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Project evaluation Page

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College of Engineering and Applied Science

ECE 4820 Senior Design

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Real-Time Testbed for Smart Grid Recloser Controller

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Abstract

The growing need for a low voltage recloser has become apparent due to the rise in requirements for a smart grid. This includes more detailed management of power flow forward (towards load) and backward (towards generation), source synchronization in real time, more in-depth fault responses, and the use of green energy. The SEL-651R-2 relay is a device that can manage these needs, especially in fault response and synchronization, and is commonly used in systems called microgrids. Microgrids are distribution level systems that are able to operate separated from the main grid, are typically installed much closer to the load(s), and are fed by distributed energy resources (DERs), such as wind, solar or diesel generators.

The SEL-651R-2 is normally used in the field with presets operative settings, but the Western Michigan University (WMU) Center for Interdisciplinary Research on Secure, Efficient and Sustainable Energy Technology (WMU InterEnergy Center) wished to test this device in its range of capabilities for microgrid application. A Hardware-In-the-Loop (HIL) testbed was implemented and used through the Real Time Digital Simulator (RTDS) using the RSCAD software to test the SEL-651R-2's use cases and functions. The testbed includes a microgrid with interconnection to a larger main grid, and the relay is meant to control the recloser at the point of common coupling (PCC) between the main grid and microgrid. The testbed shows how basic protections, reclosing, and synchronization checks function when handling faults that affect both the microgrid and the main grid.

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TEAM MEMBERS NAMES:

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_______Ethan Weldert__________		04/07/2025
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Acknowledgements

We would like to extend our gratitude to the many people who made this project possible. Our first thanks goes to Dr. Pablo Gomez and the WMU InterEnergy Center for sponsoring this project and providing the technology needed to complete it, including the SEL-651R-2 and the RTDS system. Thanks should also be given to one of the graduate students also working under Dr. Gomez, Mark Booge, as he was integral in teaching us how to use RSCAD among other things. Overall, he was a guiding hand along with Dr. Gomez for the completion of this project. Additional thanks go to the US Department of Energy for initial funding to the WMU InterEnergy Center for acquisition of the RTDS and SEL 651R-2 devices, as well as to FM Global for providing further funding for this project.

Representatives from both SEL and RTDS provided support through meetings to give information about RSCAD, the RTDS, and the SEL-651R-2. From SEL, both Tim Lewis and Nicholas Jones offered many hours of information to provide direction for the project. From RTDS, Arun Sakthivel provided similar amounts of information on RSCAD for project direction. All of these representatives made many of the challenges presented with this project much more surmountable.

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1. Introduction

As the use of renewable energy increases, smart systems are more extensively applied to interconnect, manage and control different power components of the electric grid. Specifically, systems called microgrids have been used recently to connect renewable sources together, supply local loads, and connect these sources to the larger distribution grid. Through Hardware-in-the-Loop (HIL) testing of protection and control devices, the correct operation of these complicated and expensive interconnections under normal and abnormal conditions can be simplified to a real-time simulation, with similar fidelity and results.

1.1 Purpose and Scope

The purpose of the proposed testbed is to provide an economical way to test the functionality of the SEL-651R-2 without the need for a physical test grid. This involves less environmental cost (construction, procurement of resources needed for construction, and manufacturing of resources), and monetary cost for the university. This also provides a safer way of testing the relay, as the high voltages involved in microgrid protection can be dangerous. Although the SEL-651R-2 could be simulated, having the physical device allows more precise configuration and allows for proper usage of the device without simulation approximations. This project aims to have the SEL-651R-2 interconnected with the RTDS' microgrid model for functionality testing and verification through the RSCAD HMI, as well as documentation for further use for other research projects.

2. Discussion

2.1 Overview

Due to the increasing use of renewable energy in the United States, major changes to our power grid are happening, including the application of collections of smart microgrids to support or replace parts of the current wider grid. These microgrids are powered by Distributed Energy

Resources (DERs), electrical generation devices connected directly to the grid without transmission, closer to the loads. Microgrids allow a higher robustness in the grid through sectionalizing it into smaller, independent grids that supply smaller loads. This means that the number of loads affected by outages in generation for these microgrids will be smaller than for a traditional grid. A simplified diagram of a microgrid is shown in Fig. 1.

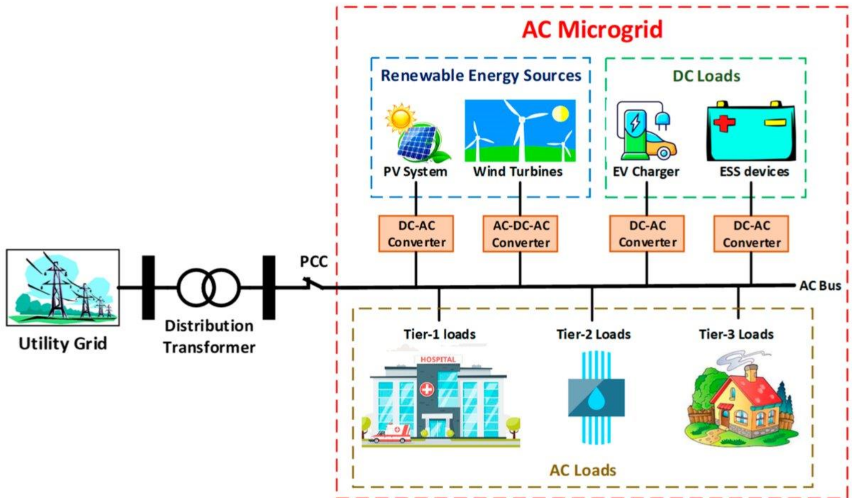

Figure 1: Microgrid diagram [12]

One important feature of microgrids is the recloser breaker (specifically at the point of common coupling, or PCC), which allows automatic disconnection from the main grid in case of failures. This ability protects the microgrid from failures in the main grid and protects the main grid from failures within the microgrid. Displays of fidelity for the devices used to control these reclosers are beneficial in both technical research and educational purposes to help foster the continued push for improving the United States' electrical power infrastructure.

2.1.1 Background

For this project, we use Western Michigan University's (WMU) real-time digital simulator (RTDS, a.k.a. NovaCor) shown in Figure 2, with an SEL-651R-2 recloser relay, shown in Figure 3. Both devices are top of the line in their respective fields. We aim to interconnect these devices using the Distributed Network Protocol (DNP3) communication protocol defined by the IEEE 1815-2023 standard. The simulation is built on the software, RSCAD, which is a Power System Simulation Software. A simulation model is a fully simulated microgrid completed with a renewable source, energy storage, and a possible traditional power source (diesel), and a PCC with a larger grid. The model should be also able to introduce faults. The relay is configured using AcSELerator Quickset. The RTDS's Novacor software generates the voltage, current and phase at a selected node. The information of the simulated node is digitally communicated to the SEL-651R-2. The SEL-651R-2 sends different signals (TRIP and CLOSE) depending on the type of fault selected, which can be received by the RTDS (and therefore the breaker that is simulated inside of it). This process can also be simulated in real time using DNP3 to keep track of the communication between the SEL-651R-2 and the RTDS. The user can view the resulting plots and other information on their computer to analyze different events through the simulation's runtime.

Figure 2: RTDS/NovaCor device

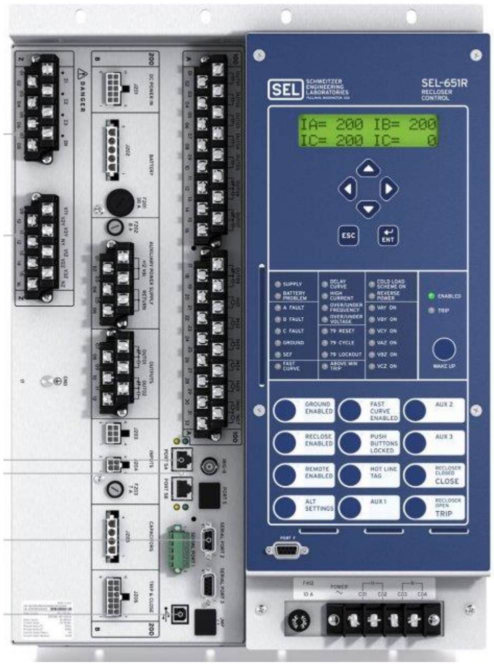

Figure 3: SEL-651R-2

The sponsor for this project is the WMU InterEnergy Center directed by Dr. Pablo Gomez, who is also our project's faculty advisor. This Center was founded recently and is comprised of professors from multiple fields of study related to energy research.

2.1.2. Need Statement

The recloser controller, if found to be beneficial to microgrid functions, could be used in the future to manage a smart microgrid on campus, which would help boost the use of renewable energy locally. It advertises the capability to automatically synchronize local and main grids, isolate the local grid from the main grid, and manage individual power sources within the local grid. Though more testing is needed to realize the recloser controller's full potential, the project's cost is limited. Therefore, Dr. Gomez proposes creating a virtual testbed specifically for the recloser to test the capabilities of the device. The testbed must be easy to understand, accurate to real-world environments and scenarios the device would interact with, and easy to modify for specific testing regarding the recloser. This document is the final report describing the implementation of a real-time testbed for the SEL-651R-2 to display the capabilities of this device for microgrid applications.

2.1.3 System Diagram

Figure 4 shows the main diagram depicting the interconnection between the RTDS/NovaCor and the SEL 651R-2. The NovaCor simulates a real-time testbed, produced and managed through the RSCAD simulation. It then uses the GTAO port to produce three main signals. The first signal is a scaled-down voltage from the breaker to the main grid transformer, labeled in the image as V1Y. The second signal is a scaled down voltage from the breaker to the rest of the microgrid, labeled in the image as V1Z. Both signals produce a voltage of +/- 20V peak-peak. The last signal produced is a 2.4 VDC supply. This supply runs to two normally open switches within the SEL-651 recloser: OUTO1 and OUTO2. These switches are activated by the recloser as TRIP and RECLOSE commands respectively; they are observed by the NovaCor's GTAI card, which is returned to the simulation and used as a command to the PCC breaker within the simulation.

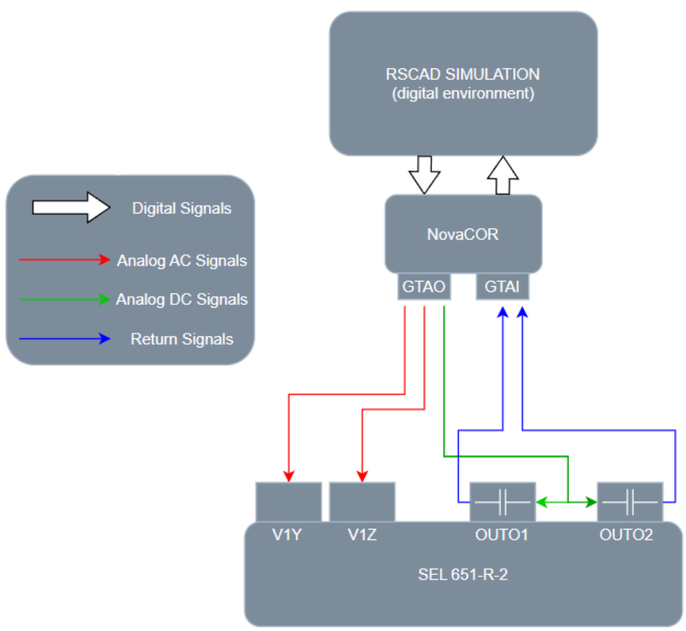

Figure 4: HIL Communication Flowchart

2.1.4 Specifications

This project aims to study the functionality of the SEL-651R-2 in an economical and accessible way. This will or future use in other research projects and to reduce environmental effects, while providing a positive societal and helping provide towards the sustainability of the university.

2.1.4.1 Physical Characteristics

2.1.4.1.1 - All devices, simulated or physical, should be interconnected following a DNP3 communication protocol with ethernet connections.

2.1.4.1.2 - RTDS should be connected to a workstation for RSCAD simulation viewing.

2.1.4.1.3 - SEL-651R-2 LEDs must display current relay status.

2.1.4.1.4 - SEL-651R-2 must be powered via SEL developed DC supply to charge battery and run microprocessor in parallel.

2.1.4.1.4a SEL-651R-2 power module that is separate from the SEL developed DC supply must also be interconnected to charge capacitors internally for tripping functions.

2.1.4.2 Simulation and Relay Characteristics

2.1.4.2.1 RSCAD Microgrid Model

2.1.4.2.1.1 The model must simulate a microgrid to reasonable accuracy as to properly emulate a real microgrid, while meeting the RTDS/NovaCOR 3 processor/core limit.

2.1.4.2.1.1a The microgrid itself must be able to have grid-tied supporting and receiving, and islanded modes of operations depending on fault conditions.

2.1.4.2.1.2 The model must be able to simulate faults to test the working functionality of the SEL-651R-2.

2.1.4.2.1.2a Fault types include Line to Line, Line to Ground, and Line to Line to Ground, with tripping conditions of over/under voltage, and over/under current.

2.1.4.2.1.2b Overloading/underfrequency faults must also be included.

2.1.4.2.1.3 The model must interpret, convert, receive and transmit data to the SEL-651R-2 for voltage, current, and frequency information.

2.1.4.2.1.4 Adhere to the processing core limit of the RTDS Apparatus.

2.1.4.2.2 RTDS/NovaCOR

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

2.1.4.2.2.2 GTAO board must output transmitted simulation voltage, current, and frequency data to the relay.

2.1.4.2.2.3 GTNETx2 card must receive data from the SEL-651R-2 and the RSCAD simulation.

2.1.4.2.2.3a GTNET-DNP firmware found on GTNETx2 to be used to interpret DNP3 communication.

2.1.4.2.2.3b GTNET-PB firmware found on GTNETx2 to be used to connect SEL-651R-2 with the RTDS.

2.1.4.2.3 SEL-651R-2 Relay

2.1.4.2.3.1 The relay should be able to read and interpret the digitally exported analog data from the RSCAD simulation data.

2.1.4.2.3.2 The relay's internal logic, configured using AcSELerator Quickset, should be able to make decisions about tripping, reclosing, and locking out in the event of a fault.

2.1.4.2.4 Documentation

2.1.4.2.4.1 Provide documentation such as manuals and datasheets of this simulation's functionality for future use in research.

