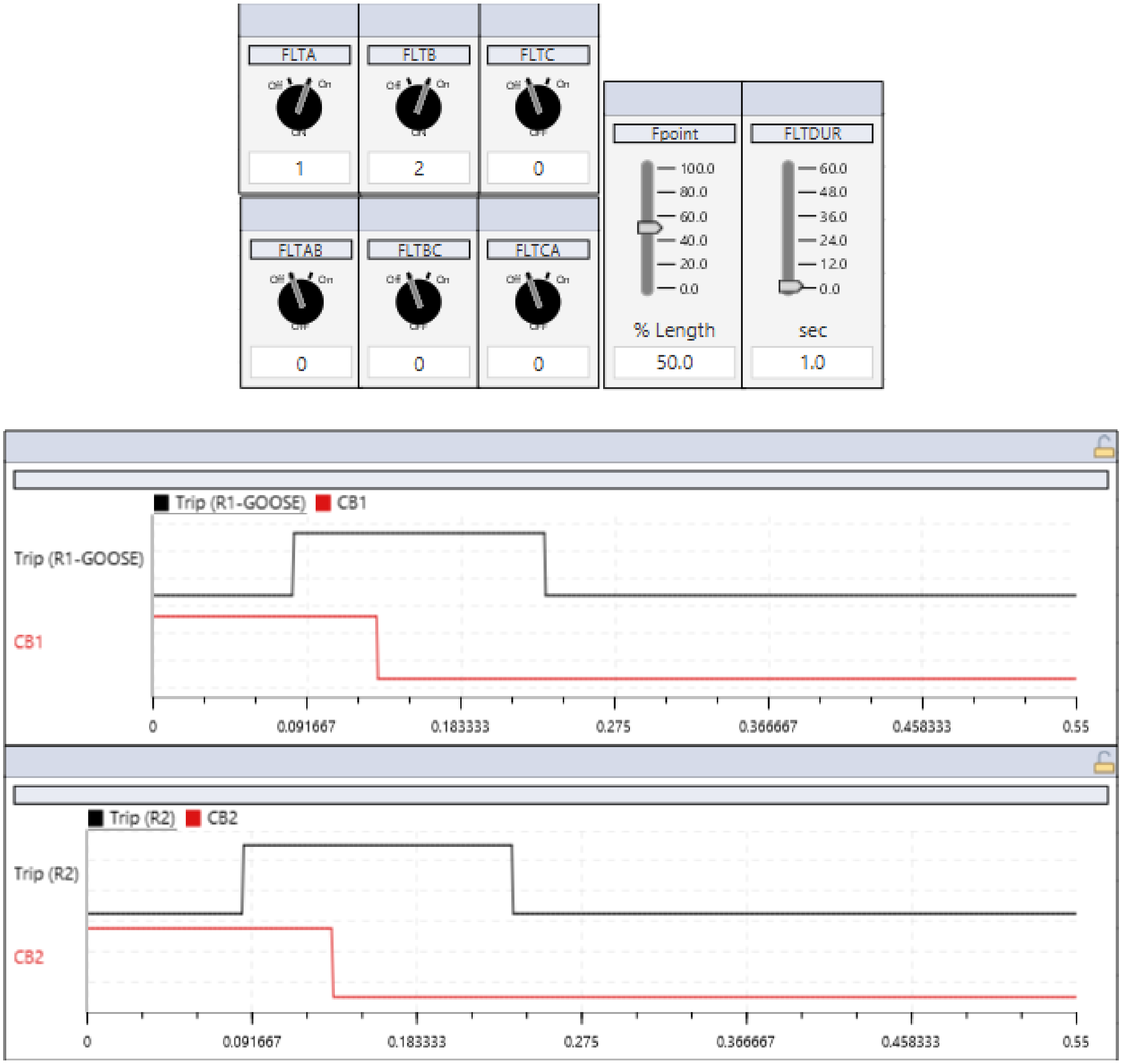
FLTBC 0

FLTCA 32

Fpoint 90.0 % Length

FLTDUR 0.2 sec

Figure H: Phase (AC) Fault, SEL-421-7 Zone 2, No Trip



FLTA 1

FLTB 2

FLTC 0

FLTAB 0

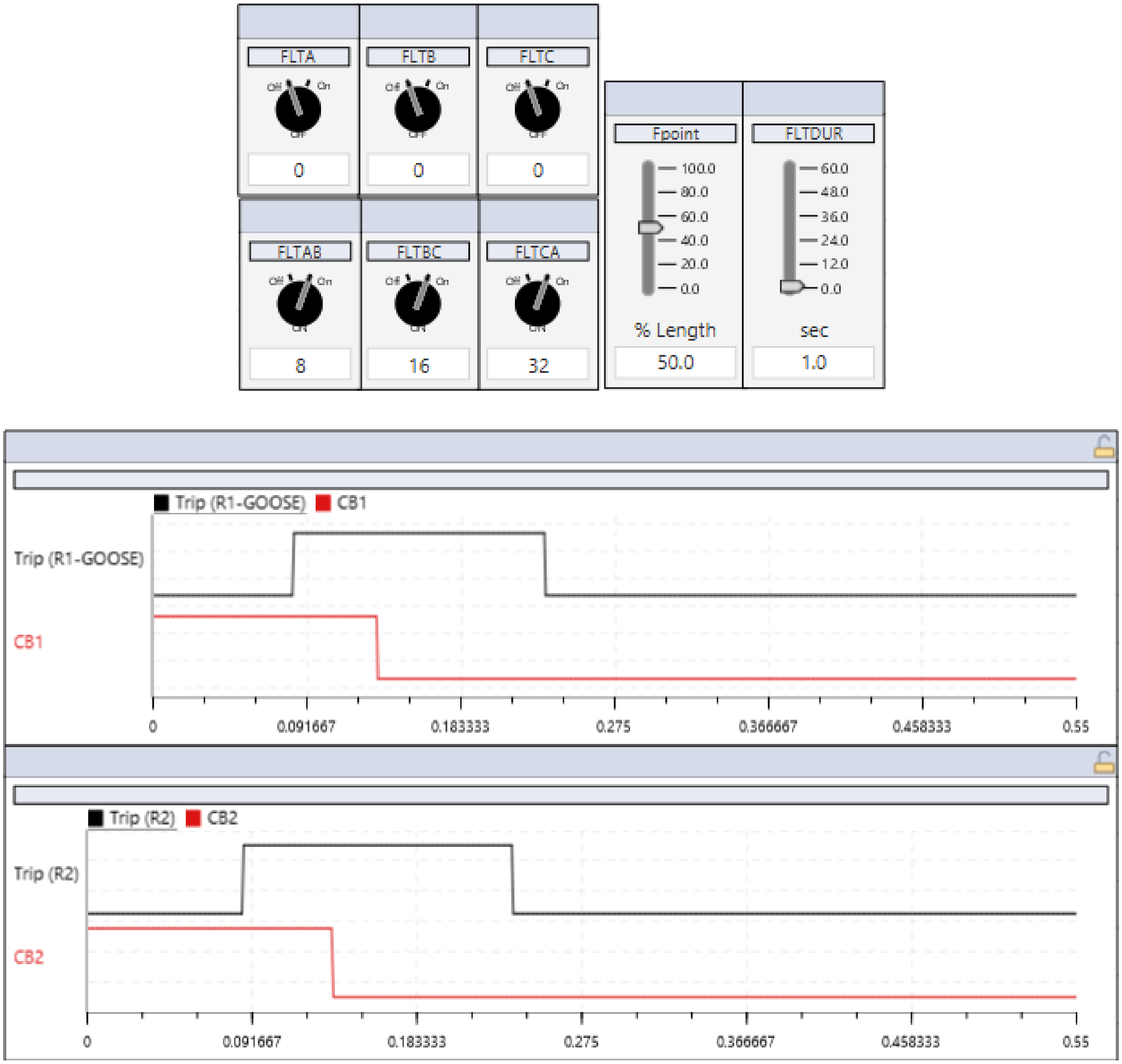
FLTBC 0

FLTCA 0

Fpoint % Length 50.0

FLTDUR sec 1.0

Figure I: Two Phase to Ground Fault (ABG), SEL-421-7 & Virtual Relay Zone 1