2.1.4.3 Applicable Standards

IEEE 1547-2018 provides rules for all ways DERs can interconnect with the Area EPS (utility's power system). This includes the communication systems allowed (DNP3 or Modbus), the organization of devices (controllers, protections, communication, and generation), and the types of devices required. This standard deals specifically with operating modes (support, receive, and islanding) via control of the Point of Common Contact (PCC) in a microgrid when interconnecting [1]. This part of the standard is the most relevant one to the project.

IEC C37.90 supplies all ratings and testing requirements for all protection relays that protect and control a power system. This standard is helpful because it allows to understand how each relay should be tested and designed. It is not possible to overload the SEL-651R-2 with voltage supplied from the RTDS, unless it is connected incorrectly, but this standard defines the electrical and thermal ratings for each relay [11].

IEEE 1815-2012 defines the communication protocol DNP3. This protocol is created for the remote control of outstation devices through a master that is human-controlled and several outstations that can be monitored and controlled through the master. This protocol is used for automated systems (such as this microgrid's protection system) and is built in with time synchronization support [7]. This functionality is very useful for the proposed testbed.

IEEE 1782 is a standard for determining a power system's reliability through an interruption event. An interruption event is a length of time in which a transmission line does not have any power in that area [10]. A fault is not normally categorized by this, but a fault can be strong enough or last long enough to cause damage that would lead to a power outage.

2.1.5 Deliverables

This project has significant differences over other projects done by WMU students, where a physical prototype is implemented to address the need of a sponsor, in which case the completed prototype is the main deliverable. However, similar projects to the one proposed here have been completed at the WMU InterEnergy Center [8]. Following in their steps, the implemented testbed can be prepared for use in research and education, although education is a secondary goal. Therefore, the main deliverable of this project, besides the completed testbed itself, is the documentation describing the use of the RSCAD model driven by the RTDS NovaCor and interconnected with the SEL-651R-2. This is done in a tutorial/manual format (see Appendix).

2.1.5.1 Hardware

There are no hardware deliverables that are designed by the group. However, the RTDS NovaCor and the SEL-651R-2 recloser controller are the hardware elements configured by the design team through software and firmware. The SEL-651R-2 is the resulting main hardware component from this project which is tested and configured. This relay is tested via the RSCAD simulation and RTDS NovaCor hardware.

2.1.5.2 Software

The software deliverables for this project, listed in Table 1, are the configuration file for the SEl-651R-2 that is compatible with AcSELerator software, and the RSCAD model to be executed using the RTDS NovaCor. The AcSELerator program itself can be included for simple configurations of the relay (tripping threshold, slight behavioral changes, etc.) for future research/study.

Table 1: Software Project Deliverables

Number	Software component
1	RSCAD Model of a Microgrid
2	AcSELerator Configuration for SEL-651R-2
3	AcSELerator Program

2.1.5.3 Simulation Manual & Device Documentation

This project's main directive was to create a baseline for working with the SEL-651R-2 and gaining insight into its functions in microgrid applications. More insights can be found if future research can be carried out. Manuals based on the basics of the project (relay configuration, communication configuration, physical interconnection of devices, running the simulations, etc.) are needed to achieve this goal. They are provided specifically as listed in Table 2.

Table 2: Documentation and Lab Manual Deliverables

Number	Lab Manual & Device Documentation
1	Provide an instruction manual for use of the RSCAD simulation, including expected outputs from the relay given base configuration.
2	Provide documentation on all connections between RTDS internal components.
3	Create a riser diagram with all communication connections for internal (RTDS Novacor CPU, GTNET card) and external (SEL-651R-2) devices.
4	Instruction manual for configuring certain functionalities of the relay.

2.2 Design and Implementation

2.2.1 Initial Design

The goal of this senior design project is the integration of the RTDS real-time microgrid model with an SEL-651R-2 recloser controller relay using DNP3 communication protocol for educational and research purposes. The objective is to test and demonstrate the functionality of the SEL-651R-2 by introducing faults in the RSCAD simulation. This would enable a safe, accurate and user-friendly system that ensures its proper use by students, faculty and other users.

For this design, the RSCAD software is used, which is provided by RTDS Technologies for its use with the NovaCor hardware. RSCAD can model a variety of power systems for real time simulation while communicating with connected hardware [1], [11]. Utilizing the RTDS and RSCAD in this way allows for a safer simulation.

Four key areas for development have been identified. The first is configuring the SEL-651R-2 by setting up logical equations and setting up DNP3. Secondly, setting various parameters to improve device communication, based on previous references [1], [5], [7]. The third focus area is fault simulation utilizing RSCAD models. It will start with a basic model involving one or two nodes [9], making improvements and expansions for different fault types. Lastly, the SEL-651R-2 is programmed to effectively respond to faults in the simulated transmission lines, coordinated with the communication protocol [1], [2], [6], [7].

Illustrated in Fig. 5, we can see this protocol in action during a simulated fault scenario within the RTDS system. The system efficiently relays the fault messages to the recloser controller via DNP3 in a HIL configuration, which then executes the necessary responses.

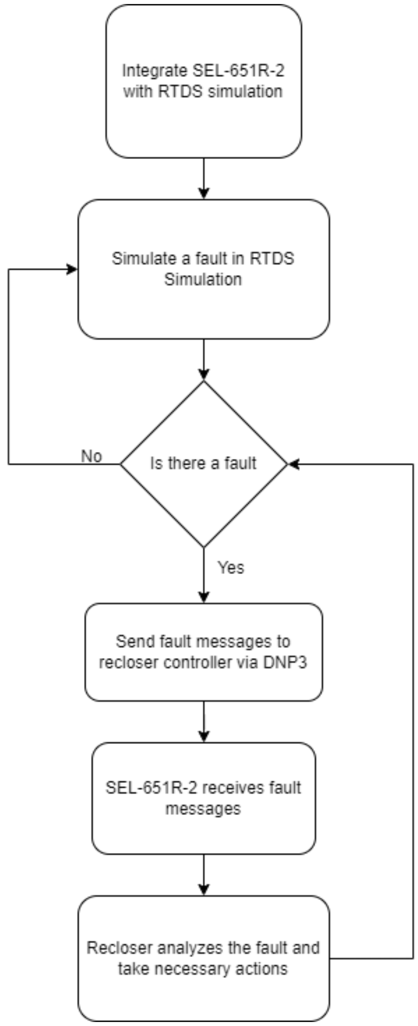

Figure 5: Initial HIL Communication Flowchart

The SEL-651R-2 recloser controller is an integrated solution designed for protection and control in microgrids [1], [4]. It allows for complete control of microgrid through voltage, current, and frequency elements for complete microgrid behavior control while it is interconnected. It is time synchronized internally via an NTP (network time protocol) server with 5ms accuracy, or an external satellite clock that can be synchronized via the IRIG-B port. Fig. 6 illustrates the operational setup of the system with HIL interconnection, which includes the workstation, RTDS, and SEL-651R-2, as well as the protocols throughline.

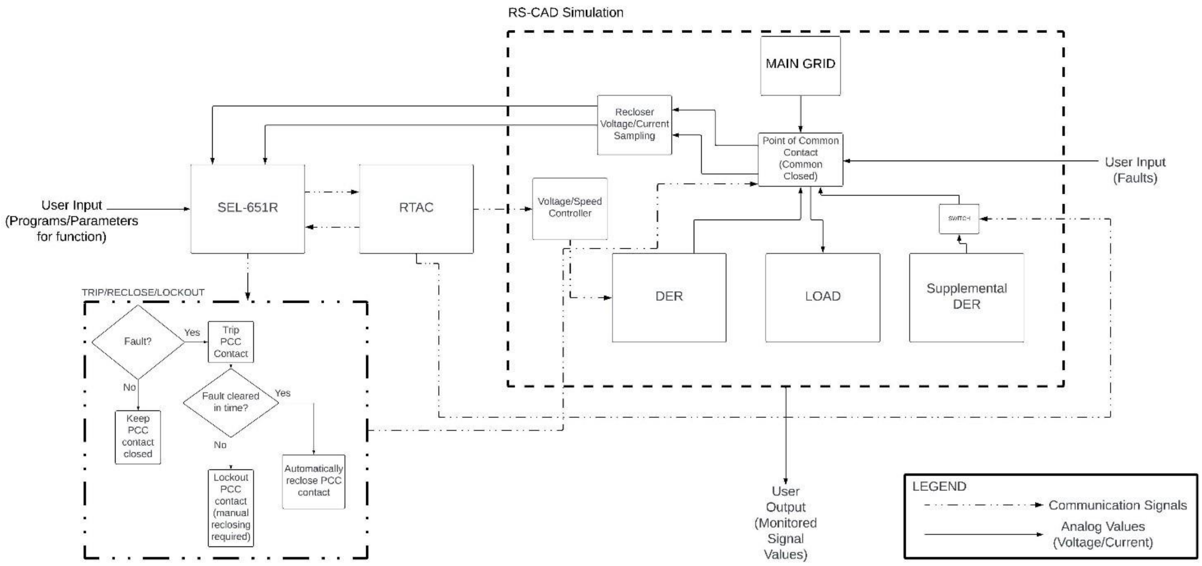

Figure 6: Initial Project Design

Several microgrid topologies were available from RSCAD to be used as a base model for our testbed. Although each had useful aspects, the team selected the Microgrid 2B simulation model (Fig. 7). This model met the RTDS core limit and has mid-level complexity, including 3 DERs, 7 loads, a PCC breaker/recloser, load shedding/frequency compatibility, and connection to the main grid.

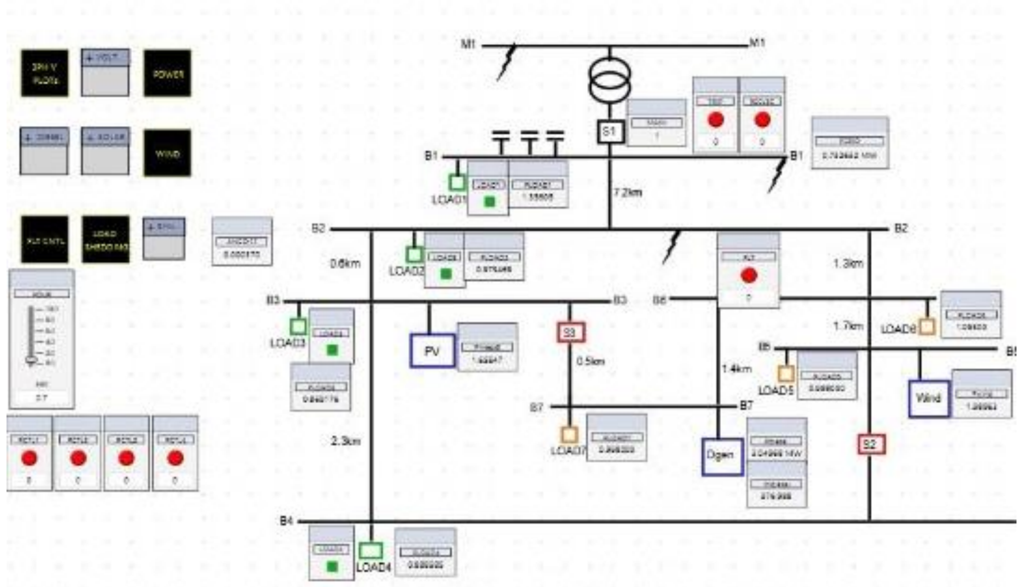

Figure 7: RSCAD model "Microgrid 2B"

<u>Alternative Design #1: Microgrid 1</u>

This microgrid model from RSCAD is extremely basic, allowing modularity through simple ease of use. It contains only three components: a battery, a generator, and a renewable resource. Although the characteristics of this model match the design specifications of our proposed testbed, it represents an ideally balanced system and does not support more complicated procedures such as frequency modulation and load shedding. Therefore, this design would have had to be heavily modified to be more useful.

<u>Alternative Design #2: Microgrid 2A</u>

This microgrid topology was initially considered as another potential model, but it requires more cores within the RTDS chassis as the simulation resolution is higher. Even though this model provides more realistic simulations containing higher quality signals, such resolution has a negligible effect on the recloser operation and would require hardware capabilities of the RTDS that go beyond what is currently available.

Alternative Design #3: Banshee Microgrid

This topology is based on a real-world microgrid and contains a massive number of sources, loads, and branches. This microgrid was also used in previous designs to communicate using DNP3, which makes it a valuable design for the proposed testbed. However, the RTDS processing power required to run this model would cause fundamental issues when used in the testbed. Additionally, the complicated nature of the design prevents its modularity.

2.2.2 Final Design

The final design, whose simplified overall physical setup can be seen in Fig. 8, eliminates the use of DNP3 communication protocol because of issues with the relay accepting analog input values through the protocol and using them for protection. All interconnections and communications are done via wired analog signals, with the GTAO feeding in line values to the SEL-651R-2, and the GTAI receiving 2.5VDC from the GTAO through the switches OUT01 (TRIP) and OUT02 (CLOSE) closing to interpret relay responses.

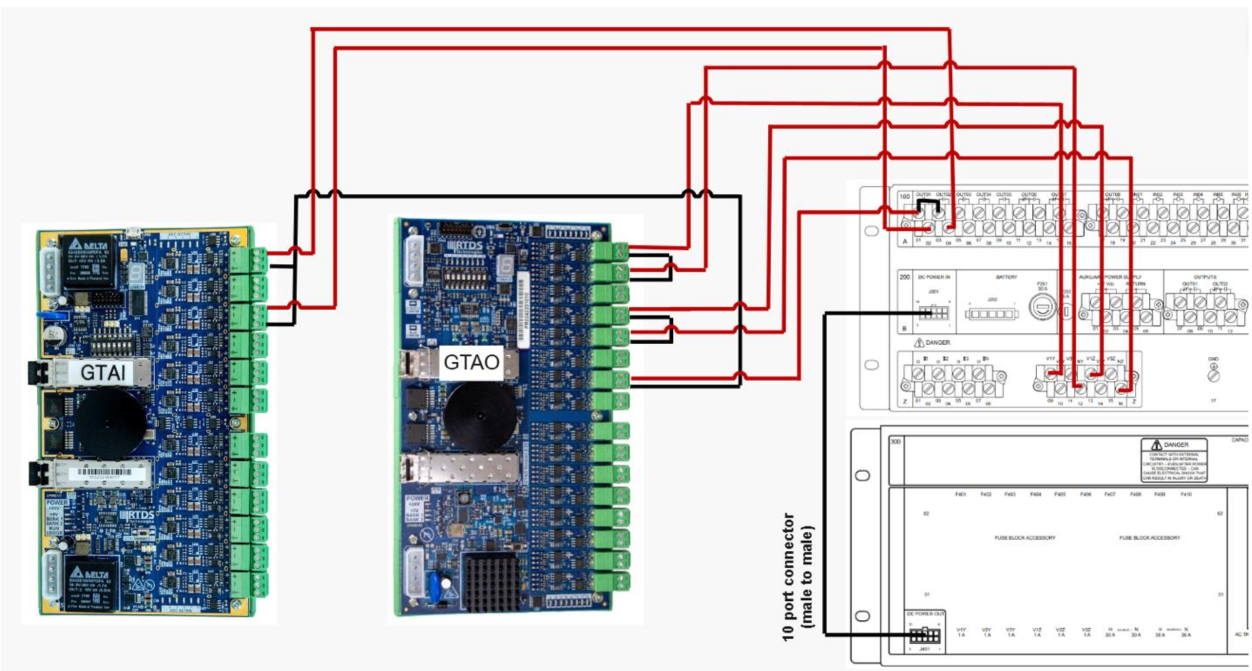

Figure 8: Wiring diagram of HIL interconnection

GTAO and GTAI cards configuration, shown in Figures 9a and 9b, along with the changes to the PCC breaker, have been added to the RSCAD simulation outside of the base model. The GTAO cards configuration includes outputting M1 and –M1 (main grid phase A voltage), N1 and –N1 (microgrid side phase A voltage), and 0.5 (2.5VDC). The positive and negative of each voltage signal is outputted so that V1Y and V1Z on the relay can receive twice the maximum GTAO voltage as an input (which allows for synchro-check to occur). The GTAI receives 2.5VDC from the GTAO from either OUT01 (TRIP) or OUT02 (CLOSE) closing and interprets it as TRPSIG_IN (TRIP) and RCLSIG_IN (CLOSE). The RSCAD simulation finally equates 2.5VDC to a digital 1 and pushes the corresponding signal to the "Trip" and "Close" commands on the simulated breaker.

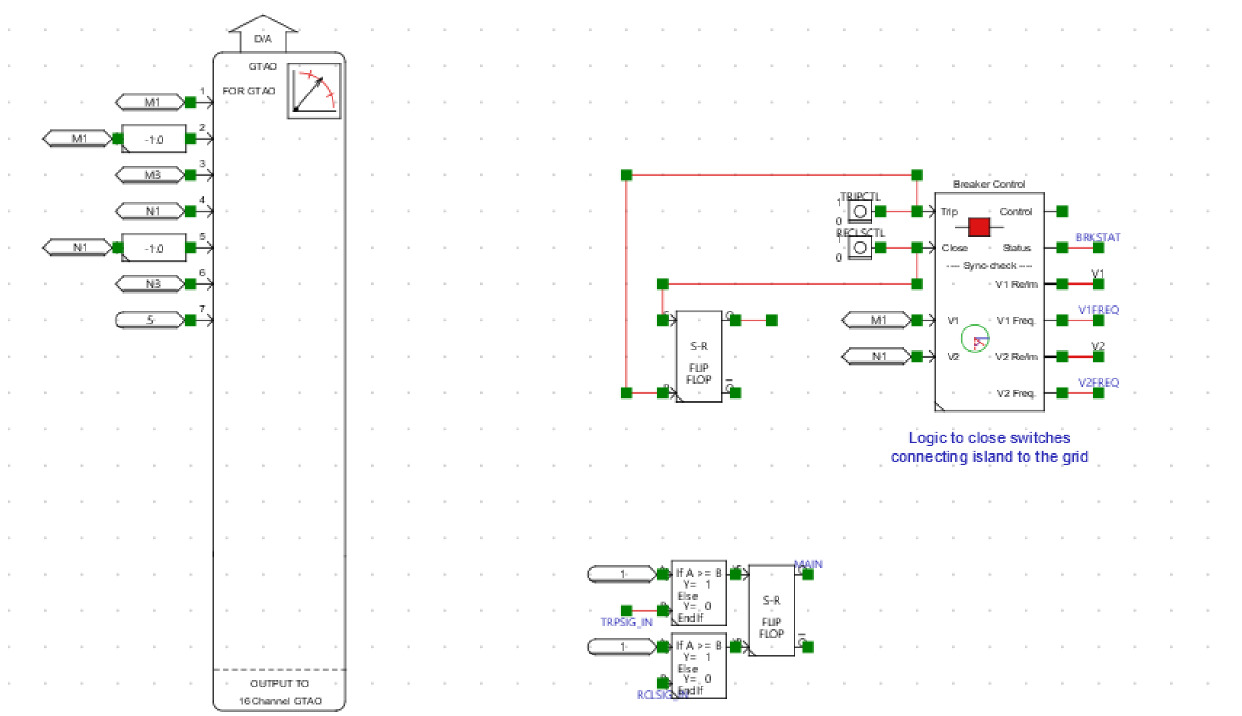

Figure 9a: GTAO configuration element, input signal interpretation, and simulated breaker

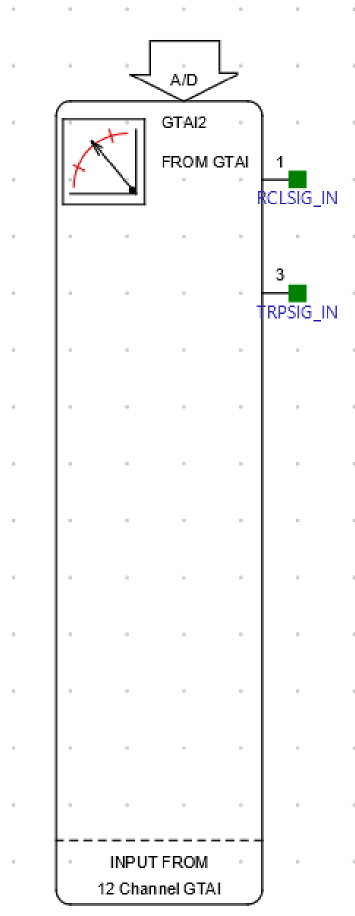

Figure 9b: GTAI configuration element

Certain values are tracked in runtime to get an idea of the fault response (Fig. 10). The SEl-651R-2 is programmed via AcSELerator to trip on an undervoltage at 0.8 p.u. (80% nominal line voltage on either the main grid or microgrid bus). It will only reclose if the fault is shorter than 0.25 sec and both the buses match in voltage, magnitude, frequency, and phase within 10 seconds of the fault clearing (synchro-check). The main grid voltage, microgrid voltage, current through breaker, TRPSIG_IN and RCLSIG_IN from the relay, the breaker status, and the phase difference between the bus voltages are all tracked during a fault event to understand the full behavior of the system. This includes where the fault occurred, the effect of the fault, and the response to the fault by the breaker/relay.

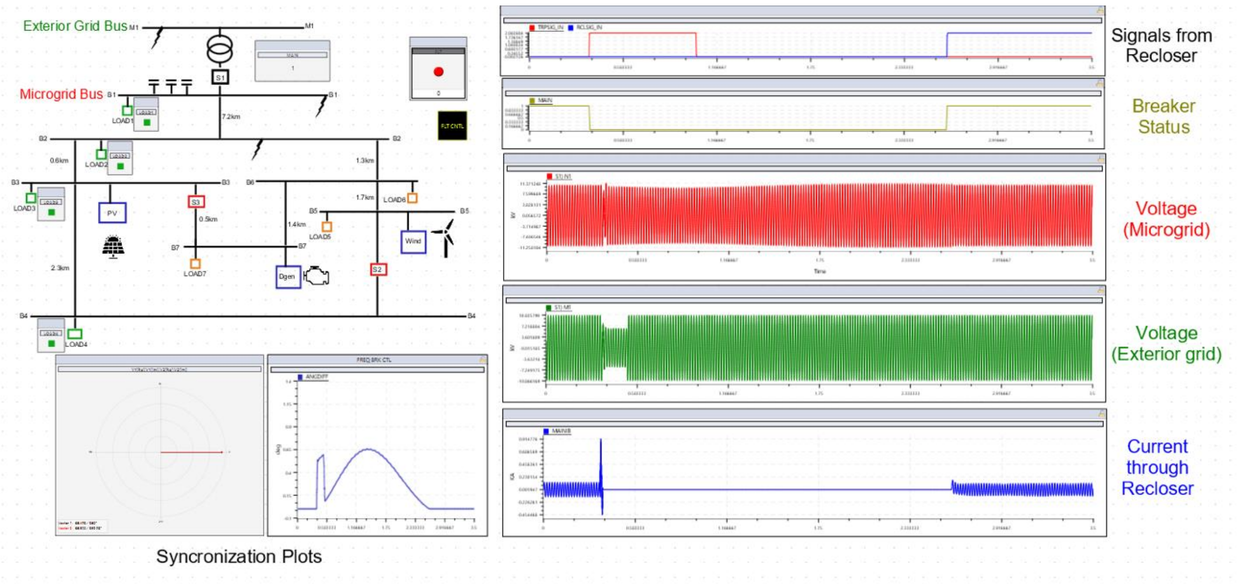

Figure 10: RSCAD plots for 0.15 sec main grid side line-ground fault

2.2.3 Design Considerations and Impacts

To create a product that is useful, safe, and well made, one must identify the constraints relevant to its design. Identifying these constraints allows engineers to be more aware of the purpose of the design. Therefore, it is essential to address the constraints that shape the scope of the simulation. These constraints will emerge from technological, financial, societal, or even regulatory considerations. These constraints are used in tandem with technical specifications to ensure that the final product adheres to the initial purpose of the project.

2.2.3.1 Economic

System constraints for the device require an RTDS Novacor device with at least two licensed cores and an SEL-651R-2. The cost for these components is estimated to be close to $200,000. However, since the chassis and tested device have been purchased by WMU InterEnergy Center, these are not costs needed for this testbed's implementation. Any costs outside of these devices are financed by the WMU InterEnergy Center. The major economic impact of our device comes from the advents of microgrid design in general. More renewable energy-based microgrid implementations with more robust protection and control systems would lead to less operational issues and a decrease in financial expenses in infrastructure repair and maintenance.

2.2.3.2 Global Impact

This testbed can be used in any area which can sustain power to the RTDS chassis, and the findings gained from the testbed can be used anywhere relevant to the recloser. Although the device is configured according to US standards, the testbed can be reconfigured to represent the needs of other countries. Therefore, this testbed can have a positive impact on the initial design process of microgrid topologies in 1^{st}, 2^{nd}, and 3^{rd} world countries.

2.2.3.3 Environmental/Sustainability

This testbed has the capability to simulate multiple real-world devices and scenarios, saving time and environmental resources in the production of real-world testbeds. Additionally, the ability to test multiple layouts of microgrids in quick succession will increase the efficiency and robustness of the final product.

Due to the rise of renewable microgrid use in the fight against climate change, this device is made to aid in the process of designing a microgrid capable of supporting renewable energy resources, contributing to the reduction of carbon emissions.

2.2.3.4 Cultural Impact

This project does not have any direct cultural impact that guides or restricts its design or development. This is mainly because this project is more focused on infrastructure, efficiency and reliability of electric power distribution, which upkeeps our current society and its functions.

2.2.3.5 Public Health, Safety, and Welfare

This project involves analyzing a grid recloser controller, which means that any operational issues that can be relevant to the safety of grids using this equipment could be found during this analysis. In the event that this occurs, it is our ethical responsibility to ensure the production company is aware of and addresses these concerns. Its environmental impact can also help reduce climate change-caused illness or harm through the use of renewable energy.

2.2.3.6 Societal Impact

This project can increase the robustness of the power grid through the implementation of microgrids, which would ensure power during natural disasters or other emergency situations. However, to ensure proper meshing with the current grid network, we must ensure our device adheres to standards listed in the specifications.

2.3 Performance Testing and Analysis

The verification of the functionalities of the testbed validates the specifications laid out. The relay and RSCAD model can communicate back and forth with live HMI feedback. The RSCAD model sends the relay analog data through the GTAO, and the relay responds using switches on its backside to command the break to trip or close. The RSCAD model meets the specifications about functionality and microgrid element requirements, except for the introduction of varied fault types within the simulation, as the only implemented type was line-to-ground fault at three locations. The relay also has status LEDs that tell the user what is happening in real time internally. None of the DNP3-related specs were met as the DNP3 communication protocol did not have the kind of interconnection capabilities needed for this HIL testbed. Instead, all interconnections and communications between the RTDS and the SEL-651R-2 were completed via wired analog signals.

The relay and simulation run in tandem in real time, the relay reacts to transients/faults from the simulation, and the relay matches the behavior that was intended while programming it, therefore meeting all other performance specifications. This is shown in Figures 11a and 11b with two specific fault cases corresponding to short duration and long duration faults.