FLTA 0

FLTB 0

FLTC 0

FLTAB 8

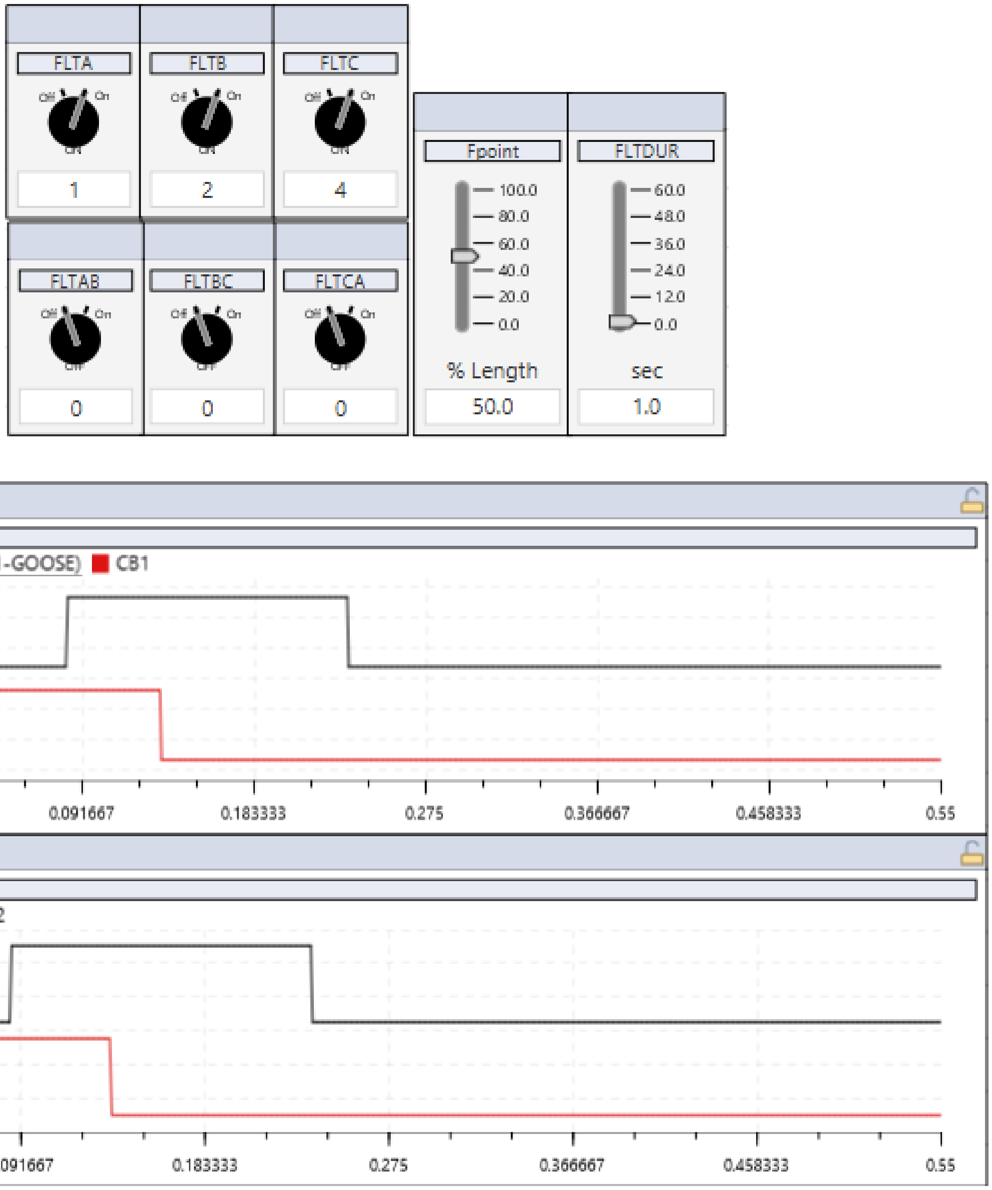
FLTBC 16

FLTCA 32

Fpoint % Length 50.0

FLTDUR sec 1.0

Figure J: Three Phase (ABC) Fault, SEL-421-7 & Virtual Relay Zone 1

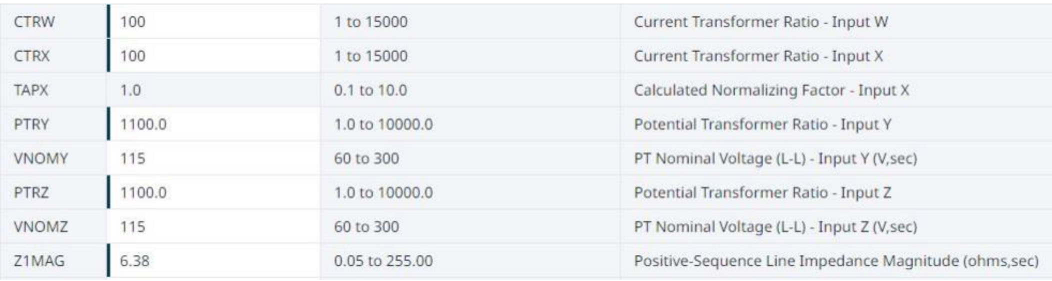


FLTA 1
FLTB 2
FLTC 4
FLTAB 0
FLTBC 0
FLTCA 0
Fpoint % Length 50.0
FLTDUR sec 1.0