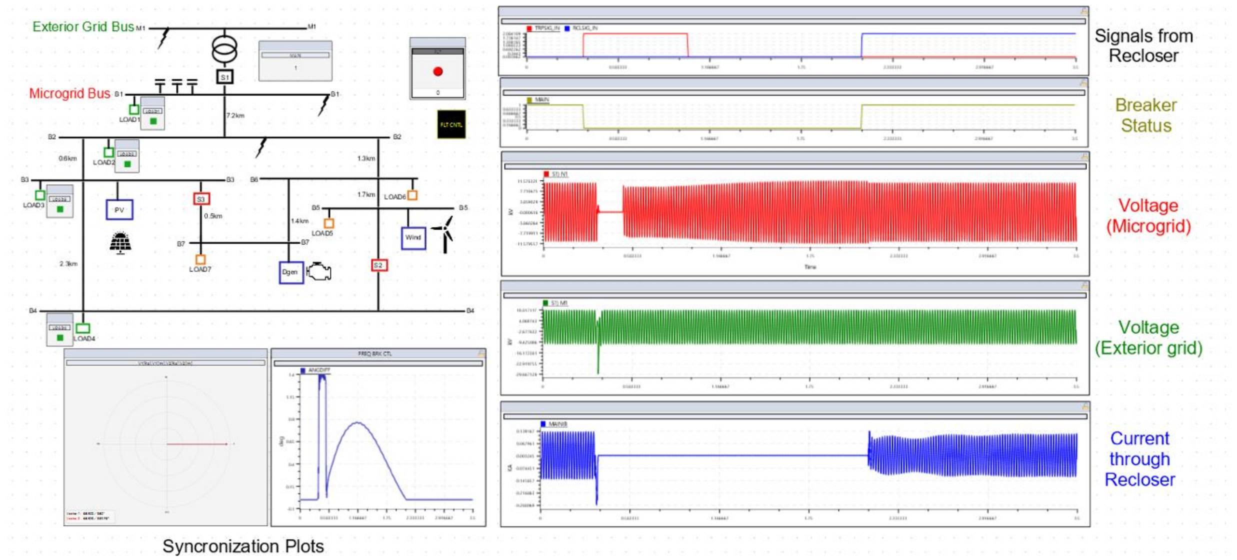

Figure 11a: RSCAD plots for 0.15sec microgrid side line-ground fault

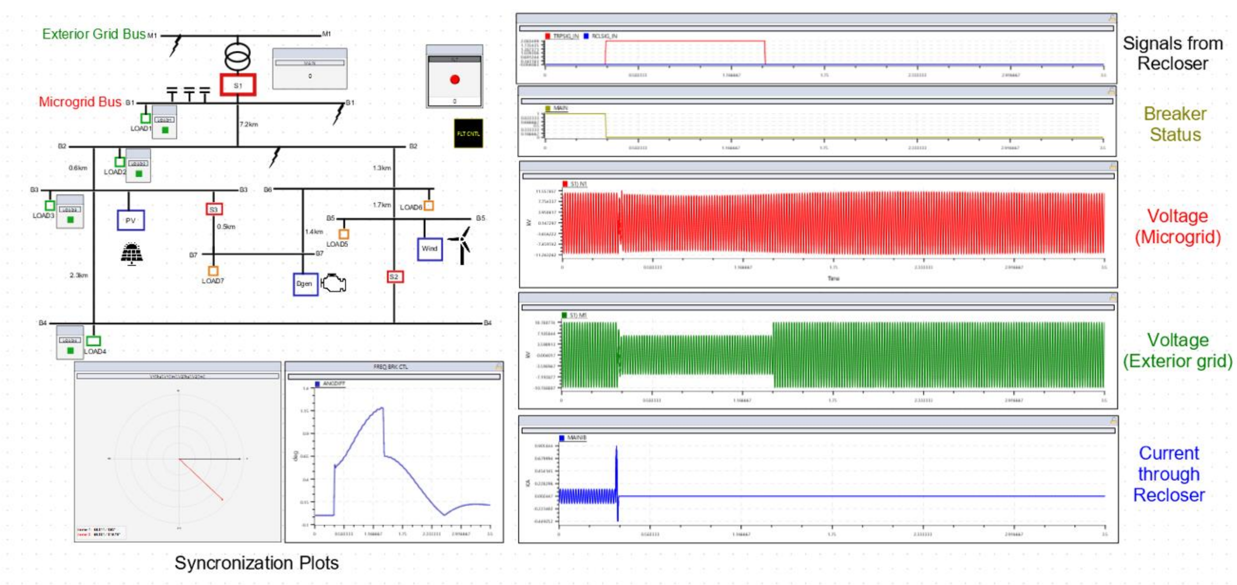

Figure 11b: RSCAD plots for 1sec main grid side line-ground fault

Under fault for any period of time, the relay sends a trip pulse to isolate the fault effects to one of the grids. For the fault under the duration threshold, the relay waits until the bus voltages are synchronized (when the phase plot has a zero crossing) before reclosing. On the other hand, over the fault duration threshold a phase zero crossing occurs within 10 seconds and synchro-check passing is possible. The relay does not reclose, since reclosing is blocked due to the fault duration being too long. It can be therefore concluded that the relay and simulation work in tandem, and the relay acts as programmed.

3. Conclusions

Overall, this testbed provides a safer and cost-effective way to test the functionalities of the SEL-651R-2. This opens up many possibilities for future use in research, and documentation is provided to facilitate such future use.

3.1 Application of Project

In modern times, microgrids help to improve energy efficiency and reliability by enabling localized power generation and integration of renewable energy. Hence, it is important for students, faculty, and researchers to understand the functionality of recloser controllers and learn about the device's response behavior to several types of faults. Hardware-in-the-loop (HIL) refers to a testing method where a physical hardware component is connected to a simulated environment that mimics the real world. Using this method provides both a safer and more accessible way of testing, allowing for more efficient research in the future for this device.

3.2 Experiences Gained

Throughout this project, the team gained valuable hands-on experience on integrating industry-standard hardware and software through the Hardware-in-the-Loop (HIL) system. We learned how to configure the SEL-651R-2 through the SEL ACSelerator software, and we gained proficiency in RSCAD software to model high fidelity microgrid models, to perform fault simulations and to analyze system responses. Real-world engineering challenges were encountered and resolved, such as synchronization logic, debugging issues, integration-related hardware and software issues, and troubleshooting protective relay settings. Support from industry experts and faculty members played a crucial role in the completion of this project.

Overall, this project has honed the team's skills in collaborative problem solving, technical documentation, analyzing and interpreting data from live tests records. This experience gave the team confidence in the ability to design, test and validate advanced electrical protection systems.

4. Recommendations

The recommendations for the project include integrating multiple reclosers with the microgrid model and establishing the DNP3 communication protocol. It is also recommended to explore compatibility with other types of microgrid models. Additionally, efforts should be made to enable the relay to read and measure current for protection purposes. New types of fault scenarios, such as line-to-line, should also be implemented to enhance the robustness of the system.

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Documentation for Real-Time Testbed for Smart Grid Recloser

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Asker Akil Islam

Dr. Pablo Gomez

Introduction:

This documentation serves as a user manual for the Real-time Testbed for Smart Grid Recloser. It provides a detailed overview on how to setup the RSCAD and RTDS, wiring between the RTDS and the SEL-651R-2 relay, and how to navigate through AcSELerator Quickset to configure the SEL-651R-2.

RSCAD

RSCAD is a proprietary design software for the development of real-time power system models to be executed using RTDS/NovaCor. Upon opening the program, the user will have access to many examples and tutorial cases (located within the library at the top left). It is highly recommended to use these example cases as first steps in the program. The user can also use an example case as a base model for their project. Many of the example cases also come with documentation to test out the grid, listed in the file manager as pdfs.

Once the user opens a tutorial or example case (e.g., Microgrid 2B), they will be greeted by two separate tabs, the “draft” tab and the “RUNTIME” tab. The draft tab communicates with the NovaCor to produce the simulation that the user plans to run. The draft tab is customized using blocks from the library connected with signal wires. Each of these blocks has a corresponding explanation of how the block works, located in the help manual (accessible when right clicking on a block, or from the application tab “Help”.) This draft file requires the user to compile the case and cannot be edited when the file is running. The RUNTIME tab allows the user to change values, receive data, and issue commands to the draft tab while the device is running. The RUNTIME tab can be customized using shapes, images, and runtime signals displayed in a search bar on the top left of the screen. Controls available from the runtime platform include buttons, switches, dials, etc. If, while running a case file, the user wants to find where a signal goes, they can use CTRL+F to search for that signal throughout the draft layout.

GTAO (GT - Analog Output)

The GTAO card is a card located at the rear right of the NovaCor chassis. It communicates with the RSCAD software through the GTAO block. It refreshes output every 1µs and can be altered through the digital GTAO block to have a smoother refresh rate if needed. It provides any output between +/-10V, with a constant 100mA of current. However, during our project, we were able to double its output by sending duplicate signals to two of the outputs and placing them in series. Though it was not required for our project, it may be possible to further amplify the GTAO output in this way.

GTAI (GT – Analog Input)

The GTAI provides analogue inputs from external equipment to the simulation. It only receives voltage, and refreshes data every 1µs. The GTAI also has a digital block within the program which it connects to, from which a runtime signal can be created to view in a plot or data block. In our configuration, a constant signal was sent from the GTAO port to a recloser switch then back to the GTAI, which allowed us to view the status of the recloser.

NovaCor:

The NovaCor is a processing hardware that has additional components including a GTAI, GTAO, GTDI (GT-Digital input), GTDO (GT-Digital Output), Analog Output (not GT), GTFPDI (GT- Front Panel Digital Interface), and GTNET cards which allow it to send and receive information, including capabilities for GOOSE-SV, DNP3, and analog signals. Each of these capabilities has a card corresponding to it which allows the device to communicate with the simulation. The cards are connected to the GTNET module through fiber optic cables. The cable port the card connects to determines the Port number inputted into the digital block during configuration. The NovaCOR also has three licensed cores, meaning that it is able to run any example case that requires this number of cores or less.

<u>Initial Setup of RSCAD & RTDS:</u>

1) Find your example case from RSCAD model library (in our case, we chose the MICROGRID2BV5 example case file).
2) Launch RSCAD, then from “File Manager”, choose MICROGRID2BV5 to open, as shown in Figure A.1.
3) Go to “SYNCHRONIZATION” and then disconnect the “Breaker Control”, as shown in Figure A.2.
4) Add in the logic block (Figure A.3).
5) To set up the GTAI and GTAO blocks, go to the block library and introduce the GTAO and GTAI blocks (marked in black) as shown in Figure A.4.

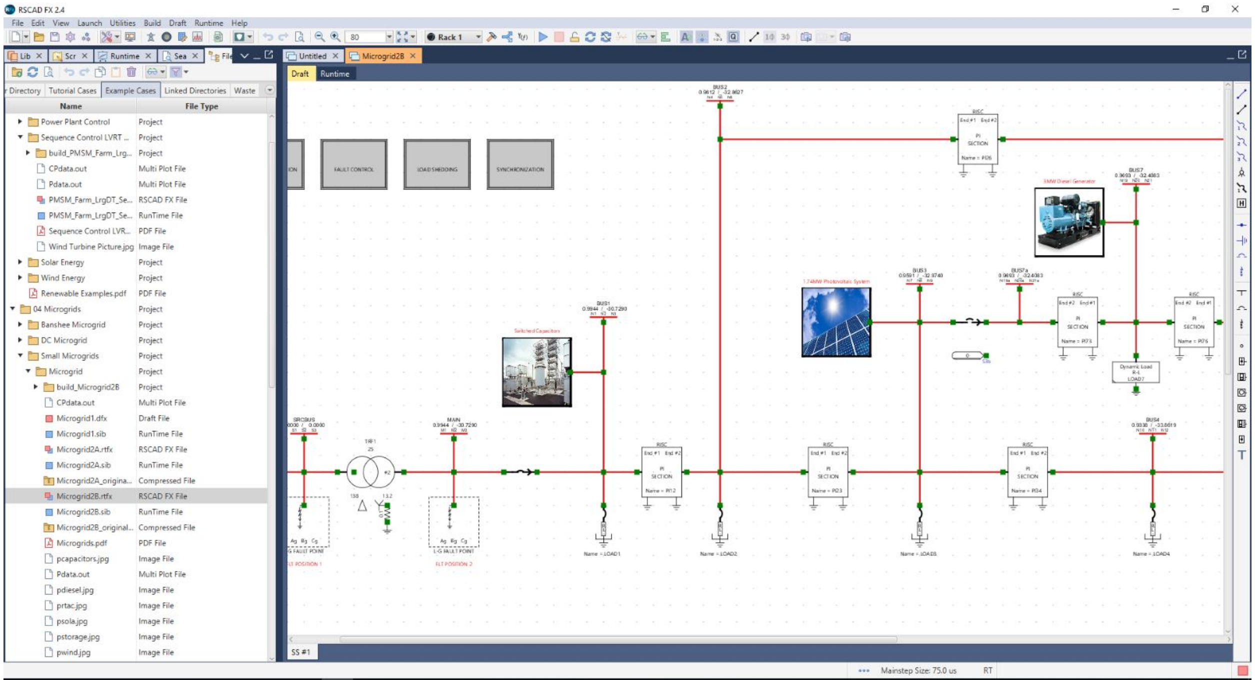


Figure A.1: Launching RSCAD and opening MICROGRID2BV5

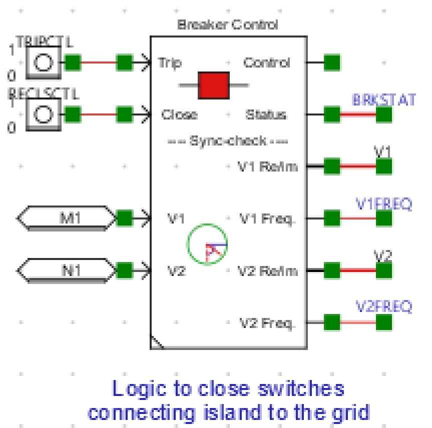


Figure A.2: Breaker Control Logic Block

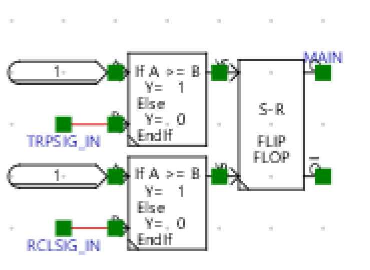


Figure A.3: Adding in logic block

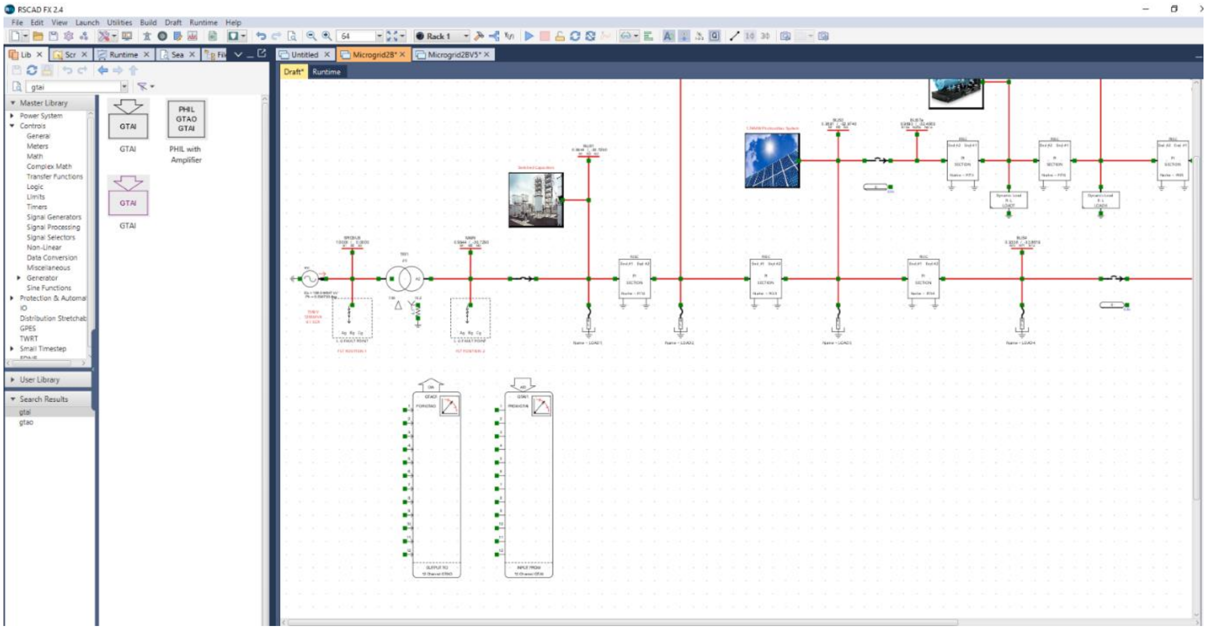


Figure A.4: Adding in GTAO and GTAI blocks

6) The GTAI block will contain two made up signals labelled “TRPSIG_IN” and “RCLSIG_IN”

7) The GTAO block will contain the “FLOAT” signals shown in Figure A.5.