Figure K: Three Phase to Ground (ABCG) Fault, SEL-421-7 & Virtual Relay Zone 1

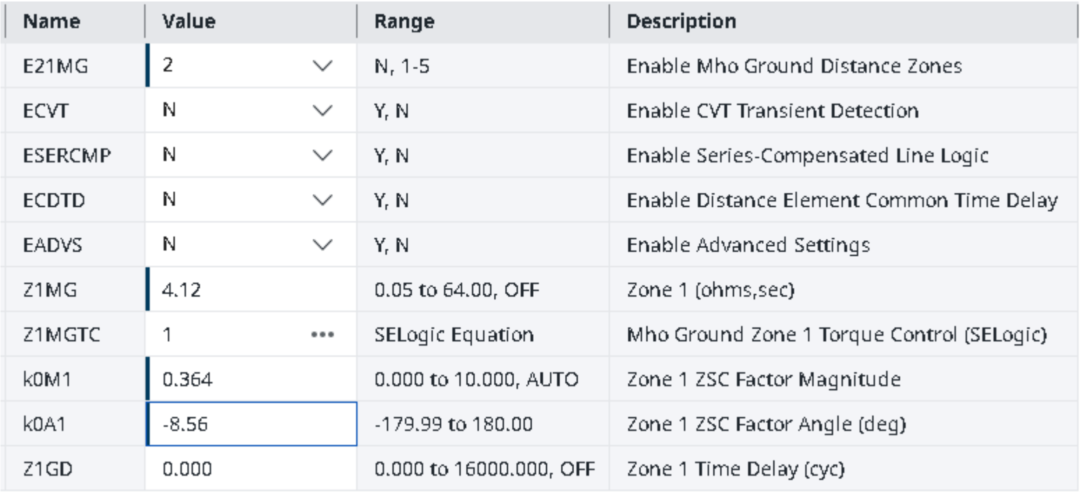
5.6 SEL Grid Configurator Settings

Table 2: Relevant Grid Settings



CTRW	100	1 to 15000	Current Transformer Ratio - Input W
CTRX	100	1 to 15000	Current Transformer Ratio - Input X
TAPX	1.0	0.1 to 10.0	Calculated Normalizing Factor - Input X
PTRY	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Y
VNOMY	115	60 to 300	PT Nominal Voltage (L-L) - Input Y (V,sec)
PTRZ	1100.0	1.0 to 10000.0	Potential Transformer Ratio - Input Z
VNOMZ	115	60 to 300	PT Nominal Voltage (L-L) - Input Z (V,sec)
Z1MAG	6.38	0.05 to 255.00	Positive-Sequence Line Impedance Magnitude (ohms,sec)

Table 3: Mho Ground Distance Zone 1 Settings

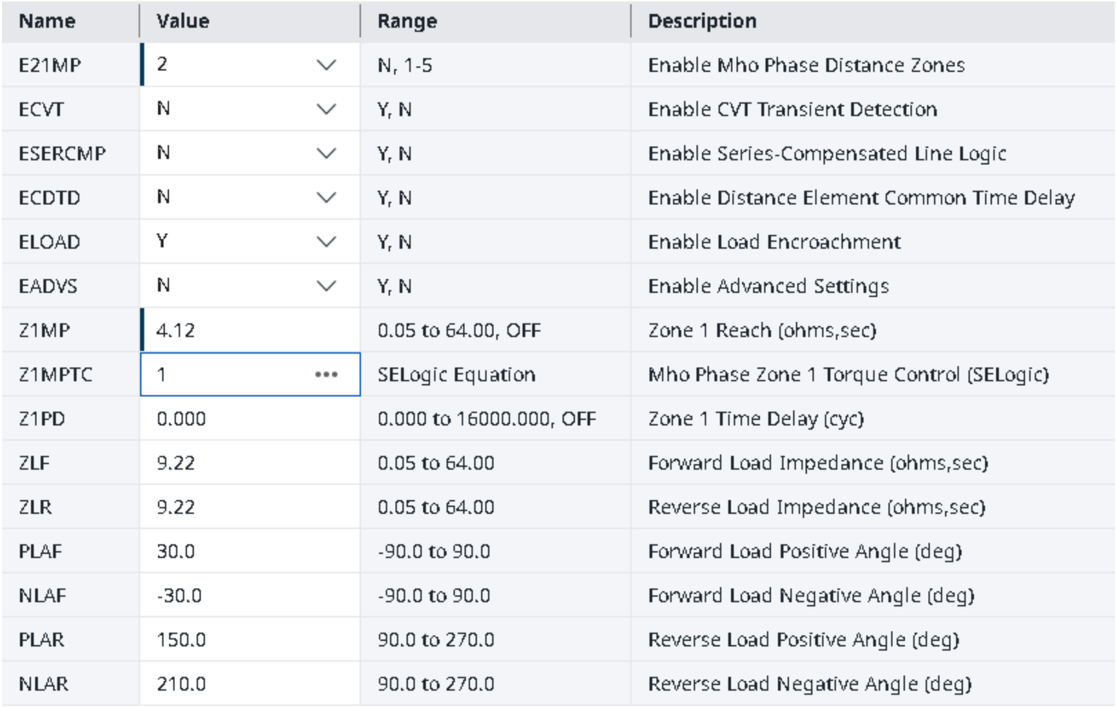


Name	Value	Range	Description
E21MG	2	N, 1-5	Enable Mho Ground Distance Zones
ECVT	N	Y, N	Enable CVT Transient Detection
ESERCMP	N	Y, N	Enable Series-Compensated Line Logic
ECDTD	N	Y, N	Enable Distance Element Common Time Delay
EADVS	N	Y, N	Enable Advanced Settings
Z1MG	4.12	0.05 to 64.00, OFF	Zone 1 (ohms,sec)
Z1MGTC	1	SELogic Equation	Mho Ground Zone 1 Torque Control (SELogic)
k0M1	0.364	0.000 to 10.000, AUTO	Zone 1 ZSC Factor Magnitude
k0A1	-8.56	-179.99 to 180.00	Zone 1 ZSC Factor Angle (deg)
Z1GD	0.000	0.000 to 16000.000, OFF	Zone 1 Time Delay (cyc)

Table 4: Mho Ground Distance Zone 1 Settings

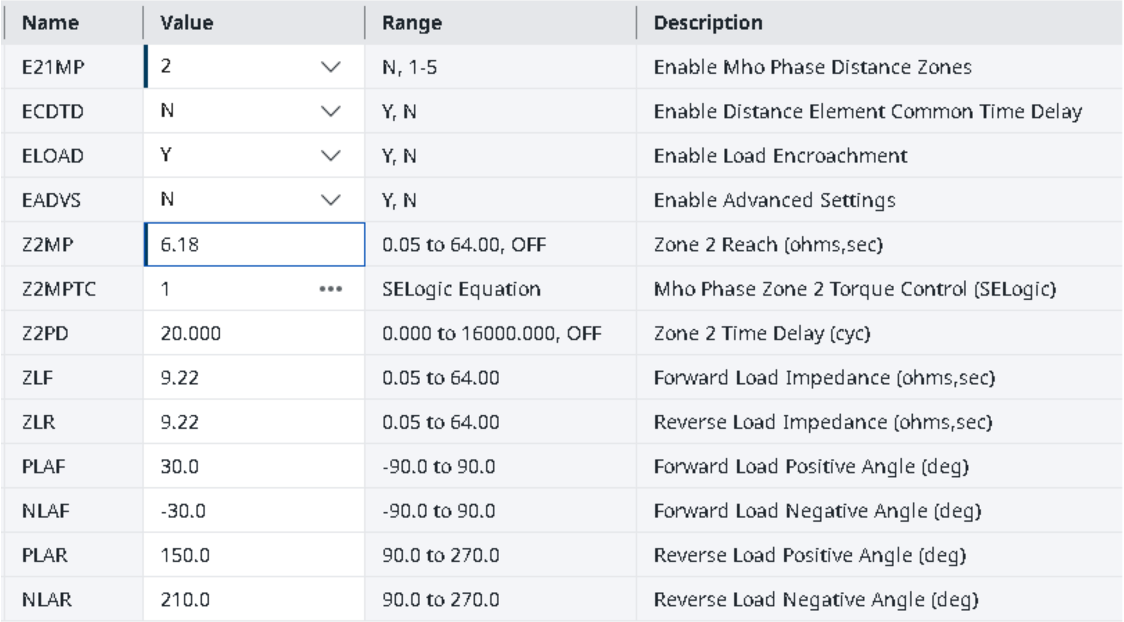
Name	Value	Range	Description
E21MG	2	N, 1-5	Enable Mho Ground Distance Zones
ECDTD	N	Y, N	Enable Distance Element Common Time Delay
EADVS	N	Y, N	Enable Advanced Settings
Z2MG	6.18	0.05 to 64.00, OFF	Zone 2 (ohms,sec)
Z2MGTC	1	SELogic Equation	Mho Ground Zone 2 Torque Control (SELogic)
Z2GD	20.000	0.000 to 16000.000, OFF	Zone 2 Time Delay (cyc)