8) Configure the GTAO block according to Figures A.6, A.7 and A.8.

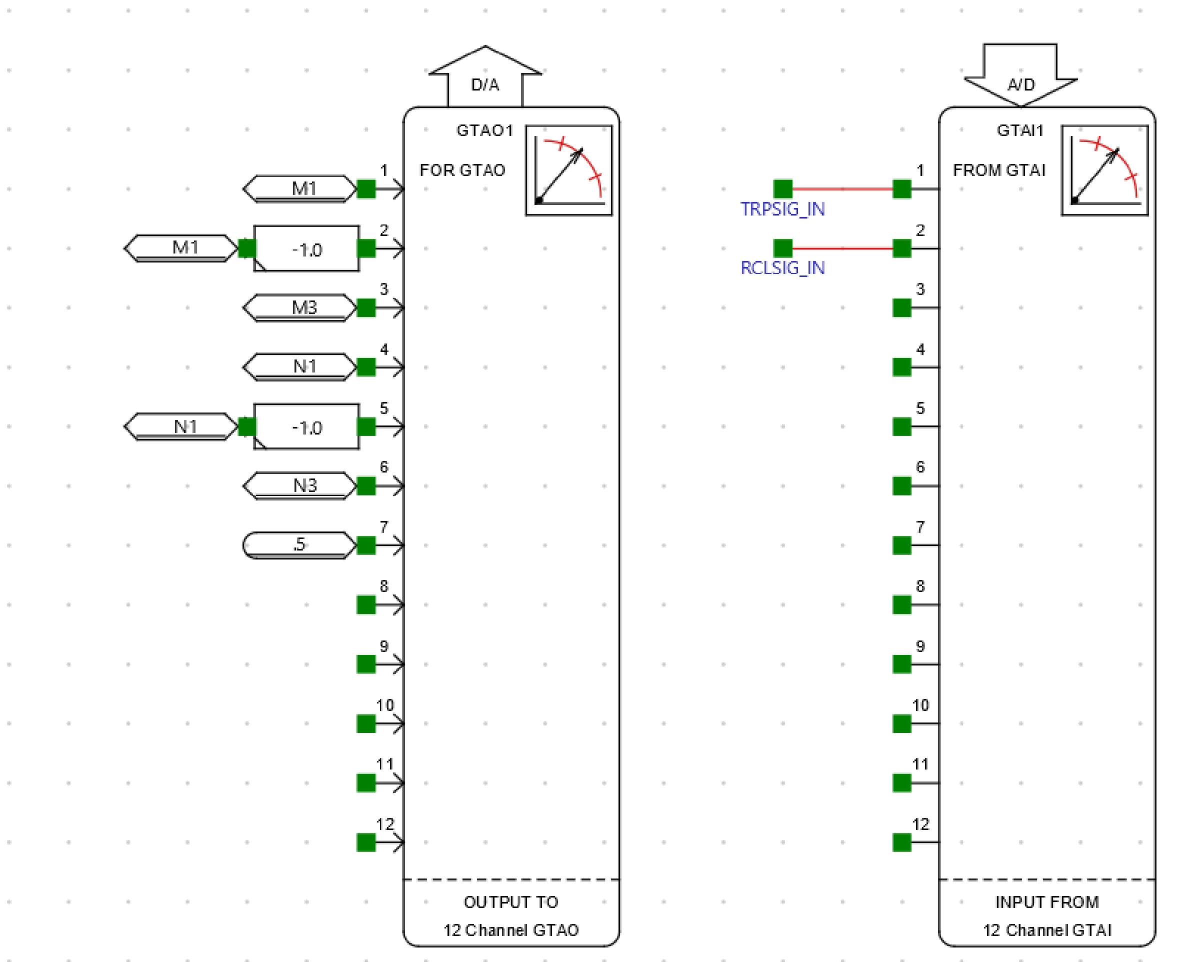


Figure A.5: GTAI and GTAO blocks

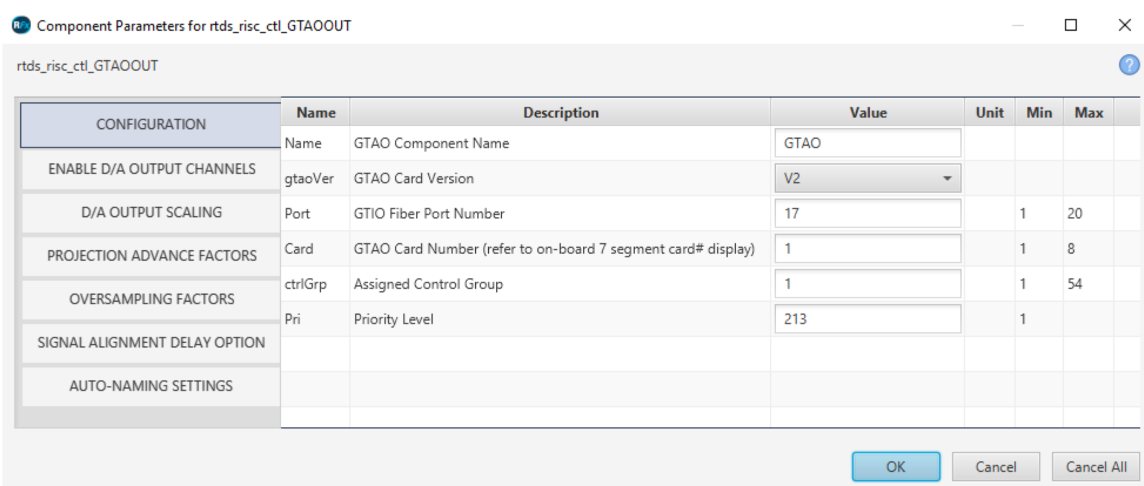


Figure A.6: Configuration of the GTAO block

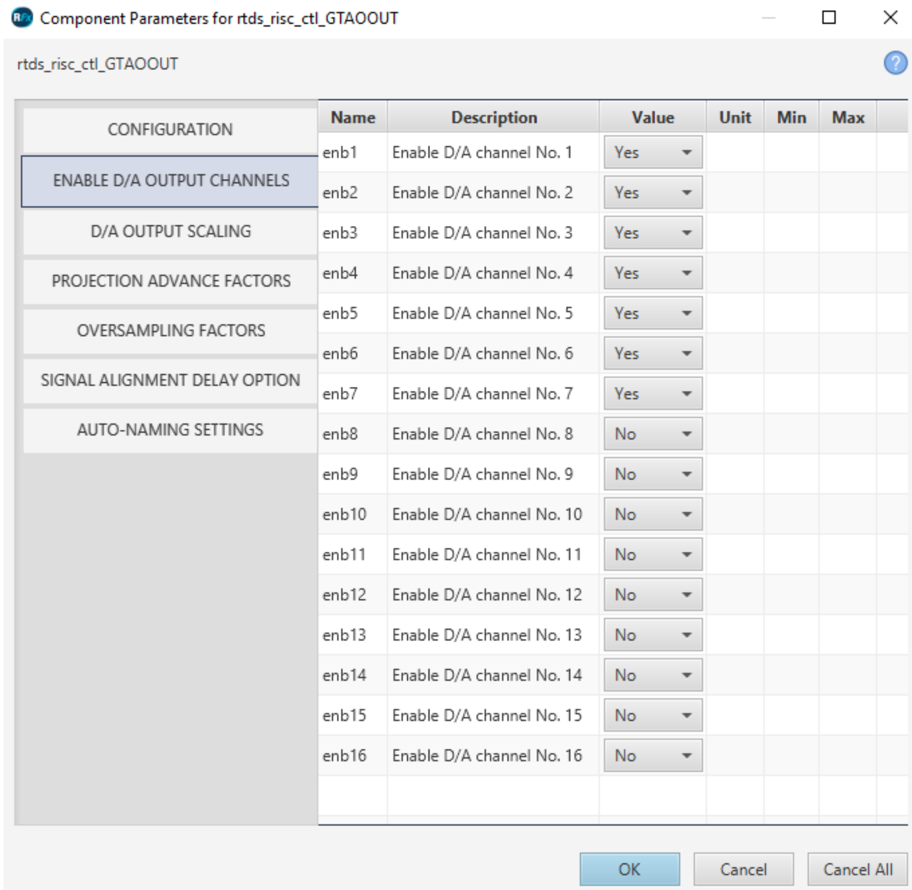


Figure A.7: Configuration of the GTAO block (continuation)

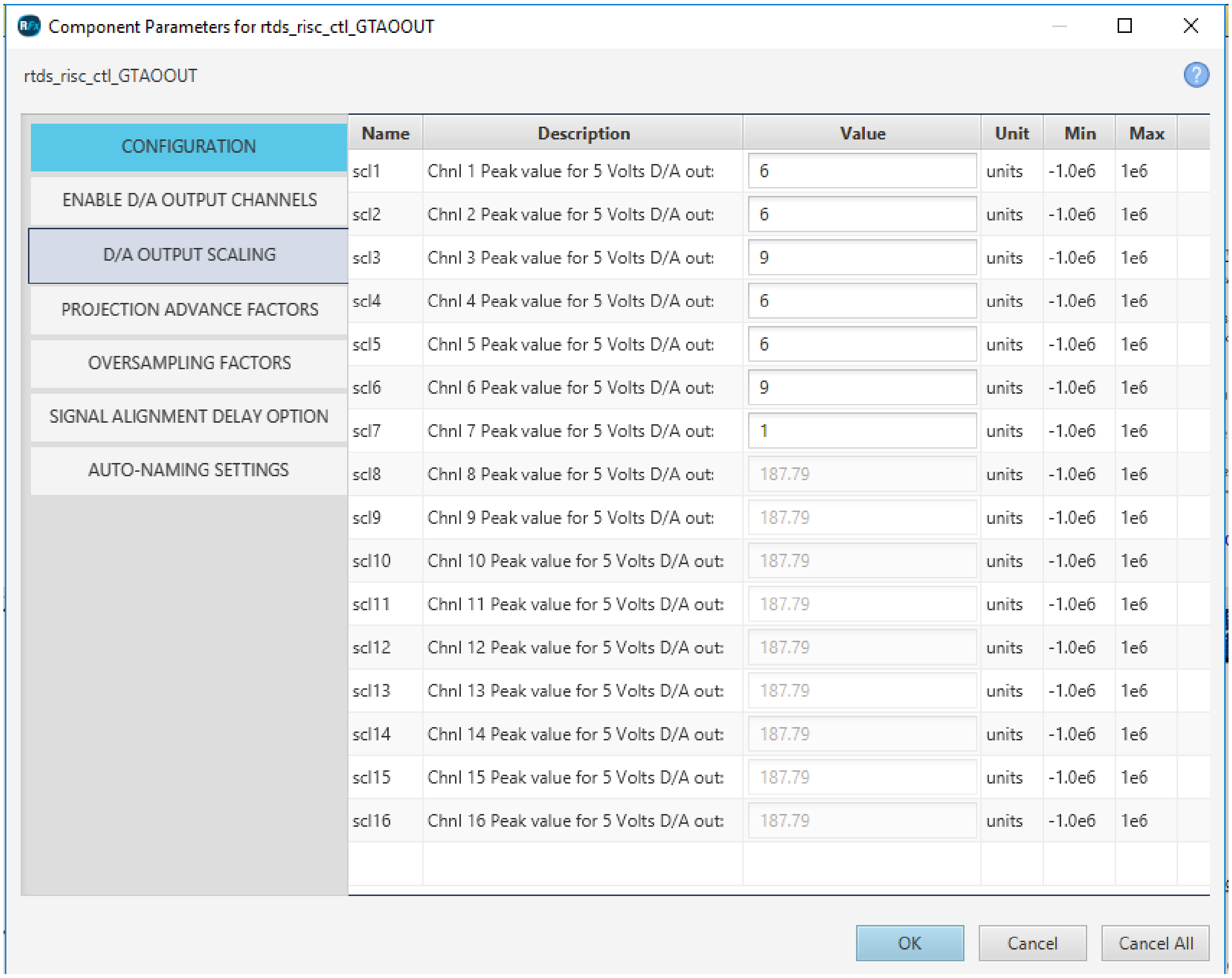


Figure A.8: Configuration of the GTAO block (continuation)

9) Folow a similar procedure to configure the GTAI block, as shown in Figures A.9, A.10 and A.11.

10) The fault position 2 is moved after the breaker and the fault position 3 is moved besides the PCC according to Figure A.12.

11) Go to the “Load Shedding” block and replace frequency logic with a constant 60 (Figure A.13).

12) For the Capacitor Block, add the logic blocks according to Figure A.14.