Table 5: Mho Phase Distance Zone 1



Name	Value	Range	Description
E21MP	2	N, 1-5	Enable Mho Phase Distance Zones
ECVT	N	Y, N	Enable CVT Transient Detection
ESERCMP	N	Y, N	Enable Series-Compensated Line Logic
ECDTD	N	Y, N	Enable Distance Element Common Time Delay
ELOAD	Y	Y, N	Enable Load Encroachment
EADVS	N	Y, N	Enable Advanced Settings
Z1MP	4.12	0.05 to 64.00, OFF	Zone 1 Reach (ohms,sec)
Z1MPTC	1	SELogic Equation	Mho Phase Zone 1 Torque Control (SELogic)
Z1PD	0.000	0.000 to 16000.000, OFF	Zone 1 Time Delay (cyc)
ZLF	9.22	0.05 to 64.00	Forward Load Impedance (ohms,sec)
ZLR	9.22	0.05 to 64.00	Reverse Load Impedance (ohms,sec)
PLAF	30.0	-90.0 to 90.0	Forward Load Positive Angle (deg)
NLAF	-30.0	-90.0 to 90.0	Forward Load Negative Angle (deg)
PLAR	150.0	90.0 to 270.0	Reverse Load Positive Angle (deg)
NLAR	210.0	90.0 to 270.0	Reverse Load Negative Angle (deg)

Table 6: Mho Phase Distance Zone 2



Name	Value	Range	Description
E21MP	2	N, 1-5	Enable Mho Phase Distance Zones
ECDTD	N	Y, N	Enable Distance Element Common Time Delay
ELOAD	Y	Y, N	Enable Load Encroachment
EADVS	N	Y, N	Enable Advanced Settings
Z2MP	6.18	0.05 to 64.00, OFF	Zone 2 Reach (ohms,sec)
Z2MPTC	1	SELogic Equation	Mho Phase Zone 2 Torque Control (SELogic)
Z2PD	20.000	0.000 to 16000.000, OFF	Zone 2 Time Delay (cyc)
ZLF	9.22	0.05 to 64.00	Forward Load Impedance (ohms,sec)
ZLR	9.22	0.05 to 64.00	Reverse Load Impedance (ohms,sec)
PLAF	30.0	-90.0 to 90.0	Forward Load Positive Angle (deg)
NLAF	-30.0	-90.0 to 90.0	Forward Load Negative Angle (deg)
PLAR	150.0	90.0 to 270.0	Reverse Load Positive Angle (deg)
NLAR	210.0	90.0 to 270.0	Reverse Load Negative Angle (deg)

5.7 Standards Table

These are the applicable standards that we followed when creating our testbed. Most of these standards involve the communication protocol used and safety in a lab setting.

Table 7: Applicable Standards

Standard	Description
UL 61010-1	Safety with electrical equipment for laboratory use
IEC 60255-121 IEC 60255-151	Measuring relays and protection equipment
IEEE C37.90	Relays and relay systems associated with electric power apparatus.
IEC/TR 61850-1	Standard for real-time communication between intelligent electronic devices at substations.
IEEE 1782	Collecting and managing data about power interruption events for power systems.
IEEE 1159	Method for the monitoring the efficiency of electric power systems
IEC 61850	Standard for the GOOSE communication Protocol

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