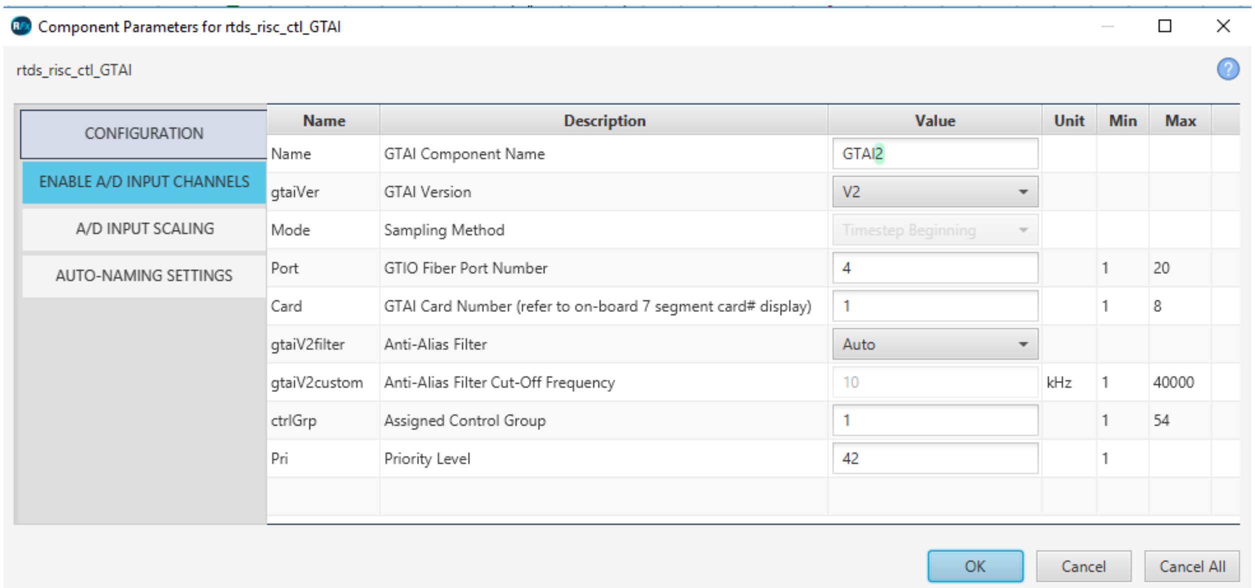


Figure A.9: Configuration of the GTAI block

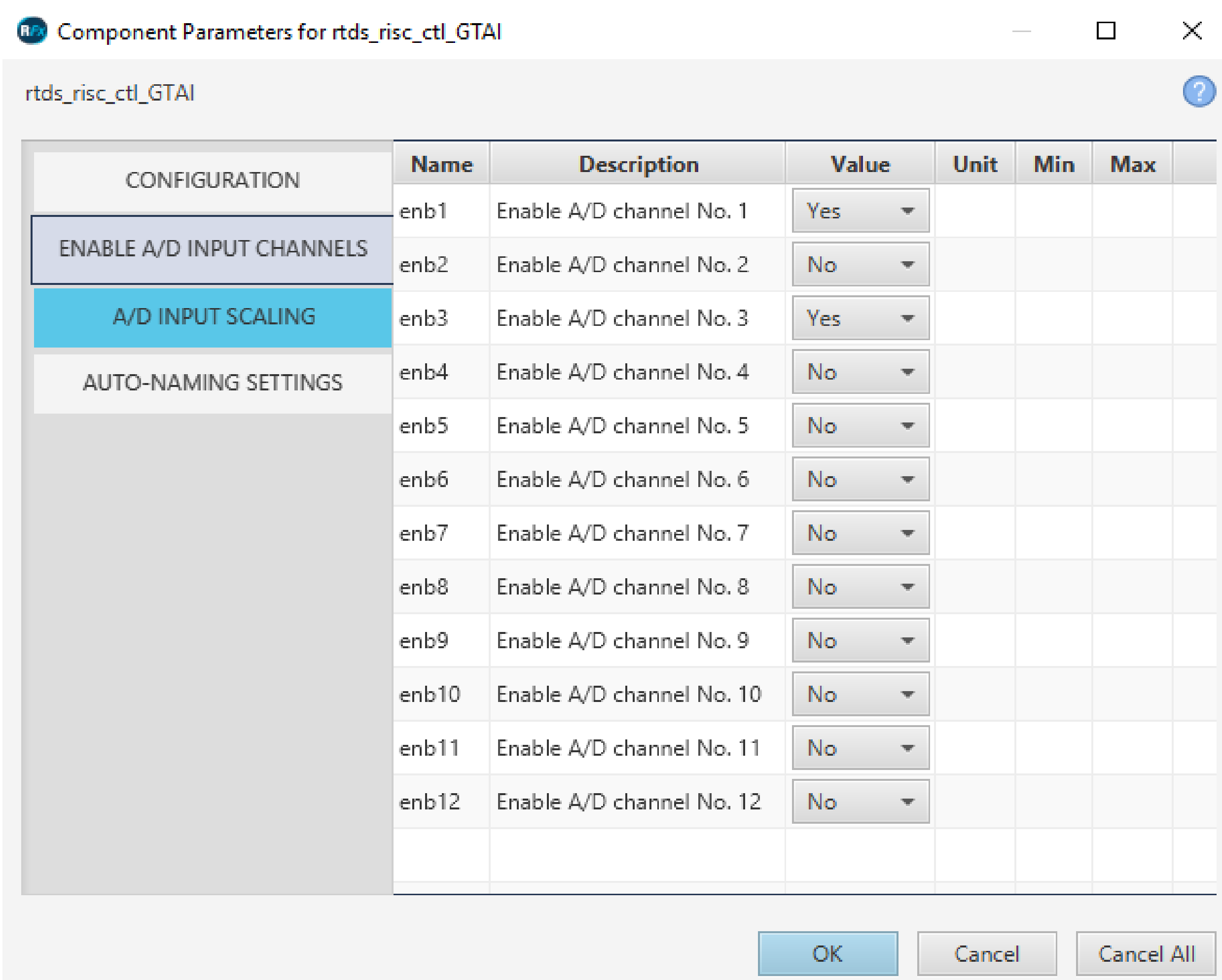
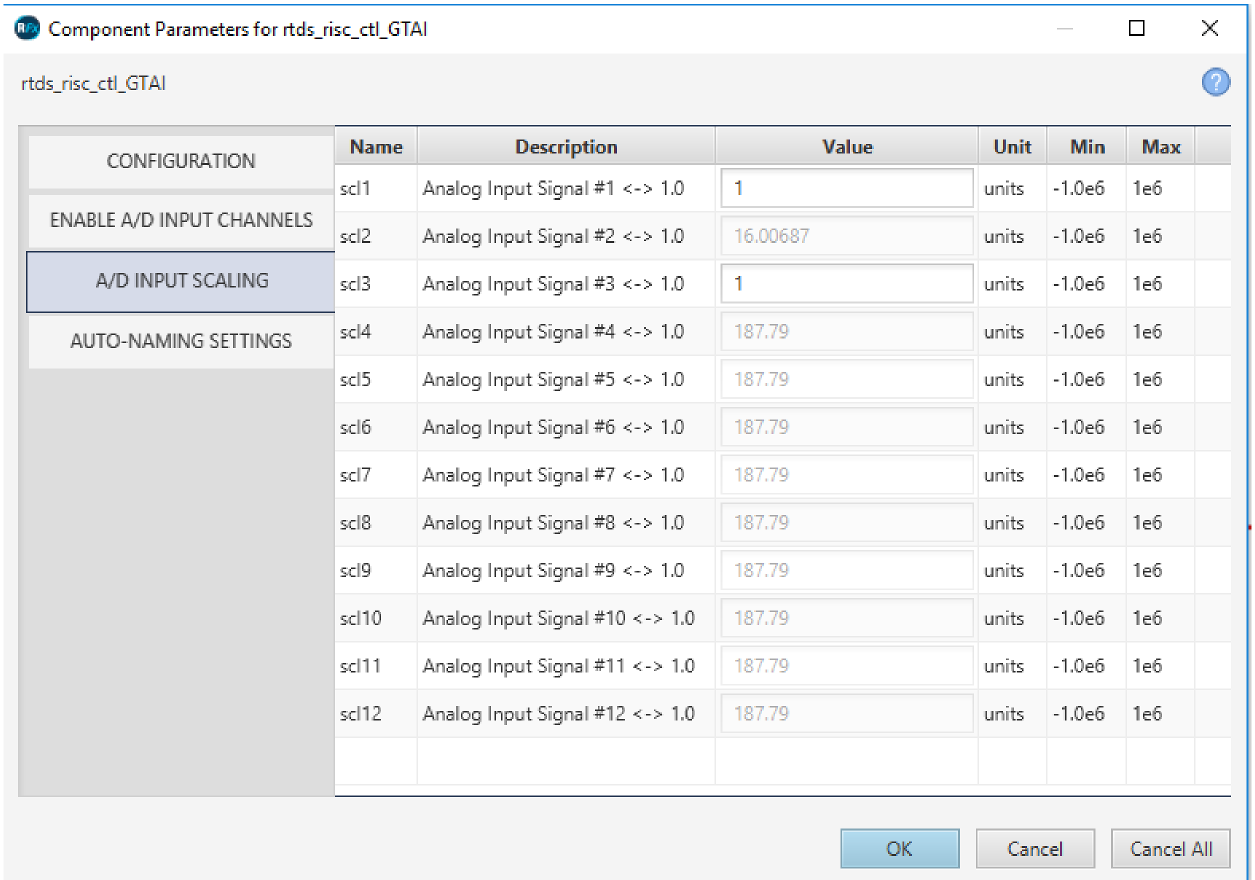


Figure A.10: Configuration of the GTAI block (continuation)



Name	Description	Value	Unit	Min	Max
scl1	Analog Input Signal #1 <-> 1.0	1	units	-1.0e6	1e6
scl2	Analog Input Signal #2 <-> 1.0	16.00687	units	-1.0e6	1e6
scl3	Analog Input Signal #3 <-> 1.0	1	units	-1.0e6	1e6
scl4	Analog Input Signal #4 <-> 1.0	187.79	units	-1.0e6	1e6
scl5	Analog Input Signal #5 <-> 1.0	187.79	units	-1.0e6	1e6
scl6	Analog Input Signal #6 <-> 1.0	187.79	units	-1.0e6	1e6
scl7	Analog Input Signal #7 <-> 1.0	187.79	units	-1.0e6	1e6
scl8	Analog Input Signal #8 <-> 1.0	187.79	units	-1.0e6	1e6
scl9	Analog Input Signal #9 <-> 1.0	187.79	units	-1.0e6	1e6
scl10	Analog Input Signal #10 <-> 1.0	187.79	units	-1.0e6	1e6
scl11	Analog Input Signal #11 <-> 1.0	187.79	units	-1.0e6	1e6
scl12	Analog Input Signal #12 <-> 1.0	187.79	units	-1.0e6	1e6

Figure A.11: Configuration of the GTAI block (continuation)

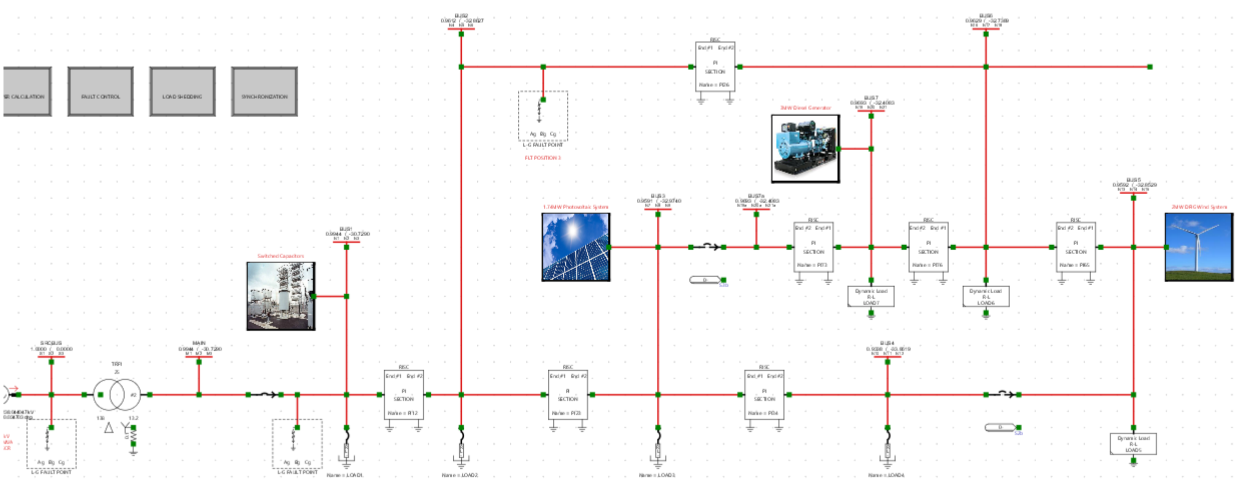


Figure A.12: Moving the Fault Positions

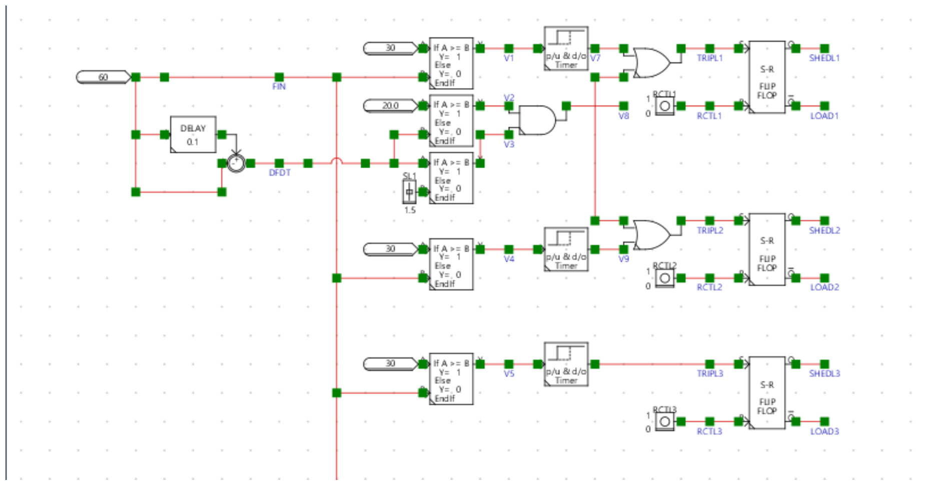


Figure A.13: Load Shedding Block

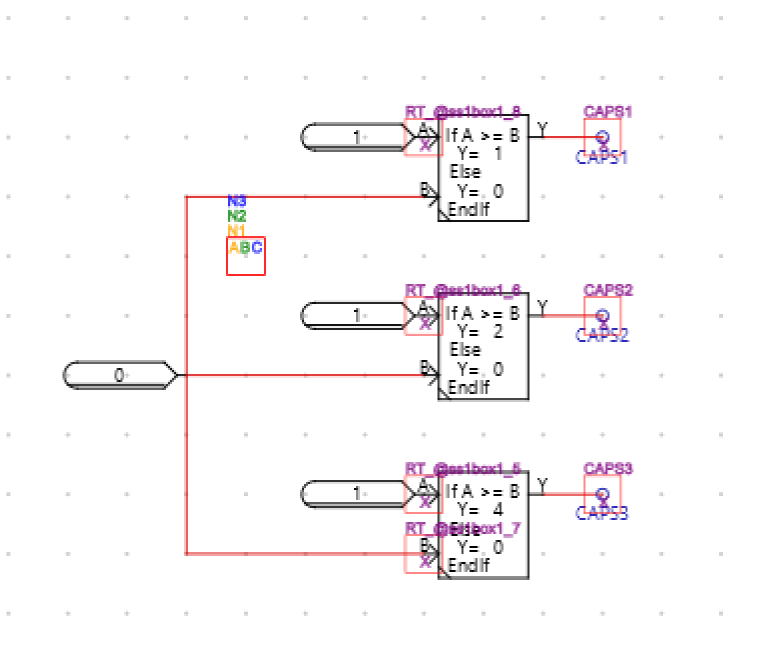


Figure A.14: Capacitor Block

13) For demonstration purposes, several plots have been added. For this, click on the runtime block, click on the SYNC Control and unlock the FREQ BRKR CTRL BLOCK. Figures A.15 to A.18 demonstrate the process.

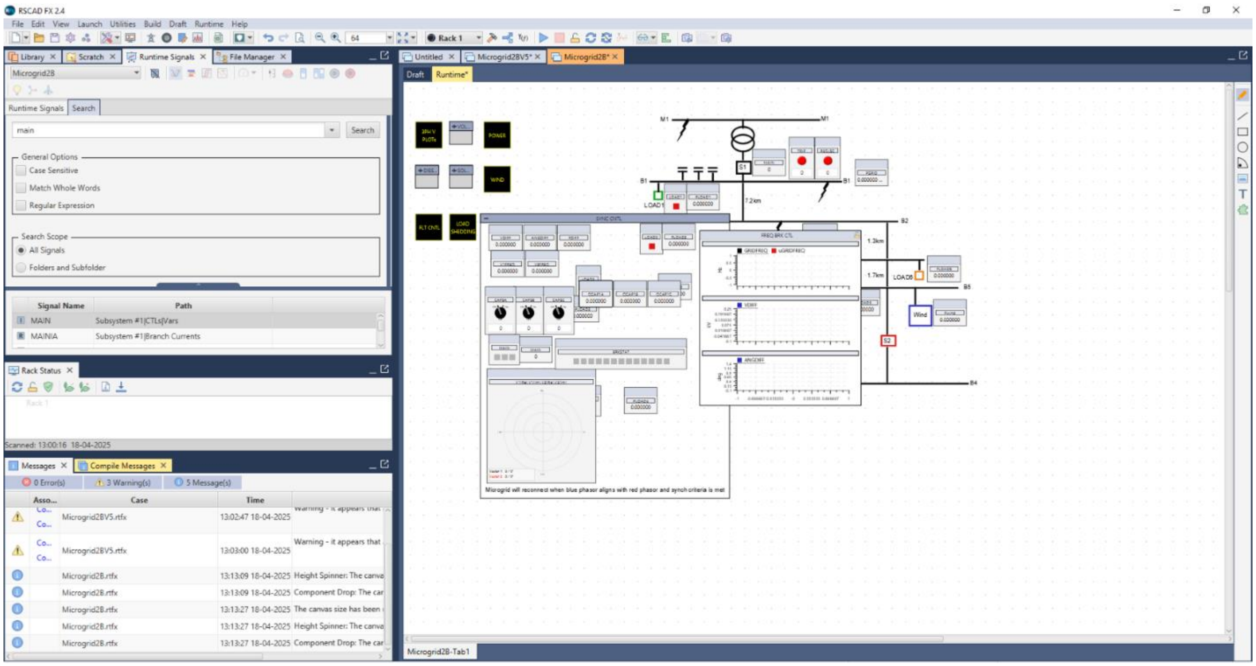


Figure A.15: RSCAD after unlocking FREQ BRK CTRL box

14) Copy the FREQ BRKR CTRL BOX and add it to the main runtime screen. You may also reconfigure the fault locations to match those made in the previous draft file, but this step is purely cosmetic.
15) Using Runtime Signal Search Box, add the desired signals into the plot box. In our case, we added TRIP_SIGIN, RCLSIG_IN, MAIN1, MAINIB, N1.

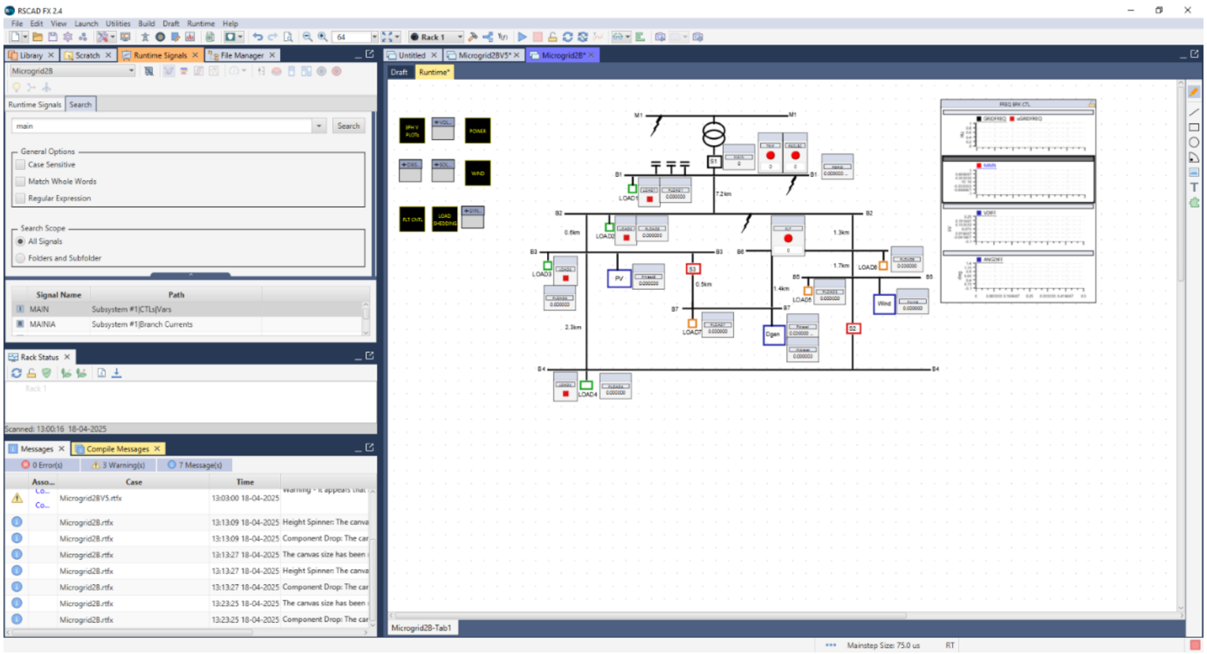


Figure A.16: RSCAD after adding runtime MAIN signal

Figure A.17: Signals added to the plot box

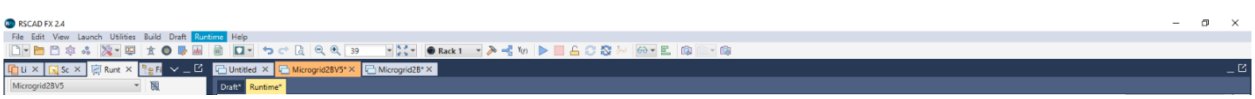


Figure A.18: File compilation and execution

Wiring Between RTDS and the relay (using the GTAO and GTAI cards):

Figures A.19 to A.22 provide insight into the physical connections between the GTAO/GTAI cards in relation to the SEL-651R recloser. Note the power module needs to be connected to 120VAC and the 10-port connector needs to connect from DC POWER OUT to DC POWER IN.

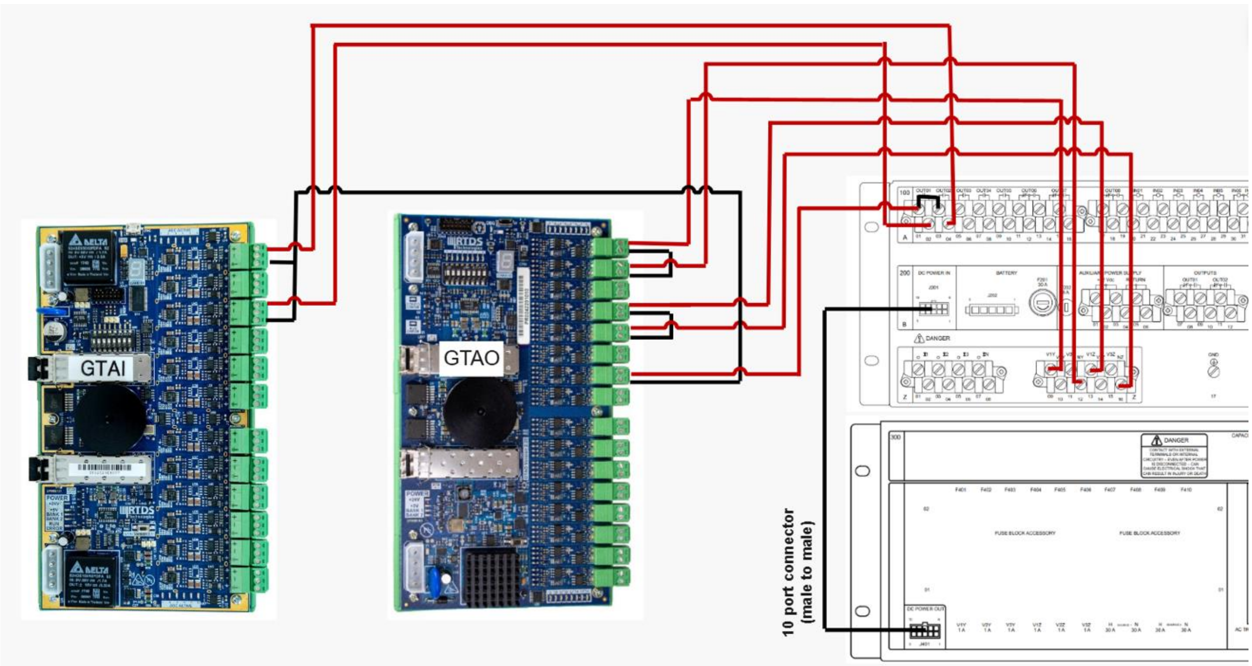


Figure A.19: Representation of physical connections. Black wires are Neutral/Jumper connections

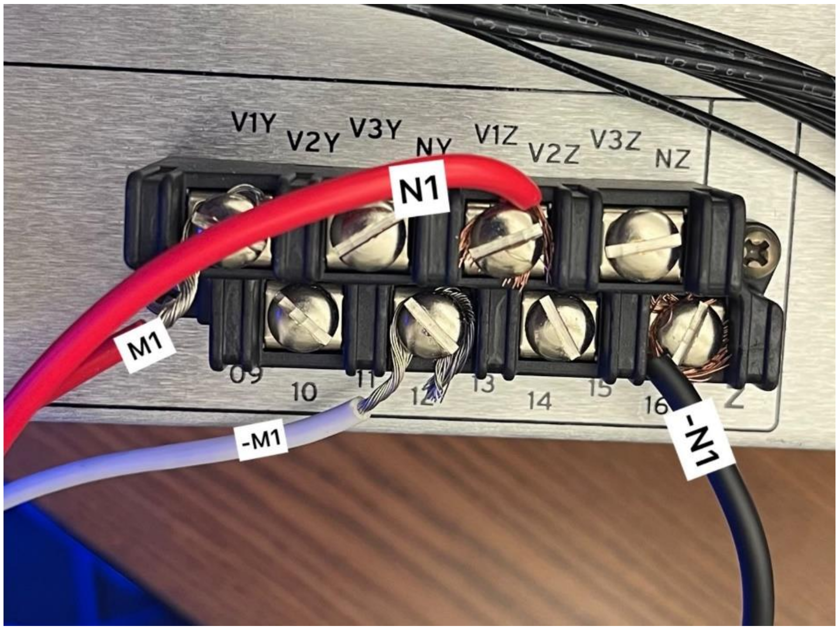


Figure A.20: Wiring as seen from the SEL-651R-2 inputs

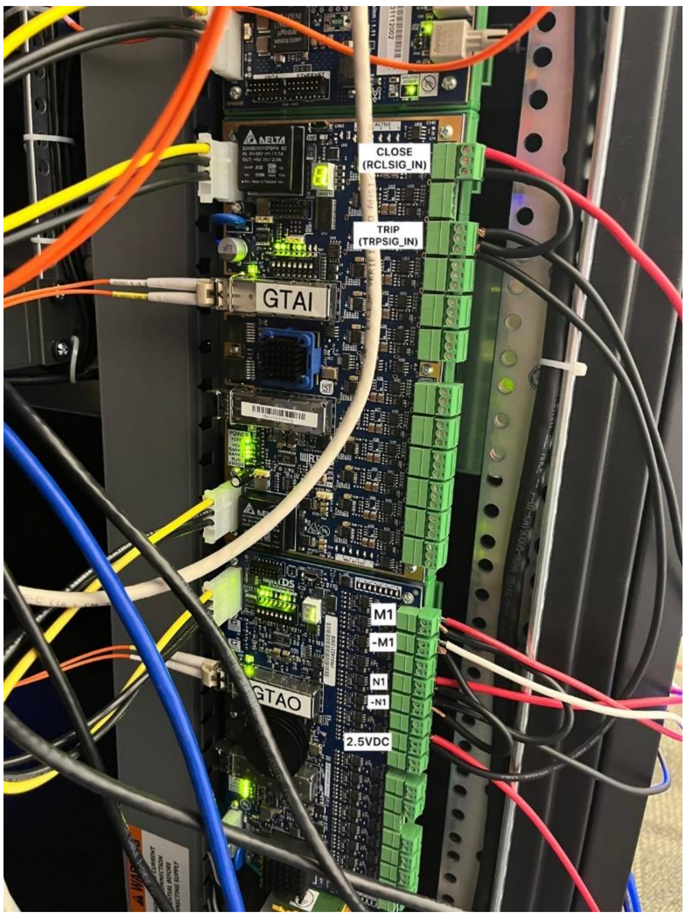


Figure A.21: Wiring as seen from the NovaCor

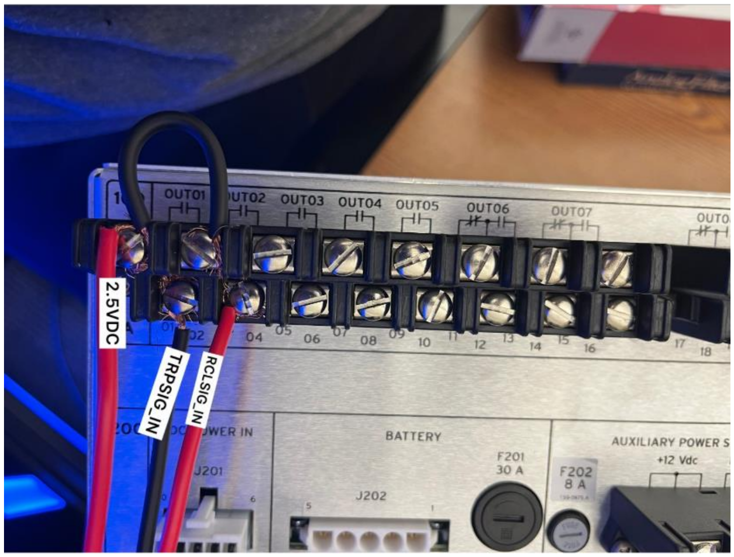


Figure A.22: Wiring as seen from the SEL-651R-2 switches

<u>AcSELerator Quickset Overview:</u>

This section gives a brief explanation of how to use AcSELerator Quickset from SEL so that further configuration of the relay can be done.

1) Open AcSELerator Quickset.
2) From the starting menu, open “Communication” -> “Parameters” and make sure the settings match Figure A.23.
3) The relay has a square shaped port on the top left of the front panel. Take a printer cable and plug it in the USB side of the cable into a computer USB port, and the printer cable side to that square port on the relay.
4) In the main menu, press “Read”. The interface shown in Figure A.24 should appear after 1-2 minutes. From the main settings menu, a few settings are relevant to the configuration of the relay for frequency and voltage as used in this project. They are shown in Figures A.25 to A.27. The main explanation of these settings can be found in the “SEL-651R-2 Instruction Manual” found on the SEL site.

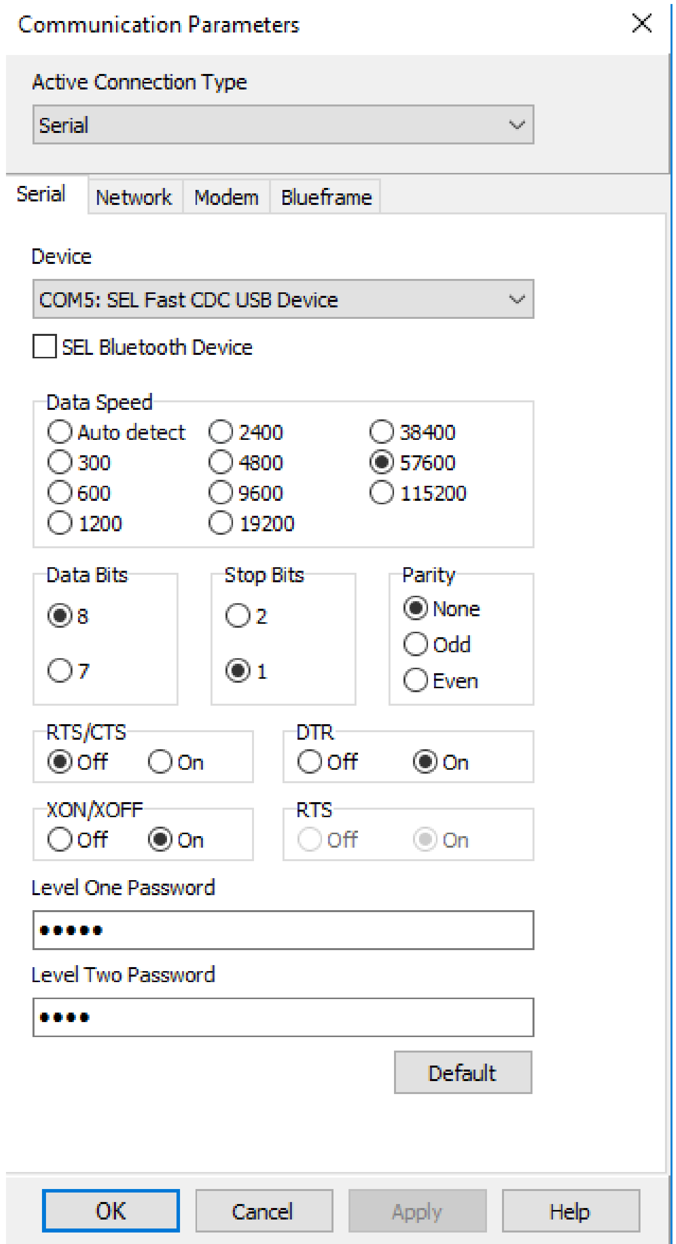


Figure A.23: Communication Parameters

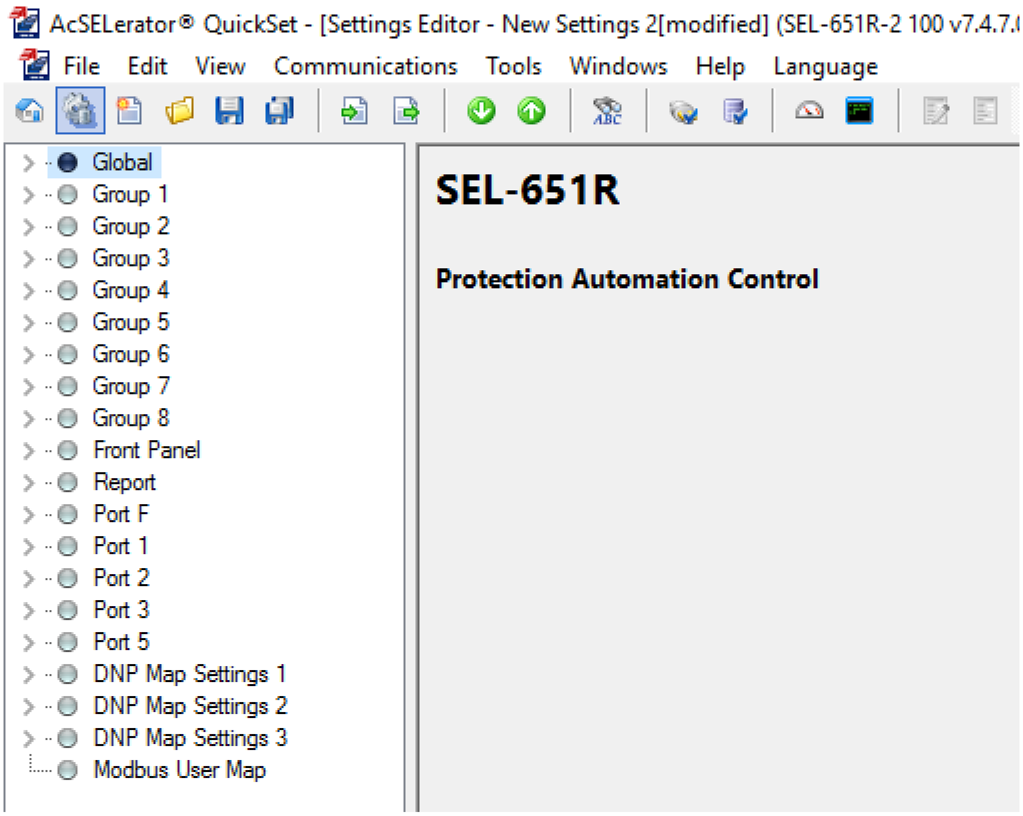


Figure A.24: Main SEL-651R-2 settings menu

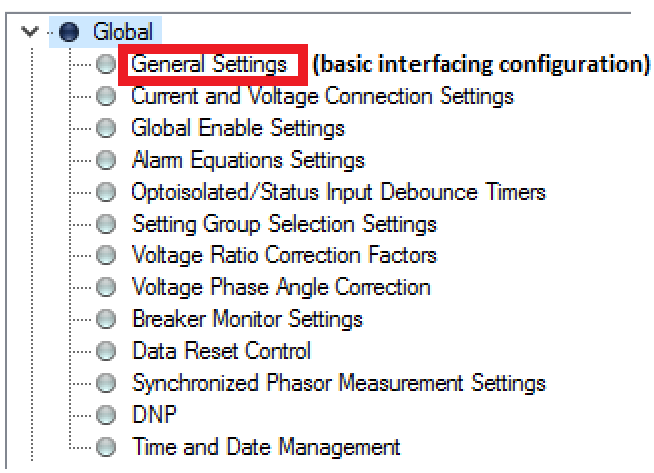


Figure A.25: Relevant Global Settings

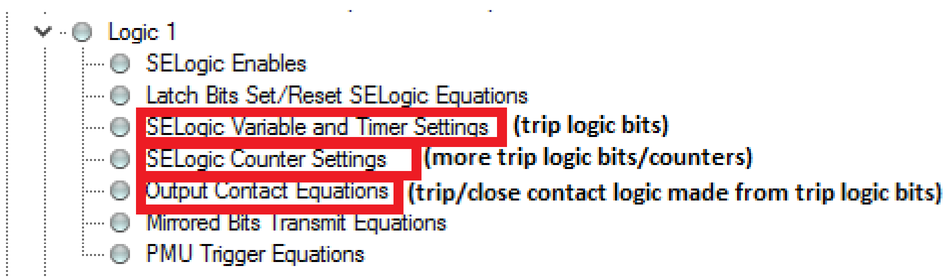


Figure A.26: Relevant Logic 1 Settings (under Group 1)

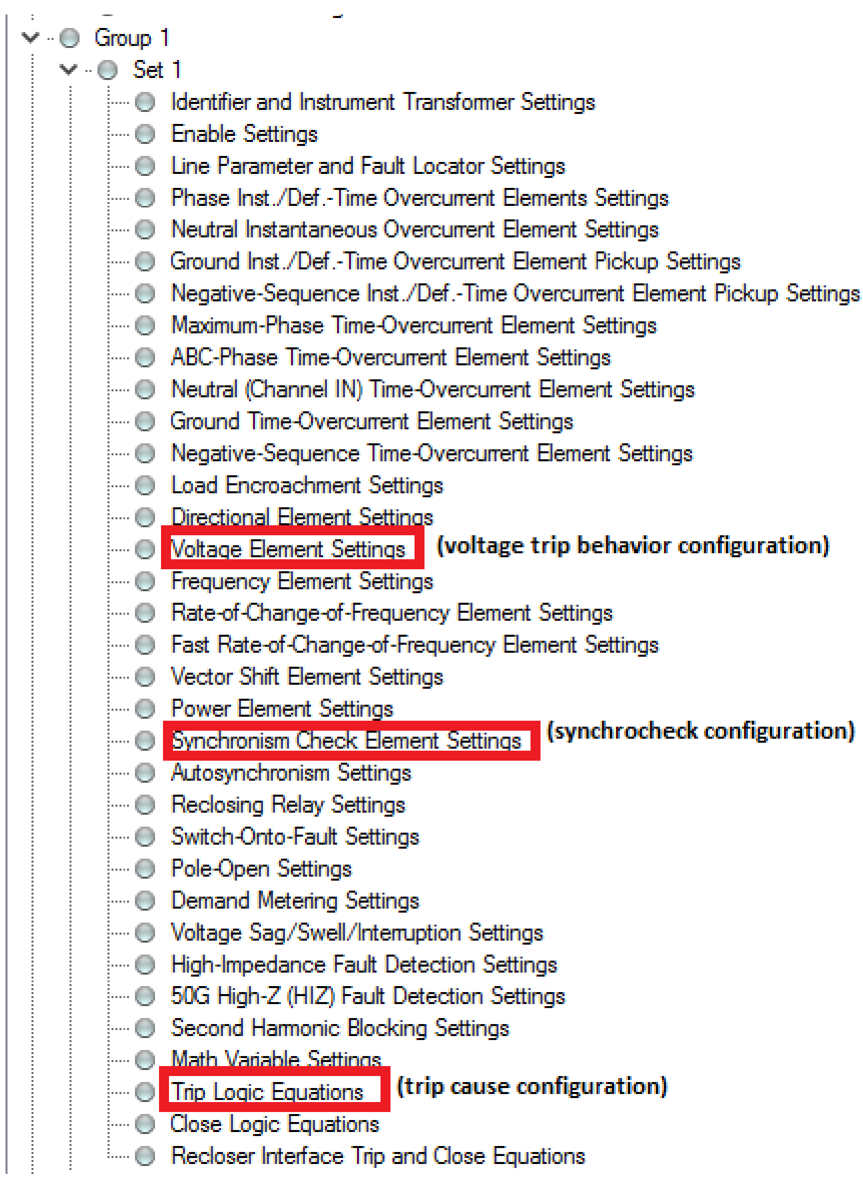


Figure A.27: Relevant Set 1 Settings (under Group 1)

5) For any changes in configuration for LED feedback from the relay, select “Front Panel” in Quickset.
6) For any other configuration outside of these settings, consult the “SEL-651R-2 Instruction Manual” found on the SEL site after creating an account.